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Flood Risk Assessment in the Netherlands: A Case Study for Dike Ring South Holland

Sebastiaan N. Jonkman,[1,2]* **Matthijs Kok,**[1,3] **and Johannes K. Vrijling**[1]

Large parts of the Netherlands are below sea level. Therefore, it is important to have insight into the possible consequences and risks of flooding. In this article, an analysis of the risks due to flooding of the dike ring area South Holland in the Netherlands is presented. For different flood scenarios the potential number of fatalities is estimated. Results indicate that a flood event in this area can expose large and densely populated areas and result in hundreds to thousands of fatalities. Evacuation of South Holland before a coastal flood will be difficult due to the large amount of time required for evacuation and the limited time available. By combination with available information regarding the probability of occurrence of different flood scenarios, the flood risks have been quantified. The probability of death for a person in South Holland due to flooding, the so-called individual risk, is small. The probability of a flood disaster with many fatalities, the so-called societal risk, is relatively large in comparison with the societal risks in other sectors in the Netherlands, such as the chemical sector and aviation. The societal risk of flooding appears to be unacceptable according to some of the existing risk limits that have been proposed in literature. These results indicate the necessity of a further societal discussion on the acceptable level of flood risk in the Netherlands and the need for additional risk reducing measures.

KEY WORDS: Flood defense; flood risk; loss of life; quantitative risk analysis; risk evaluation

1. INTRODUCTION

1.1. General

The catastrophic flooding of New Orleans due to Hurricane Katrina in the year 2005 showed the world the catastrophic consequences of large-scale floods. More than 1,100 people were killed in the State of Louisiana and the majority of fatali-

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ties occurred in the flooded areas of New Orleans. A study by the Interagency Performance Evaluation Team[1] provides estimates of the direct damages to residential and nonresidential buildings (US $21 billion) and damages to public structures and utility infrastructure (US $ 7 billion). Almost two years after the disaster, the City of New Orleans has got merely a half of its population back, and business activity is reviving slowly.[2] The flooding after Hurricane Katrina illustrates the vulnerability of modern societies that are situated in low-lying areas in deltas. This is particularly the case in the Netherlands, where more than 60% of the country is below sea level or the high water levels of the rivers (see also next section). The anticipated effects of climate change, the expected sea level rise, and a growth of the population and economy in flood-prone areas are expected to result in an increase of flood risk levels in the future. It is

important to have insight into the possible consequences and risks of flooding to support decision making regarding flood defense strategies and protection standards.

The objective of this article is to show how the flood risks for such flood-prone areas in the Netherlands can be determined and evaluated. The analyses in this article focus on the hazards to people and potential loss of life, as this is one of the most important types of consequences. The presented analyses are based on a method that has been developed for the estimation of loss of life due to floods[3] and information from the project "Flood Risk and Safety in the Netherlands" (FLORIS).[4–6] That project has aimed to give insight into flood risk levels in the Netherlands by determining the probabilities and consequences of flooding due to failure of primary flood defenses (dikes, dunes) in the Netherlands. Results are presented for the area South Holland, as this is the largest and most densely populated area in the Netherlands (see Section 1.3 for a further description).

The article is structured as follows. The remainder of Section 1 gives general background information regarding flood defense in the Netherlands and the case study area. The methods used for risk quantification are summarized in Section 2. Results are presented in Section 3. A discussion of the results is provided in Section 4, in which the calculated flood risk levels are compared with the risk levels in other sectors and existing criteria for risk evaluation. Concluding remarks are given in Section 5.

1.2. Flood Defense in the Netherlands

Large parts of the Netherlands are below sea level or the high water levels of rivers and lakes. Without the protection of dikes, dunes, and hydraulic structures (e.g., storm surge barriers) approximately 60% of the country would be flooded regularly. Due to this situation, the Netherlands has a long history of flood disasters. The last disastrous flood occurred in 1953. A storm surge from the North Sea flooded large parts of the southwest of the country. Apart from enormous economic damage, more than 1,800 people drowned during this disaster. After this event, the Delta Committee was installed to investigate the possibilities for a new approach to flood defense. The committee proposed new safety standards for flood defenses. These standards were based on an econometric analysis in which the incremental investments in more safety were balanced with the reduction of the risk.[7] The flood-prone areas in the Netherlands

are divided into so-called dike ring areas, i.e., areas protected against floods by a series of water defenses (dikes, dunes, hydraulic structures) and high ground. The safety standards for the various dike rings are shown in Fig. 1. The height of these standards depends on the (economic) value of the area and the source of flooding (coast or river). For coastal areas design water levels have been chosen with exceedance frequencies of 1/4,000 per year and 1/10,000 per year. For the Dutch river area, the safety standards were set at 1/1,250 per year and 1/2,000 per year. Some smaller dike ring areas bordering the river Meuse in the south of the country have a safety standard of 1/250 per year. For every dike ring area, design water levels are determined with a probability of exceedance that corresponds with the safety standard. The current design criteria for flood defenses and the process for safety evaluation are based on these design water levels.

These safety standards were mostly derived in the 1960s. Since then, the population and economic values in these dike ring areas have grown drastically. A recent investigation[8] concluded that these standards are no longer in proportion to the economic and societal values that are meant to be protected by the flood defense systems. In the last decade, the Dutch Ministry of Transport, Public Works, and Water Management has initiated the FLORIS project[4] to reinvestigate the level of flood risk in the Netherlands. The outcomes of this study will be used to assess and evaluate the level of flood risk in the Netherlands and the need for alteration of the current policies and standards.

1.3. Study Area: Dike Ring South Holland

South Holland (dike ring number 14 in Fig. 1) is the largest dike ring in the Netherlands. It is the most densely populated area in the country and it includes major cities such as Amsterdam, Rotterdam, and Den Haag. The area has 3.6 million inhabitants and the total potential direct economic damage is estimated at €290 billion.[5] Fig. 2 gives an overview of the area and the main cities. The area is threatened by floods from the North Sea and the river system in the south (the Nieuwe Waterweg and Hollandsche IJssel). The flood defense system consists of sand dunes along the coast and earthen dikes along the rivers. As part of the delta works, storm surge barriers have been constructed in the river system (e.g., the Maeslant barrier near Hoek van Holland and a barrier in the Hollandsche IJssel) to prevent storm surges in the North Sea leading to flooding in
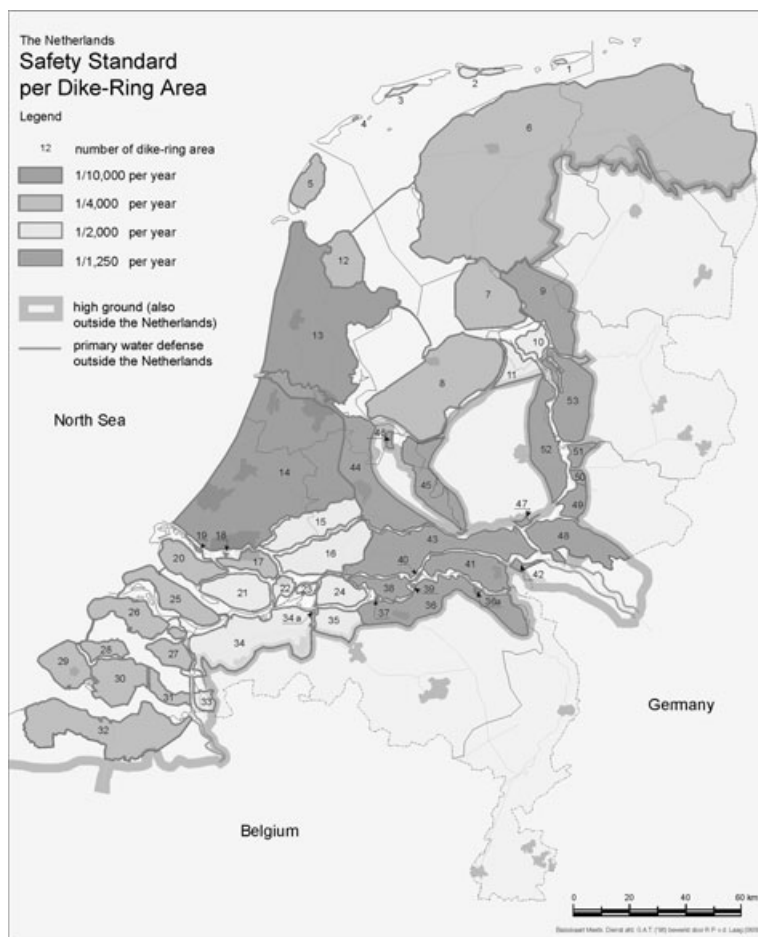
Fig. 1. Dike ring areas in the Netherlands and safety standards (source: Rijkswaterstaat). Smaller dike ring areas along the river Meuse are not shown.

