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SOCIETAL FLOOD RISK ASSESSMENTS: AN ADVANCED PROBABILISTIC METHOD AND ITS APPLICATION TO THE RHINE-MEUSE DELTA

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ABSTRACT: In the Netherlands the potential of societal disruption by floods plays an important role in the discussion on flood risk management strategies. One of the indicators to assess societal disruption is societal flood risk. Societal flood risk is related to the probability of many fatalities during a single event. In deltas protected by flood defences, such as the Netherlands, impacts of extreme events depend on the location and number of breaches in the flood defences. The number and location of breaches in a flood event is affected by the river discharges and storm surge levels, strengths of the defences and the outflow of river water through the breaches into the flood-prone areas. These outflows reduce the river water levels and discharges and thus the probabilities of more breaches downstream.

For the assessment of societal flood risks in deltas protected by defences, we developed a combined probabilistic-deterministic method which enables (1) the joint analysis of both storm surges and river discharges (2) the incorporation of hydrodynamic interaction of loads and breaches at different locations to include the retention effect and (3) a complete and dynamic analysis of flood probabilities, breach growth, flood patterns, and flood consequences. The method results in FN curves which provide the probability of events with N or more fatalities. Results further include the potential loss of life (expected annual number of fatalities) and the contribution of different regions to the total societal flood risk.

To support the discussion on flood risk management strategies, the calculated societal risk of various flood risk management strategies were compared with views on possible tolerable risk levels. The paper discusses the approach adopted, the calculation method, the results for the Rhine-Meuse delta and its use in the discussion on future flood risk management strategies.

Key Words: Flood Risk Analysis, Fatality Risk, Societal flood risk, The Netherlands

1. INTRODUCTION

Flood fatality risks play an increasingly important role in flood risk management. They are considered in policies and are the topic of research in the USA (US Department of the Interior, 2011), France, the UK (Di Mauro et al., 2012), Belgium (IMDC, 2005), Indonesia (Marchand et al., 2009) and The Netherlands (Min. V&W, 2009). Furthermore, there is a tendency to not only consider economic risks, but also fatality risks, in the assessment of current and alternative flood risk management strategies.

Fatality risks can be considered from an individual or societal viewpoint. In the Netherlands economic risks, individual and societal flood risks are all considered in the discussion on the future flood risk management strategy (De Bruijn *et al.,* 2010; Min. V&W, 2009, Van Alphen, in prep.). To find *efficient* strategies, economic risk reduction is compared with costs to be made to reduce risks in cost benefit analyses (CBA) (Kind, 2013). Since the outcomes of a CBA may result in a very *unequal* risk distribution, the individual risk is assessed as well. This indicator is used to determine whether the locations with the highest risk do not become too dangerous. This individual risk (or hazard) indicator gives for each location the probability to die due to a flooding (taking into account the possibilities for evacuation). A maximum tolerable value for this indicator in the Netherlands has been proposed (Van der Most et al, in prep). This indicator does not take the number of inhabitants into account.

In some projects an indication of ‘risky places’ is used. These are places with a relatively large number of flood fatalities per hectare. This criterion is evaluated by multiplying the individual risk with the number of inhabitants. It can easily be communicated and is useful in the discussion on flood protection standards, emergency strategies or other flood risk measures. It gives, however, no indication on the flood extent or the number of fatalities which may occur in a single event and thus not in the disruptive effect of flood events. In the Netherlands, the ‘risky places criterion’ is assessed, but it is not part of the main criteria used in the flood protection standard discussion.

The Dutch government wants to reduce the possibility of floods which disrupt society. To evaluate societal disruption, the probability of flood events with large number of fatalities is studied through the criterion ‘societal flood risks’.

This paper focuses on societal flood risks: the probability of events with more than N fatalities. Societal flood risks have been assessed for the Netherlands as a whole and the contribution of different regions within the Netherlands to the national risk has been determined. For the coastal area and the area along the large lakes a probabilistic method has been used, which was developed by Beckers et al. (2011). For the riverine area a new method has recently been developed, which is the subject of this paper.

The riverine area or the Rhine-Meuse delta, includes all main branches in the Rhine and Meuse delta between Lobith (along the Rhine at the German-Dutch boundary), Lith (along the Meuse), Maasmond and the IJssellake and the surrounding flood-prone areas (see figure 1). The area is threatened by flooding both due to high river discharges and due to storm surges at sea. The area is densely populated and potential damage and fatality figures are high. The area is protected by flood defences. Flood protection standards vary between once in 1250 and once in 10.000 years. Flooding occurs if flood defences fail.

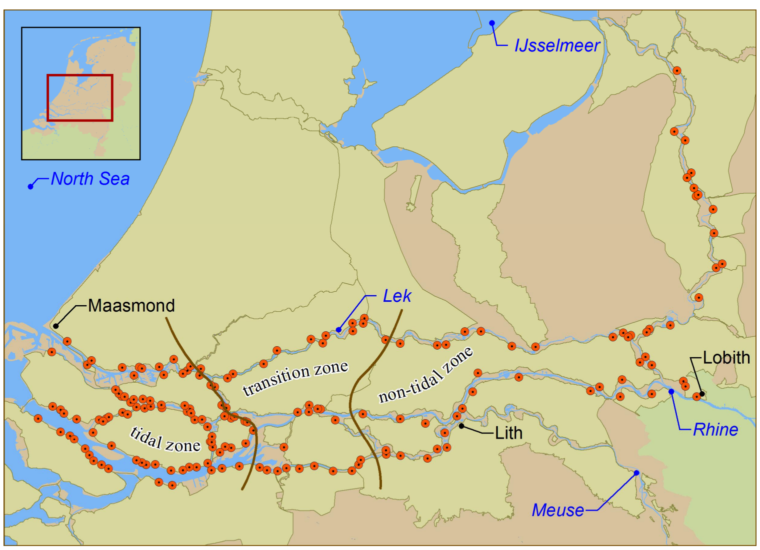


Figure 1: Rhine-Meuse delta in the Netherlands and the three subzones: tidal, non-tidal and transition zone.

The paper explains how societal flood risk is assessed in the Netherlands, how strategies were developed to reduce this risk and how societal risk was used in the discussion on potential future flood protection standards.

2. APPROACH

At first, societal flood risks have been assessed for the reference situation, which corresponds with a set of flood probabilities which are expected to be realized in 2015 after implementation of all planned flood protection projects. This societal flood risk is then evaluated. There are, however, no official standards in the Netherlands for tolerable levels of societal risk. In the Dutch Deltaprogram (Van Alphen et al., 2014) the framework of Vrijling et al. (1998) is used which provides orientation lines for tolerable risk levels for different risk types. Risk types are distinguished based on degree of voluntariness of and the benefit of the risky activity for the people at risk. The level of risk acceptation is indicated by a β value, which indicates the height of an orientation line with tolerable risk levels. High tolerable risk levels are found for activities with direct benefits for the risk takers and which are carried out voluntarily such as mountaineering and car driving (β is respectively 100 and 1), while very low tolerable levels are used for risks for inhabitants caused by chemical installations in the neighbourhood (β = 0.01). In the Netherlands the tolerable level of societal flood risk is expected to lie between 0.1 and 1. The tolerable probability of events with 1000 or more fatalities is 10^{-3} if β is 1 and 10^{-5} if β is 0.1. Not only the height of the orientation line is important, but also its slope. The slope of the orientation line is defined based on the assumption of risk aversion: the acceptability of larger numbers of fatalities is assumed to be disproportionately low (the tolerable probability of events with 10 times more fatalities is 100 times smaller). Figure 2 provides an example of an FN curve which just touches the β is 1 orientation line and also shows two lines with lower β values.

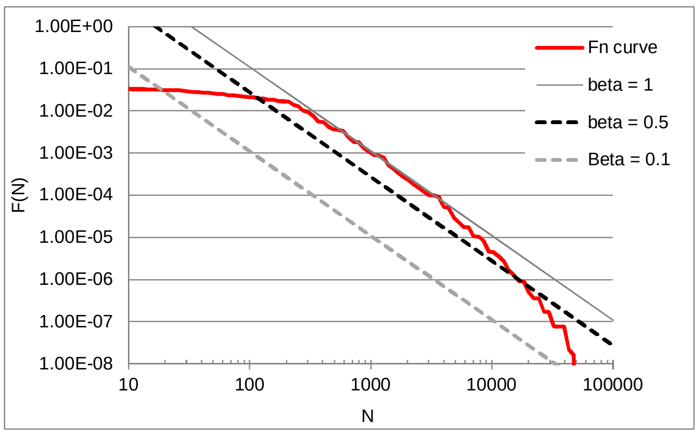


Figure 2: Example of an FN curve and three risk-averse orientation lines (slope of -2 on log-log scale) corresponding with a β of 0.1, 0.5 and 1.