the lower river system. Depending on the location of a breach, substantial parts of this dike ring can be flooded, as the area includes some of the lowest parts of the Netherlands. Some of these areas are almost 6 meters below mean sea level.

Assessment of the risk for this area is of particular interest as: (1) it is the largest dike ring area in the Netherlands with the highest potential damage; (2) the first safety standards and design water level (with a 1/10,000 year probability of exceedance) were determined for this area by the Delta Committee in the 1960s;[7] (3) it can be flooded from the coast and rivers, leading to different damage patterns and particular challenges with respect to evacuation of the population.

2. METHOD FOR FLOOD RISK ANALYSIS

2.1. General Approach

Methods for the analysis of flood risk, see, e.g., References 9 and 10, generally include three main

steps: (1) determination of the probability of flooding; (2) simulation of flood characteristics; and (3) assessment of the consequences. In theory, the risk estimate should be based on a fully probabilistic analysis in which all the possible loads on the flood defense system, the resistance of the system, and possible breaches, flood patterns, and their consequences are included. Such an approach would require a numerical elaboration and a very large number of simulations. Due to limitations in time and resources a simplified approach has been chosen in this study. A limited number of so-called flood scenarios has been selected and elaborated. Each scenario refers to a breach at a certain location in the flood defense system (or a set of multiple breaches) and the resulting pattern of flooding. For the selected flood scenarios the course of flooding and consequences have been analyzed by means of deterministic methods. By combination of information on the probability of the scenarios and their consequences the risk can be estimated. The selection of flood scenarios should ideally be based on their contribution to the overall
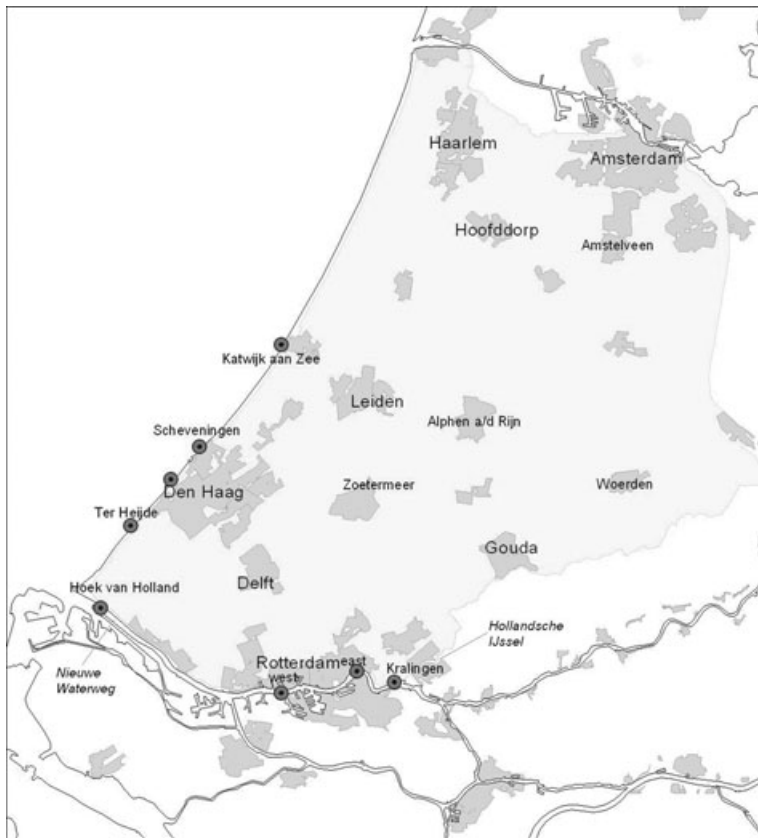
Fig. 2. Overview of dike ring South Holland. Breach locations that are used for analysis of flood scenarios are indicated in the figure with dots.

risk level,[11] but this would require numerical elaboration of all the flood scenarios. In this study, the flood scenarios have been selected with the largest contribution to the overall flooding probability. It is expected that these scenarios are also the most relevant in terms of risk. For the studied case, the probability of scenarios with very extreme consequences is very small so that their contribution to the risk is relatively small (see also Section 3.1 for further discussion). This approach for scenario selection has its limitations and several refinements and improvements are possible. However, this approach is expected to provide realistic and indicative estimates of the actual risk level. Below, the methods that have been used in the FLORIS project for the analysis of the probability of flooding, the flood event, and the consequences are further described.

2.2. Determination of the Probability of Flooding

In assessing the probability of failure of a flood defense system it is necessary to take into account that failure of different elements in the system and (for each element) different failure mechanisms can lead to flooding.[12] The elements in the studied system include dune and dike sections and hydraulic structures. In the assessment of the failure probability the hydraulic load conditions and the resistance (or strength) of the flood defense are taken into account. The most important load characteristics are the water level and waves. The resistance properties include the geometry of the flood defense and the soil characteristics. For every type of element in the system, the relevant mechanisms that can lead to failure are taken into account. For example, relevant failure mechanisms for a river dike include overflowing, instability, and seepage/piping. For sand dunes along the coast erosion of the dune is the most important mechanism. A limit state function is used for each failure mechanism and it describes which combination of load and resistance leads to failure. For example, a dike section will fail due to overflow/overtopping if the outside water level exceeds the height of the dike.

The resistance and load characteristics are characterized by means of stochastic variables. Both inherent uncertainties (e.g., related to the occurrence

of water levels in time) and knowledge uncertainties (e.g., limited knowledge of the soil characteristics or uncertainties in a model) are described by means of stochastic distributions. The two types of uncertainty are integrated into one numerical estimate of the probability of failure by means of Bayesian probability theory (see also Section 2.6 in Reference 13 for further background). This means that statistical information and expert opinions are combined to provide quantitative estimate of the probability.[14] The resulting probability values are expressed as probabilities per unit time, i.e., per year.

The above approach has been implemented in an advanced program for reliability analysis of ring dike systems: PC-RING. It considers all principal dike failure modes for the elements in a system and takes into account dependencies between failures of the elements (see References 15 and 16 for a further description). With this model, the probability of occurrence can be determined for a so-called flood scenario. A flood scenario refers to one breach or a set of multiple simultaneous breaches in the dike ring and the resulting pattern of flooding, including the flood characteristics. To determine a set of possible flood scenarios, the dike ring system is first divided into different stretches. The stretches are chosen in such a way so that the flooding pattern and damage will be very similar for different breaches within one stretch. Especially in the Netherlands where the terrain behind the flood defenses is relatively low-lying and flat such homogeneous stretches can be identified.[9] The probability of a breach in a stretch is determined with the PC-RING model by considering the contribution of different elements within one stretch to the flooding probability. Also, possible flood scenarios with multiple simultaneous[4] breaches in different stretches are considered in the assessment. As output, the probabilistic PC-RING model provides insight into the set of the (physically) possible flood scenarios and their probabilities. The sum of the probabilities of all the flood scenarios equals the flooding probability of the whole system.

2.3. Simulation of Flood Characteristics

To assess the damage of a flood it is necessary to have an understanding of its hydraulic characteristics, such as depth, velocity, rise rate, and arrival

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[4] With simultaneous breaches we refer to the occurrence of multiple breaches during the same flood event (e.g., during one high river discharge or one storm surge).

time. These are determined for different flood scenarios. For South Holland, several flood scenarios have been analyzed to account for the differences in flood patterns and resulting consequences. For each flood scenario a representative location of breaching has been assumed and the outside hydraulic load conditions (water level, waves) and breach growth rate have been determined. Given the simplified approach adopted in this study (see Section 2.1), deterministic estimates of the hydraulic boundary conditions and breach growth have been used as input. These have been chosen somewhat more conservatively than the design water level that follows from the probabilistic analysis to account for the possibility of higher boundary conditions. However, in theory, the full range of loading variables and the resulting flood patterns would have to be analyzed.[11]

The development of the flood flow in the area has been simulated with a two-dimensional hydrodynamic model (Sobek 1D2D) that has been developed by WL|Delft Hydraulics. The model gives insight into the development of the inundation that results from a breach in the flood defense. As output, the model gives values of the depth and flow velocity for different time steps. The value of the rise rate of the water has been determined based on these results. An example of the results of a flood simulation for South Holland is given in Fig. 3. The presence of line elements in the area, such as roads, railways, and dikes, could influence the flood flow as they may act as compartment dikes that block the flood flow.

2.4. Assessment of the Consequences

The consequences for different flood scenarios can be estimated based on the outputs of flood simulations and information regarding population density and spatial distribution of economic assets. The direct financial economic damages have been calculated with existing damage functions.[17,18] These relate the damage level (as fraction of total value) to the occurring water depth. Below, the proposed approach for estimation of loss of life is briefly summarized. Other damage categories, such as the number of injuries and losses of ecological and historical values, have not been analyzed.

2.5. Estimation of Loss of Life

Loss of life has been determined with the method proposed in References 3 and 19. The method encompasses two main steps: (1) estimation of the
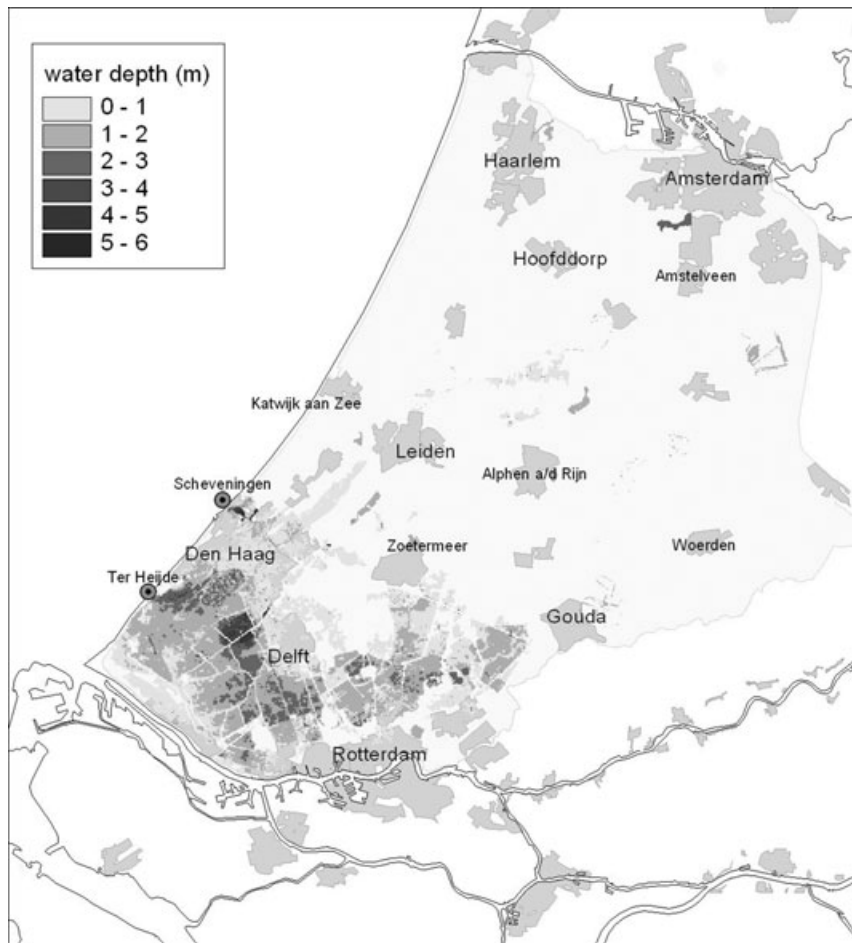
Fig. 3. Example of output of a flood simulation showing the maximum water depth for a flood scenario with breaches at Den Haag (Scheveningen) and Ter Heijde (breach locations are indicated with dots).

exposed population; and (2) estimation of mortality among the exposed population.

First, the exposed population for each flood scenario is estimated based on the time available before flooding and the time required for evacuation. The time available before flooding is determined by the possibilities to predict the flood, leading to different available times for coastal and river flooding. The time required is determined with an evacuation model.[20] This is a macro-scale traffic model that takes into account the road network and the road capacities, the locations and capacities of exits in the considered area, and the effects of traffic management. The model has been calibrated on historical traffic data in the Netherlands. As input the number of evacuees and the temporal distribution of departure of the evacuees have to be given. Delays due to decision making, warning, and response of the population have to be taken into account. As output, the model provides an estimate of the evacuated frac-

tion of the population as a function of time. If the time available is known, the evacuated fraction of the population in the exposed area can be estimated. The reduction of the number of exposed due to shelter is found by assuming that inhabitants of high-rise buildings find shelter within the exposed area. In the Netherlands, this fraction of the population can range between 0 (rural areas) and 0.2 (urban areas).

The number of people exposed has been determined for four so-called evacuation situations that differ with respect to the type of flooding and the level of organization of the evacuation (see the event tree in Fig. 4). The type of flood mainly influences the time available, while the level of organization of the evacuation influences the time required. Each situation results in a different number of people exposed.

For risk quantification, the (conditional) probabilities for these different evacuation situations that could occur for one flood scenario need to be known.
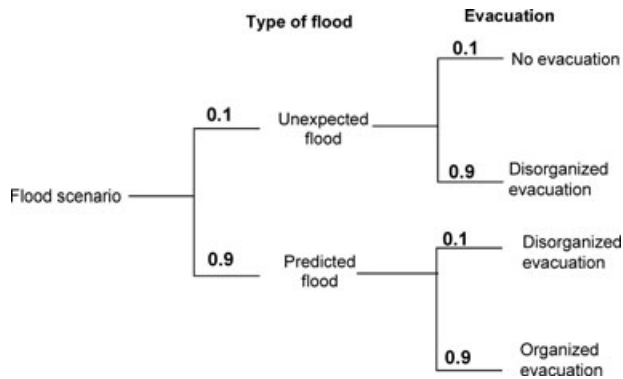
Fig. 4. Event tree showing different evacuation situations that have been used to estimate the number of people exposed.