If societal risk is too high, either the probability of flooding or the number of fatalities due to flooding should be reduced. This paper focuses on reducing flood probabilities by strengthening of the flood defences. Since the FN curve is composed of the contributions of many potential flood events with many potential combinations of defence failures, there are many strategies possible to lower the FN curve. To develop strategies to reduce societal flood risks, therefore, two lines of reasoning have been used:

A. Flood protection standards of each defence section are based on the expected number of fatalities in case of a breach in that section.
B. Flood protection standards are based on strengthening of those defence sections which contribute most to the FN curve.

The first line of reasoning results in a direct relationship between the expected number of fatalities given a breach and the flood protection standard, independently of the location of the flood defence. The advantage of this strategy is that it is easy to comprehend and to communicate by policy makers. It may, however, not be the most efficient way of lowering the FN curve for The Netherlands as a whole, since the contribution of some defence sections to the national curve is more important than that of others although they have the same number of fatalities in case of a breach. In the northern coastal area for example, there are only two sections which cause many fatalities, while in the southern coastal area there are many. Since the sections in the southern coastal area may all fail in a single event, the risk contribution of those southern sections is more significant for the FN curve, than that of the northern sections. Flood events with many fatalities have a larger probability in the northern coastal area, than in the southern coastal area, although in both areas individual defence sections exist which may result in many fatalities if they would fail. In the riverine area, the sections with many flood fatalities are located mainly in the tidal river area and transition zone (see figure 3). Strategy A has been elaborated in such a way that the national FN curve does not exceed the orientation line of β = 1. Table 1 shows the relationship between flood fatalities (including the possibility of evacuation) and flood protection standards used in strategy A.

Table 1. Flood protection standard (1/year) based on the number of flood fatalities of a defence stretch given a breach somewhere in that stretch.

N	P (1/year)
>1000	1/100.000
300-1000	1/30.000
100-300	1/3000
<100	1/300

Figure 3: Expected number of fatalities per defence stretch (in case of a breach)

For the second line of reasoning (line B) multiple starting points have been used, such as:

1. Starting from the reference situation (2015: situation after implementation of all planned flood protection projects)
2. Starting from the situation after implementation of the economic optimal flood protection standards (as determined in the CBA).

The second one is discussed here. In this line of reasoning the most contributing dike sections are strengthened until the FN curve lies below the orientation line β = 1.

3. COMPUTATION OF FN CURVES

Societal flood risk depends on:

- the hazards: the river flood waves and storm surges: their probability of occurance, height, and duration;
- the height and strength of the flood defences, which in our case is represented by the flood protection standards;
- flood extent and flood in case of breaches
- and the response: the evacuation possibilities and the number of fatalities.

The number of fatalities per flood event is directly related to the number and location of breaches in the defences. The number of breaches depends on the spatial correlation of water levels and strength of the flood defences and the reducing effect of breaches on downstream water levels. To assess fatality risks in the riverine areas a new combined probabilistic-deterministic method was developed which consists of three main steps (see figure 4):

1 The sampling of loads, strengths and evacuation success rates for N representative years;
2 The hydrodynamic modeling of the sampled loads and strengths to identify breaches;
3 The translation of the outcomes of the model to fatality figures per sample.

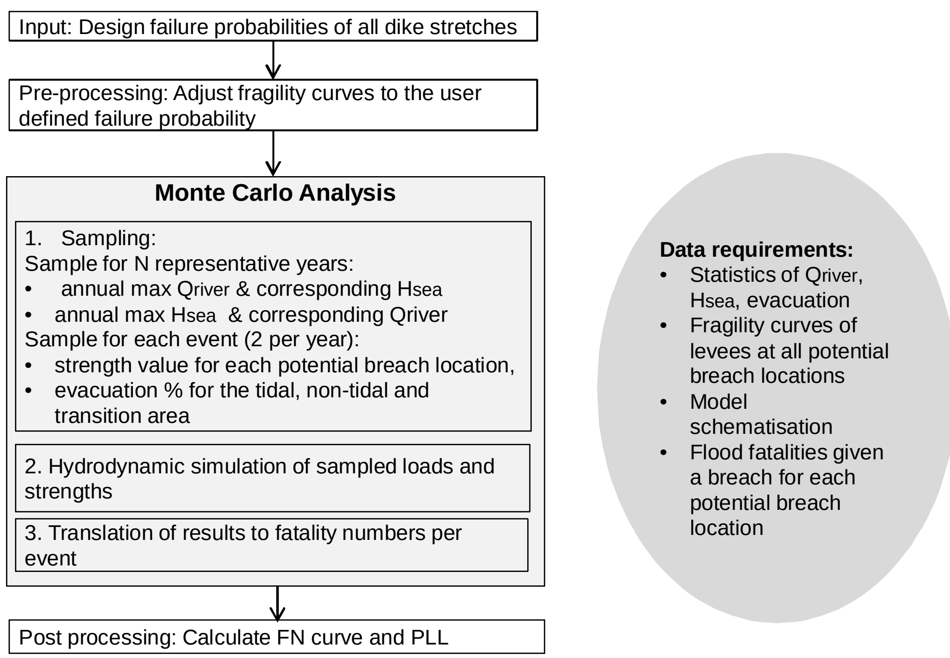


Figure 4: The methodological framework used (De Bruijn & Diermanse, 2014)

The combination of probabilistic analysis with a hydrodynamic model enables the incorporation of uncertainties, it provides insight in the river system behaviour and in the hydrodynamic interactions within the system.

The input of the method are flood protection standards or design failure probabilities of all defense sections. The most important outputs are FN curves, Potential Loss of Life (expected annual number of fatalities) for the area as a whole and the contributions of three subzones (tidal, non-tidal and transition zone) to the total risk. The method requires a 1D model, and for each of the 180 potential breach locations (see figure 1) a fragility curve and river water level statistics. The shape of the fragility curves determines the range of water levels at which a breach is most likely to occur.

To speed up the simulation an advanced importance sampling technique is used (Diermanse et al., 2014) and the flood plain modeling is simplified within the 1D model. Monte Carlo Analysis with importance sampling in areas with multiple event types requires a technique which ensures that all relevant events are taken into account. In the riverine area in the Netherlands both events with extreme discharges and events with extreme sea levels must be represented well. This required a new method in which 2 events are drawn for each sampled year: for each sampled year one annual maximum water level with a corresponding river discharge and one annual maximum discharge level with corresponding sea level are sampled. The following four steps are executed N times, i.e. for each simulated year:

First, the hydraulic load variables are sampled from the two simulated events in a year. Event 1 is the event with the annual maximum river discharge and a simultaneously occuring sea water level, event 2 is the event with the annual maximum sea water level and a simultaneously occuring river discharge. For each event, 4 variables are sampled that determine the hydraulic load (river water levels):

- discharge of the Rhine river at the upstream boundary Lobith;
- discharge of the Meuse river at the upstream boundary Lith;
- sea water level at the downstream boundary location Hoek van Holland;
- functioning of the Maeslant flood barrier.

The probability distributions of the two events are different. The probability distribution of the annual maximum discharge (event 1) differs from the probability distribution of the daily discharge (event 2). For each load variable, importance sampling is applied to increase the efficiency and accuracy of the Monte Carlo method (Diermanse et al., 2014). The river discharges of Rhine and Meuse are correlated. The correlation coefficient is equal to 0.6. For event 1, it is assumed that the relevant period of high discharges lasts 12 tidal periods (6 days). This means the peak sea water level of event 2 represents the maximum seawater level over 12 tidal periods, which is taken into account in the probability distribution from which this water level is sampled. For discharges and sea water levels an average hydrograph shape is used, with peak values corresponding to the sampled peak values.