Fig. 6. Mortality function and observations for the zone with rapidly rising waters.[3]

Conditional probabilities for these situations have been estimated by means of discussion with a group of experts.[6] They jointly gave estimates of the probabilities of different situations based on the type of threat (coast vs. river), the likelihood of unexpected occurrence of failure of the flood defense, and the level of evacuation preparedness. As an example, estimates of (conditional) probabilities for different evacuation situations for a coastal flood scenario in South Holland are indicated in Fig. 4.

Consequently, the loss of life is calculated for each situation by means of mortality functions derived from Reference 3. These functions relate the mortality (= number of killed people/number of people exposed) to the local flood characteristics, such as water depth, rise rate, and flow velocity. For a flood due to breaching of a flood defense three zones are distinguished to account for different flood characteristics and mortality patterns (see Fig. 5). For example, the breach zone will be characterized by many collapsed buildings and a high mortality due to high flow velocities just behind the breach. The zone with rapidly rising waters is also characterized by a relatively high mortality because people are less likely
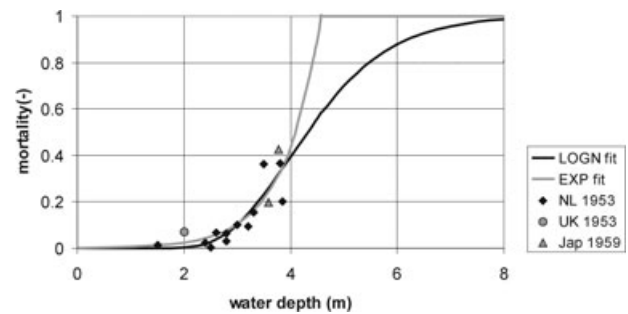
to reach shelters, higher ground, or higher floors of buildings. For each zone a mortality function has been derived based on observations for historical disasters, such as the floods in 1953 in the Netherlands and floods in Japan after Typhoon Isewan in 1959. For these historical events, data regarding the mortality and flood characteristics (depth, velocity, and rise rate) have been collected. It has been investigated whether a statistical relationship (a so-called mortality function) can be derived to relate the mortality to the flood characteristics. An example of a mortality function for the zone with rapidly rising water is shown in Fig. 6. It is noted that these functions will be associated with many uncertainties, such as the behavior of people affected. Model uncertainties in the mortality functions have been derived in Reference 3 (Fig. 7–13, p. 207) and can be presented by means of the 95% confidence interval around the best-fit mortality function. One other issue concerns the possibility of temporal differences in mortality trends, for example, due to changes in building quality and improvement of warning systems. This might reduce the validity of the derived functions that are mainly based on event data from the 1950s. However, comparison of the outcomes of the proposed method with information from relatively recent flood events
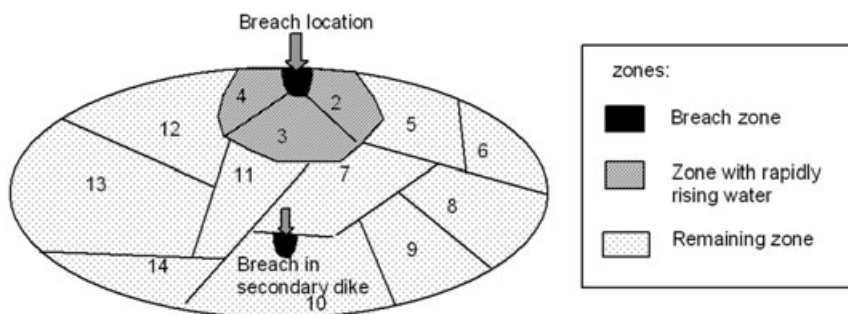

Fig. 5. Proposed hazard zones for loss of life estimation.[3]

shows that it gives an accurate approximation[5] of the number of fatalities.[3] A more detailed description of the method, including a further discussion of the main uncertainties and sensitivities, is given in Reference 3.

3. RESULTS OF RISK QUANTIFICATION

In this section, the results of risk quantification are presented. First, probability and consequence estimates for different flood scenarios in South Holland are presented (Section 3.1). These are used in Section 3.2 to calculate the individual and societal risk.

3.1. Probability and Consequence Estimates

Flooding of South Holland can occur due to breaches at different locations and various combinations of (multiple) breaches. A set of 427 physically possible flood scenarios has been identified with the available probabilistic model (see Sections 2.1 and 2.2). The overall probability of flooding for dike ring South Holland is found by summing the probabilities of all these scenarios and this results in a value of 3.99×10^{-4} per year, or approximately once in 2,500 years.[4] Table I shows the probabilities for the 10 flood scenarios with the highest probabilities in descending order.[5] It is noted that the table includes some flood scenarios with breaches at multiple locations. Each scenario is indicated by means of its breach location(s) and these locations are shown in Fig. 2. For these 10 scenarios, flood simulations have been made and the financial economic damages have been assessed (see results in Table I).

The first 10 scenarios result in a total probability of 3.94×10^{-4} per year and thereby they determine approximately 99% of the total flooding probability. Based on the estimate of maximum contribution to the risk of the remaining 417 flood scenarios[5] it is found that the selected scenarios provide a reasonable approximation of the risk level.[6] The above selection implies that flood scenarios with probabilities

Table I. Probabilities and Economic Consequences for Flood Scenarios for Dike Ring South Holland[5]

Breach Location(s)	Probability (1/Year)	Economic Damage (€10^9)
Rotterdam (Kralingen)	1.36×10^{-4}	6.8
Den Haag (Boulevard)	1.19×10^{-4}	1.9
Den Haag (Scheveningen)	7.63×10^{-5}	3.6
Katwijk	2.44×10^{-5}	11.3
Hoek van Holland	1.15×10^{-5}	2.0
Katwijk and Den Haag	8.36×10^{-6}	6.0
Den Haag (Scheveningen) and Ter Heijde	7.23×10^{-6}	22.8
Rotterdam west	4.89×10^{-6}	2.5
Rotterdam east	3.65×10^{-6}	5.7
Katwijk, Den Haag, and Ter Heijde	2.23×10^{-6}	37.2

that are smaller than approximately 10^{-6} per year have not been included in the analysis.

It is noted that the presented economic damages for the flood scenarios are substantially smaller than the absolute maximum possible economic damage for dike ring South Holland. That value, 290 billion Euros, would occur if the whole area of the dike ring South Holland were completely flooded. This indicates that the flood scenarios in South Holland are only expected to flood a certain part of the whole area.

For each flood scenario the loss of life has been estimated for different levels of evacuation effectiveness, ranging from no evacuation to a fully organized evacuation (see also Fig. 4). Results are presented in Table II, which also shows the number of people exposed in the flooded area for a situation without evacuation.

The effect of evacuation on the loss of life has been estimated with the method presented in Section 2.3, which requires insight into the time available and the time required for evacuation. Most of the elaborated flood scenarios are associated with coastal storm surges. For these events, the time available for evacuation (i.e., expected time between the final prediction and dike breach) is generally limited, and estimated to be between 10 and 20 hours. Analyses with an evacuation model show that the required time for complete evacuation of (parts of) South Holland is often more than 24 hours and sometimes more than 50 hours.[21] Depending on the considered flood scenario and the type of evacuation (organized or disorganized), the estimated evacuated fraction of the population ranges between 0.2 (for a predicted flood

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[5] For most of the considered validation cases, the predicted loss of life deviates less than a factor of two from the observed mortality.[3]

[6] The possible contribution of the remaining flood scenarios had been conservatively estimated as follows. The total probability of the 417 remaining flood scenarios (approximately 5×10^{-6}) has been multiplied with the largest consequence of the first 10 scenarios. In that conservative case, the remaining scenarios determine 10% of the expected economic damage.[5]

Table II. Number of People Exposed and Number of Fatalities by Flood Scenario (Rounded by Decimals); A Distinction Is Made Between Different Evacuation Situations

| | | Fatalities | | | |
| | | Unexpected Flood | | Predicted Flood | |
Flood Scenario	People Exposed in Flooded Area	No Evacuation	Disorganized Evacuation	Disorganized Evacuation	Organized Evacuation
Rotterdam (Kralingen)	180,880	1070	1060	900	860
Den Haag (Boulevard)	112,140	110	100	100	100
Den Haag (Scheveningen)	179,270	230	220	210	210
Katwijk	205,960	400	380	340	330
Hoek van Holland	102,690	110	100	100	100
Katwijk and Den Haag	299,280	550	530	470	460
Den Haag (Scheveningen) and Ter Heijde	706,650	3460	3290	3210	3170
Rotterdam west	107,440	190	180	170	170
Rotterdam east	187,840	600	600	510	480
Katwijk, Den Haag, and Ter Heijde	1,016,560	5090	4850	4720	4670

and an organized evacuation) and 0.01 (for an unexpected flood) (see Reference 21 for more details). These findings imply that only a very limited fraction of the population of South Holland can be evacuated in the case of a (threatening) coastal flood. Therefore, there are small differences between the fatality numbers for different evacuation situations for one flood scenario in Table II.

As an example, the output for the scenario with breaches at Den Haag (Scheveningen) and Ter Heijde is considered. For a situation without evacuation, the estimated number of fatalities is more than 3,400 and more than 700,000 people are exposed. Fig. 7 shows the spatial distribution of the number of fatalities. The majority of fatalities, nearly 1,900, occur in areas with rapidly rising waters and large flood depths, for example, South of Den Haag.

Discussion of Results

Results indicate that a flood of dike ring South Holland can cause hundreds to thousands of fatalities. In the case of flooding of South Holland, it is expected that more than 100,000 people will be affected. In the analyzed set of scenarios, the largest numbers for the exposed population (1 million—without evacuation) and loss of life (around 5,000) are found for a flood scenario with multiple breaches along the coast, i.e., at Katwijk, Den Haag, and Ter Heijde. This flood scenario affects a large part of the western part of South Holland, yet with a small probability (approximately 2×10^{-6} per year). For

this scenario (and one other flood scenario) the estimated number of fatalities is higher than the loss of life caused by the flood disaster in New Orleans due to Hurricane Katrina in the year 2005. That event led to more than 1,100 fatalities in the State of Louisiana and most of these fatalities occurred in the flooded areas.[3] This illustrates the catastrophic potential of large-scale flooding of low-lying areas in the Dutch delta.

The results from Table II reflect the differences in outcomes between flood scenarios. Mortality by scenario (i.e., the number of fatalities divided by the number of people exposed) varies between 0.1% and 0.6% with an average of 0.3% for the considered set of scenarios. The mortality values are relatively constant because the flood conditions (depth, velocity, rise rate) for the various flood scenarios are fairly similar. However, larger variations in outcomes could emerge when model uncertainty in the loss of life model is taken into account. It is possible to assess the effect of the model uncertainty that is associated with the variation in and shortage of empirical mortality data that have been used to derive the mortality function. Application of the mortality functions for the 95% confidence interval from Reference 3 shows that the upper and lower bounds approximately differ by a factor of two from the values presented in Table II.

Other uncertainties can be associated with the selection and modeling of flood scenarios. The consequences for a single scenario are strongly influenced by the choice of outside hydraulic load
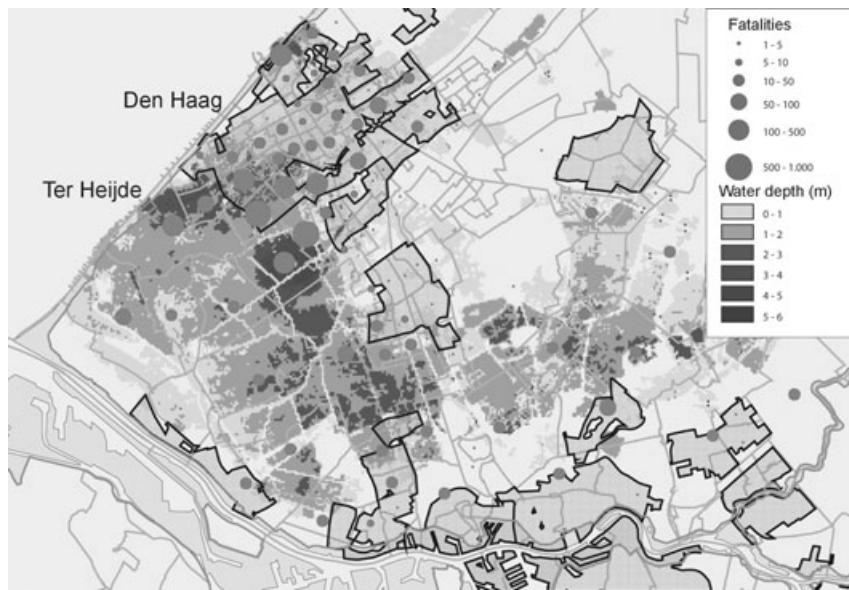
Fig. 7. Fatalities by neighborhood and flooded area for the scenario with breaches at Den Haag (Scheveningen) and Ter Heijde. Locations of the breaches are shown in Fig. 3.

conditions (storm surge height and duration), and the modeling of breach growth. Another issue concerns the assumptions with respect to the number of occurring breaches, as the number of breaches will affect the extent of the flooded area and the consequences. In the dataset, the scenario with the largest consequences has three breaches. However, documentation of historical coastal floods shows that these have been always characterized by even more breaches. Examples are the 1916 floods in the Netherlands (22 breaches),[22] 1953 floods in the Netherlands (approximately 140 breaches), the 1966 floods in Hamburg (more than 10),[23] and the flooding of New Orleans after Hurricane Katrina (approximately 25 breaches). In the remaining 417 flood scenarios that have not been elaborated for consequence analyses (see above) there are some scenarios with four or five breaches. It is expected that the consequences for these scenarios could be larger than the highest value reported in Table II. It is important to note that the probabilities of such extreme scenarios are small and in the order of magnitude of 10^{-7} to 10^{-8} per year or even smaller. It is thereby expected that these extreme scenarios have a relatively limited contribution to the expected damage, but it is recommended to take them into account in a more detailed risk assessment.

3.2. Risk Quantification

Based on the above information regarding probabilities and consequences, the individual risk and the societal risk are quantified. The individual risk indicates the probability of death for a person at a certain location in South Holland due to flooding. The societal risk expresses the probability of a disaster with many fatalities. These two so-called risk measures are used in the Netherlands and other countries to display and limit the risks in different sectors, such as the transport and storage of hazardous materials and the risks of airports.[24] In a similar way it would also be possible to determine the economic risk, e.g., in the format of an expected damage or a so-called frequency-damage or FD curve. However, given the scope of this article the presented analysis is limited to the risks of loss of life.

3.2.1. Individual Risk

First, individual risk (IR) is determined for South Holland with the following formula:

$$IR(x, y) = \sum_i P_{f,i} F_{D|i}(x, y) \qquad (1)$$

where $IR(x,y)$—individual risk at location (x,y) [yr^{-1}]; $P_{f,i}$—probability of occurrence of flood scenario i [yr^{-1}]; $F_{D|i}(x,y)$—mortality at location (x,y) given flood scenario i [–].

As input the probabilities for different flood scenarios have been used (see Table I). The mortality at a location is calculated for each flood scenario with the mortality functions described in Section 2.4 and using the results of the flood simulations as input. In the elaboration of individual risk, permanent and unprotected presence of people in the area is assumed.

The effects of evacuation are neglected and the individual risk becomes of the characteristic of a certain location. This concept is thereby consistent with the definitions used in the Netherlands in the so-called external safety domain (see Section 4.1) where the individual risk is used for spatial planning and risk zoning.[25] It is possible to take into account the effects of evacuation in the determination of individual risk by means of an evacuation factor (see also Reference 3). However, this would lead to a very small reduction of individual risk as possibilities for evacuation in South Holland are very limited (see above).

Fig. 8 shows the individual risk for South Holland. The individual risk is relatively high (higher 10^{-5} per year) for deep areas exposed to flood scenarios with (relatively) high probabilities, e.g., in the areas northeast of Rotterdam and south of Den Haag. The highest individual risk is found northeast of Rotterdam and is around 10^{-4} per year. For most of the areas in South Holland the individual risk is relatively low (below 10^{-6} per year); see also Section 4.2 for a further discussion.

3.2.2. Societal Risk

Next, the societal risk is determined by means of a FN curve and the expected number of fatalities. In the analysis of societal risk, the effects of evacuation and probabilities of different evacuation types have been taken into account. Fig. 9 shows the FN curve for South Holland. It shows the probability of exceedance in one year of a certain number of fatalities due to one event. Both axes are generally displayed in logarithmic scale. The FN curve gives information on the probability of a flood disaster with a certain magnitude of consequences and is used to display and limit the risks in different sectors.[24]

The intersection with the vertical axis equals the flooding probability of South Holland (i.e., 3.99×10^{-4} yr^{-1}). Given the selection of scenarios, the FN
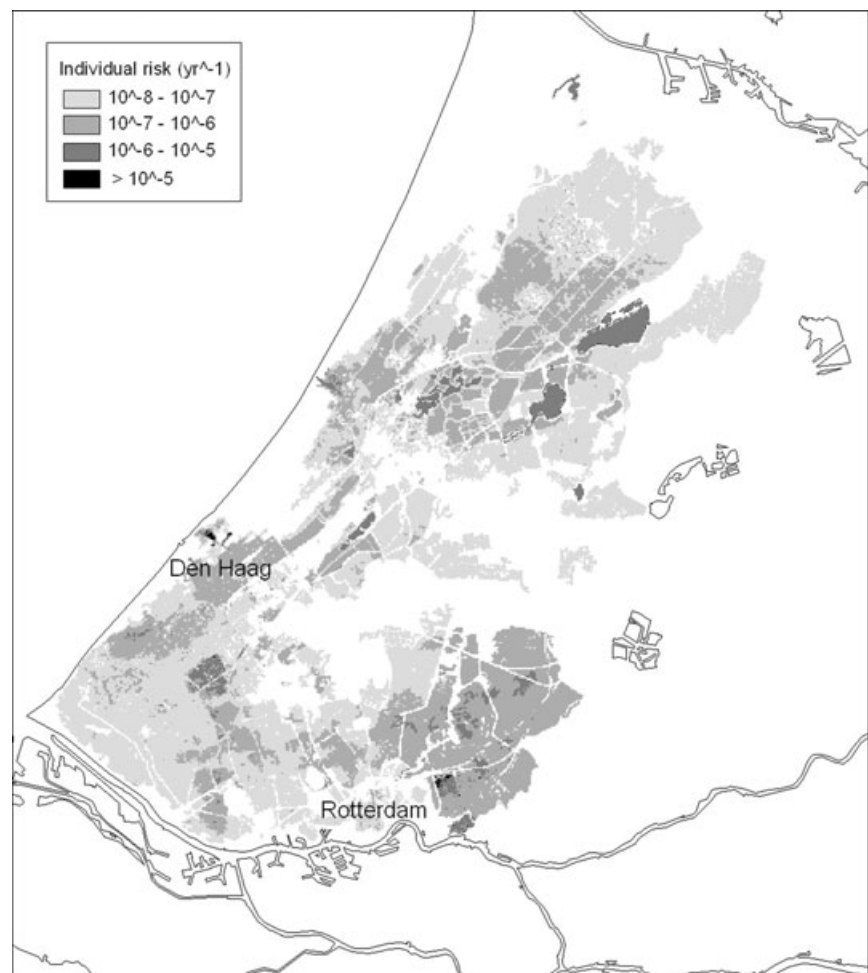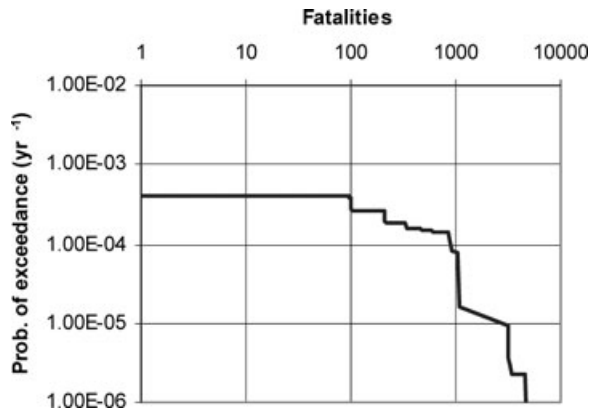

Fig. 8. Individual risk for South Holland.

Fig. 9. FN curve for flooding of South Holland.

curve is shown for values of the probability of exceedance that are higher than approximately 10^{-6} per year (see also Section 3.1). The FN curve shows that a flooding of South Holland is expected to lead to hundreds to thousands of fatalities.

Based on the probabilities and fatality numbers for the selected scenarios, the expected number of fatalities can be determined. The expected value can also be found by integrating the area under the FN curve.[26] This yields: $E(N) = 0.21$ fat/yr. The standard deviation equals: $\sigma(N) = 16.1$ fat/yr. For this type of small probability, large consequence event the expected number of fatalities per year is generally relatively small. However, for this type of event the number of fatalities in one single event can be large, resulting in a large standard deviation of the number of fatalities.

The selection of a relatively small number of scenarios in this analysis could likely affect the spatial

distribution of the individual risk (Fig. 8) and the FN curve (Fig. 9). To obtain a representative estimate of the spatial distribution of individual risk, sufficient scenarios should be analyzed that affect a certain location. To fully represent the FN curve sufficient scenarios should be analyzed for a range of probability and consequence levels. The presented analyses are limited to events with a probability larger than 10^{-6} year and the results are expected to give indicative, but realistic, first estimates of the risk level.

4. DISCUSSION

4.1. Comparison of the Societal Risk for Flooding with Other Sectors

In this section, the calculated societal flood risks for South Holland are compared with those in other sectors in the Netherlands. Fig. 10 depicts the FN curve for the external safety domain in the Netherlands and the calculated FN curve for flooding of South Holland. The external safety domain is concerned with the risks of transport and storage of dangerous goods, and airport safety in the Netherlands. The risks for this domain are assessed by means of standardized risk analyses methods and the risks for different installations are aggregated to the national level.[25] Within the standardized methodology the risk estimates for the external safety domain can be considered as best estimates. The uncertainties have been addressed in a similar way as for flooding (see also Section 2.2) and thereby the outcomes of the curves can be compared.

The societal risk for flooding of dike ring South Holland is larger than the risk for the external safety

Fig. 10. FN curve for the external safety domain for the Netherlands and flood risk for South Holland.[a]
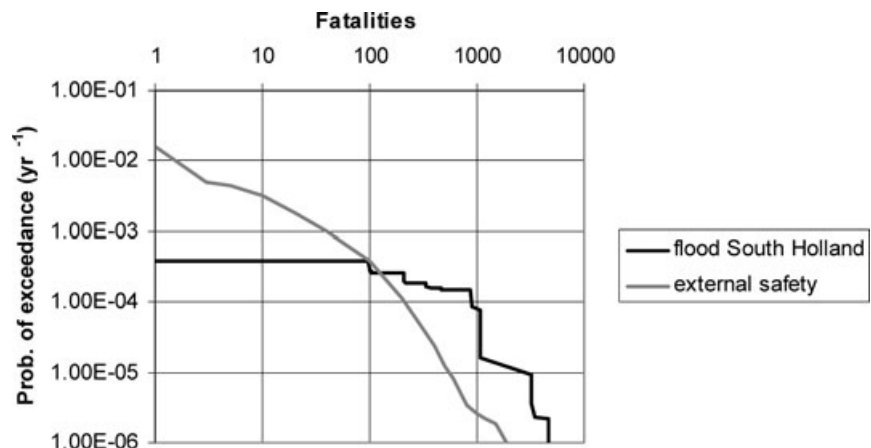
[a]Source of risk estimates for external safety: Milieu en Natuur Compendium (http://www.mnp.nl/mnc/i-nl-0303.html (accessed May 31, 2006)).

domain for events with more than 100 fatalities. The FN curves for other dike ring areas have to be added to obtain the societal risk for flooding at a national scale. The FN curves of different dike rings can be added if the risks are independent. This means that the FN curve for flooding in Fig. 10 will rise in the vertical direction as the probability of a flood disaster with certain consequences at a national scale will become larger if multiple dike rings are assessed. Based on the above results, it is expected that the flood risks in the Netherlands are higher than the risks for external safety. In general, the presented results confirm the outcomes of previous studies, e.g., Reference 8, that also concluded that the societal risk of flooding at a national scale is higher than the societal risk for the external safety domain.

The above comparison gives insight into the relative magnitude of the risks in different domains. It is noted that other risk measures, such as the expected number of fatalities and individual risk, can also be used to compare different risk domains. These types of information can be of interest for policymakers and could be used for a discussion about the necessary expenditures on risk reduction in different sectors. However, when comparing different risk sectors in decision making it is necessary to take into account the characteristics of the activities. For example, the perception of the activity and the benefits associated with the activity are important.[8,27,28]

4.2. Evaluation of the Flood Risk with Existing Risk Limits

In this section, the calculated flood risk levels are compared to existing risk limits that have been proposed in the literature. In the Netherlands, the concepts of individual and societal risk have been used to determine and limit the risk in the external safety domain. A more general framework for these risk limits has been proposed to make them applicable to other domains such as flooding. Further background on this framework is given in References 29–31.

First, the limitation of individual risk for all citizens ensures that no one will be disproportionally exposed to the risk and thus ensures equity. The following criterion for the limitation of individual risk is applied:

$$IR < \beta 10^{-4} \qquad (2)$$

In this expression, the value of the policy factor $\beta[-]$ varies according to the degree to which participation in the activity is voluntary and with the per-

ceived benefit. Available statistics regarding the risks of different types of activities have been evaluated[31] and this showed that purely voluntary activities (e.g., mountain climbing) entailed a much higher risk than involuntary activities (e.g., exposure to the risks of a hazardous installation). Based on the available statistics β values have been proposed ranging from $\beta = 0.01$ for involuntary activities to $\beta = 10$ for a voluntary activity for personal benefit.[31]

Second, a criterion for the judgment of societal risk is needed. The aggregated level of risk on a national scale could still be considered unacceptable even when the individual risks are considered acceptable. The acceptable societal risk at a national scale can be limited as follows:

$$1 - F_N(n) < C_N/n^\alpha \qquad (3)$$

where $F_N(n)$—cumulative distribution function of the number of fatalities; C_N—constant that determines the vertical position of the FN limit line at a national scale [$\text{yr}^{-1} \text{ fat}^{-\alpha}$]; α—risk aversion coefficient that determines the steepness of the FN curve.

The coefficient α reflects risk aversion toward large accidents. A standard with a value of $\alpha = 1$ is called risk neutral. If $\alpha = 2$, the standard is called risk averse as larger accidents with many fatalities are accepted with a relatively smaller probability than smaller accidents. In the further analysis, we assume a steepness of the limit line $\alpha = 2$, as this value is also used in other sectors in the Netherlands.[25] The value of the constant that determines the vertical position of the limit line at a national scale (C_N) can be derived from the following formula that has been proposed by Vrijling et al.:[31]

$$C_N = \left(\frac{\beta 100}{k}\right)^2 \qquad (4)$$

where k—constant, with a proposed value of $k = 3$ (see Reference 31 for further background).

The proposed approach takes into account characteristics of the activity by means of the policy factor β (see above). To obtain a risk limit for one installation, the nationally acceptable risk has to be distributed over the different installations/objects in one country. For a single installation a risk limit can be applied that has the same format as Equation (3), but the constant C_I is used instead of C_N to indicate the vertical position of the limit line for one installation, and $C_I \leq C_N$. In deriving the value of C_I, it seems reasonable to distribute the nationally acceptable risk over objects according to the relative size of an object at a national scale.
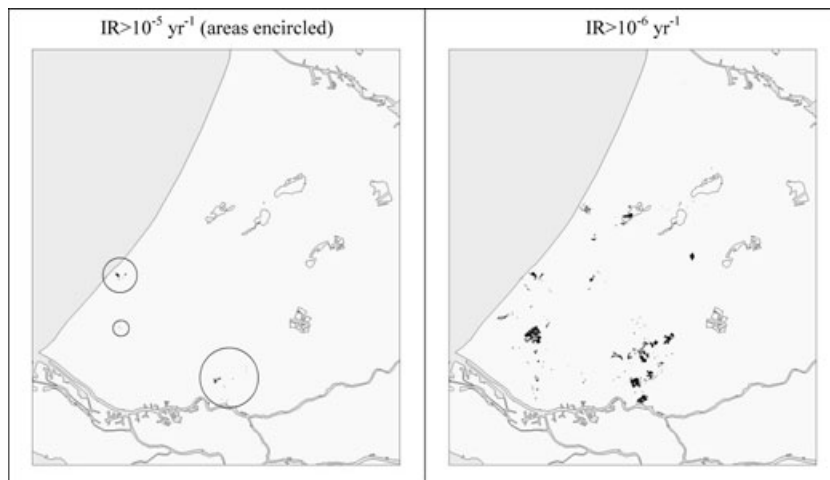
Fig. 11. Regions in dike ring South Holland that exceed the proposed limit values for individual risk due to flooding.

Finally, for a more complete risk evaluation also the use of economic optimization for this area is recommended; see, e.g., References 7 and 32. In such an approach, the sum of the investments in flood protection and the expected economic damages are minimized.

Comparison of the Flood Risk with Existing Risk Limits

First, the individual risk is analyzed with Equation (2). For flood risk, a value of β between 0.01 (characteristic for an involuntary activity with little benefit: IR $\leq 10^{-6}$ yr^{-1}) and 0.1 (characteristic for an involuntary activity with some benefit: IR $\leq 10^{-5}$ yr^{-1}) seems reasonable. These values correspond to IR limits used for chemical installations in the Netherlands.[25] Fig. 11 shows the areas of South Holland where the risks are unacceptable according

to these two proposed values. Results show that the individual risk level of 10^{-5} per year is exceeded only in a few areas. The 10^{-6} per year individual risk level is exceeded in low-lying areas south of Den Haag and east of Rotterdam.

The societal flood risk for dike ring South Holland is compared with the criteria for risk acceptance that have been discussed above. Fig. 12 compares the FN curve for flooding of South Holland with limit lines for different values of the constant that determines the vertical position of the limit line for the dike ring (C_I). According to Equation (4), a value of $C_N = 11$ for the limit line at a national scale is obtained for a value of $\beta = 0.1$. In the Netherlands, approximately 10 million people live in flood-prone areas and approximately 3.6 million of these people live in dike ring South Holland. Taking into account the relative size of South Holland would imply that the value of the constant that determines the vertical height of the limit line for the dike ring (C_I) would be approximately 36% of the constant that has been derived for the national scale (C_N) (see Reference 3 for more details). This leads to $C_I = 4$ and results show that the flood risks for South Holland would be unacceptable for this value of C_I. The actual flood risks would be considered acceptable for a limit line that corresponds to $C_I \approx 100$. It is thus found that the current societal risk for South Holland is higher than would be considered acceptable according to existing limits proposed in literature.[29–31]
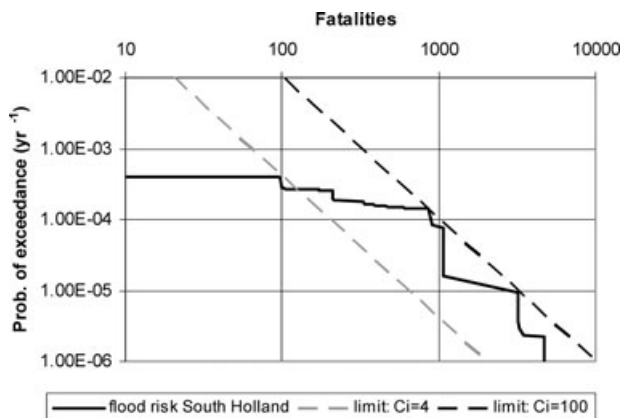
4.3. Effectiveness of Measures to Reduce the Flood Risk

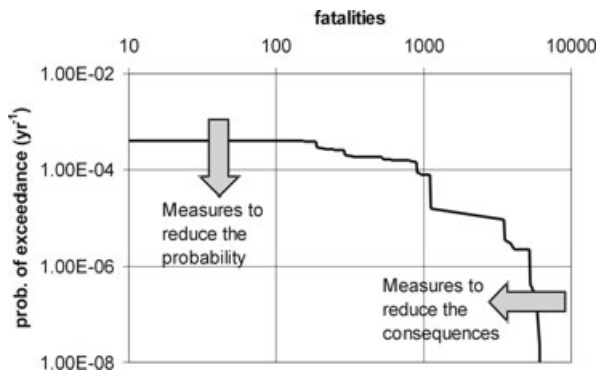If the determined risk levels are considered to be unacceptably high, it can be decided to reduce the

Fig. 12. FN curve for dike ring South Holland and two limit lines or different values of the C_I that determines the vertical position of the limit line.

Fig. 13. FN curve indicating the effects of two types of measures.

risk. A distinction can be made between measures that reduce the flooding probability and measures that reduce the consequences. The effects of these two types are indicated in the schematic FN curve in Fig. 13. Measures to reduce the flooding probability could be dike strengthening or space for rivers. Measures that aim at a reduction of consequences can include the construction of internal compartment dikes, the improvement of evacuation plans, or measures in the field of spatial planning.

In general, an analysis of effectiveness of measures requires insight into the necessary investments and the reduction of (expected) damages to economy, environment, and population. A cost-benefit analysis can be used to examine which (combinations of) measures are favorable. The cost effectiveness of measures can be specifically related to the reduction of loss of life by means of the evaluation of the cost of saving an extra statistical life (CSX) or the cost of saving an extra life year (CSXY).[33,34] This approach relates the investments in safety measures to the reduction of the expected number of fatalities, and thus the results of the presented risk calculations are needed as input to make these assessments. Such results can be presented to decisionmakers to support decisions regarding risk reduction measures.

5. CONCLUSIONS

The risks due to flooding of the dike ring area South Holland in the Netherlands have been analyzed in a case study. The results indicate that a flood event in this area can expose large and densely populated areas and result in hundreds to thousands of fatalities. Evacuation of South Holland before a coastal flood will be difficult due to the large amount of time

required for evacuation and the limited time available. Based on a quantitative analysis of the flood risk, it is shown that the probability of death for a person in South Holland due to flooding, the so-called individual risk, is small. The probability of a flood disaster with many fatalities, the so-called societal risk, is relatively large in comparison with the societal risks in other sectors in the Netherlands, such as the chemical sector and aviation. The societal risk of flooding appears to be unacceptable according to some of the existing risk limits that have been proposed in literature.

Presented results are based on the elaboration of a limited number of flood scenarios. For a more complete evaluation it is recommended to take into account a more complete set of scenarios that gives a better representation of the possible load situations, breach combinations, and flooding conditions. The flood characteristics are highly dependent on the choice of the flood scenario, especially the assumed number of breaches and their locations. In future analyses, it is important to give special attention to the possibility of more extreme flood scenarios associated with multiple breaches in the flood defense system. Although the current calculation indicates that such extreme scenarios are unlikely, documentation of historical coastal floods (e.g., in the Netherlands in 1953 and in New Orleans in the 2005) shows that these were characterized by multiple breaches. A further analysis of uncertainties in loss of life estimates is also recommended. Given the limitations in the existing analyses, the presented results must be considered as indicative, but realistic, first estimates of the risk level.

Based on these results, further investigation of possibilities for improvement of evacuation of South Holland, and development of alternative strategies, e.g., for shelter in place, are strongly recommended. Information regarding the elaborated flood scenarios and the number of people exposed can be used for the development of strategies for evacuation, shelter, and rescue operations. It is necessary to have emergency plans prepared and practiced before a serious flood occurs.

For a more complete evaluation of the flood hazards in the Netherlands the flood risks for other areas have to be determined and evaluated as well. This is done in the project "Flood Risks and Safety in the Netherlands" (FLORIS). Some of the issues found for South Holland, e.g., the lack of time for evacuation, are characteristic for coastal areas. In areas threatened by river floods, there will be more time

for evacuation, as high discharges in the river can be predicted longer in advance.

The current standards for flood protection in the Netherlands are mainly based on an econometric analysis and not on potential risks to people. It is proposed to investigate the possibilities to develop additional limits for flood risks to people.[8,35] In addition to the assessment of individual and societal risks it is also important to reevaluate the economic foundation of the current risk limits; see, e.g., References 8 and 32. In these evaluations, it is also important to take into account the possible effects of climate change and the future land-use developments in flood-prone areas.

Overall, the results indicate the necessity of a further societal discussion on the acceptable level of flood risk in the Netherlands. The decision has to be made whether the current risks are acceptable or whether additional risk reducing measures are necessary. The results presented in this article provide the input information to make these decisions.

ACKNOWLEDGMENTS

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