Secondly, for both events water level threshold values are sampled from the fragility curves of the 180 breach locations. For each location, 3 fragility curves have been used, corresponding to the failure mechanisms “erosion of the inner slope”, “piping” and “slope instability”. This means that for each event and each location, 3 water levels are sampled from the fragility curves, representing the water levels at which the dike will fail due to the corresponding failure mechanism. The lowest of the 3 water levels is the water level at which the dike will breach. Samples of fragility curves between different locations are taken uncorrelated, which means spatial correlation in the strength of the flood defence is ignored. The effect of this simplification on societal flood risk is expected to be small as spatial correlations are only relevant on scales that are smaller than the typical distances between the selected potential breach locations in our model.

Thirdly, for both events and each breach location, a success rate of the evacuation response is sampled. The probabilities of these success rates are different for the non-tidal and tidal area of the delta, because of differences in flood event characteristics (river dominated versus sea dominated). For the transition area, the probabilities are a mixture of the probabilities for the tidal and non-tidal areas: for river discharge dominated events (Rhine discharges > 12.000 m^3/s) the sampled value of the non-tidal area is used, whereas for storm surge dominated events (Rhine discharges < 12.000 m^3/s), the sampled value for the tidal area is used.

Fourthly**,** each event is simulated with a 1D hydrodynamic model, in which the flood-prone areas are schematized as reservoirs. At each simulation time step river water levels are compared with the threshold water levels for breach initiation. If a threshold is exceeded, breach growth starts and water will flow through the breach out of the river. This approach results in reasonable estimates of the outflow through the breaches, but not in reliable information on flood patterns in the flooded areas. Therefore, the water levels in the reservoirs are not used to assess flood impacts. Instead, for locations where breaches occur, existing 2D model simulation results are taken from a database with simulated flood scenarios. The flood patterns of those simulations were translated to fatality figures with the adapted version of the mortality functions of Jonkman (Jonkman, 2007; Maaskant *et al.,* 2009a).

When all 2*n* events have been simulated and fatalities per event have been quantified, the derivation of the FN-curve is relatively straightforward. Note however, that importance sampling has been applied in the sampling procedure of the hydraulic loads. This means it needs to be determined to which extent the probability of occurrence of each event has been overestimated as a result of importance sampling. This leads to a correction factor that is derived separately per event and subsequently applied in the computation of the FN-curve. For example, if the probability of occurrence of event i has been increased by a factor 100, the correction factor, c_i, for this event is 1/100. The annual probability of exceedance of a threshold of N* fatalities is equal to:

$$P\left[N > N^*\right] = \frac{1}{n}\sum_{i=1}^{2n} 1_{\left[N_i > N^*\right]} c_i \qquad [1]$$

Where P= annual exceedance probability, N = the number of fatalities in a given year, N* = possible realisation of N, $1_{[A]}$ = indicator function: equal to 1 if A is true, 0 otherwise, c_i = correction factor for importance sampling for event I, N_i = number of fatalities in event i.

The method developed includes thus the relevant hydrodynamic processes and takes into account uncertainties in loads, strengths, and evacuation success rates. The method is discussed in more detail in De Bruijn & Diermanse (2014).

The probabilistic framework is used to assess the societal flood risk for different potential sets of flood protection standards. For this objective, the flood protection levels are used as model input instead of the ‘actual’ breach probabilities. The fragility curves of the potential breach locations are shifted in an iterative procedure to ensure that the failure probabilities of each defence section correspond with the user-defined flood probability. In these user-defined failure probabilities the effect of hydrodynamic interaction is not taken into account. The shape of the fragility curves are not altered, only the mean is shifted (see De Bruijn et al, 2014).

4. RESULTS

Figure 5 shows the FN curve for the riverine area and for the Netherlands both for the reference situation. For each area the results of two cases are shown: one in which the reducing effect of dike breaching on downstream water levels in the river was taken into account and one in which this effect was not accounted for. The figure shows that the differences between these two cases are significant which means that the effect of dike breaching on downstream water levels is relevant for societal flood risk. However, because the precise effect of dike breaching on downstream water levels and flood probabilities depends on many uncertain and variable factors, such as the moment of breaching, breach growth rates, the shape of the river flood wave and the storage capacity in the flooded area, we chose to calculate both cases. The curve assessed without taking into account breach outflow can be considered as an upper limit, while the other one may be considered a lower limit. Reality is expected to be somewhere in between.

Figure 5 shows that both the riverine curve and the national curve lie far above the orientation line for tolerable risk levels corresponding with $\beta = 1$. The probability of events with 1000 or more flood fatalities is about 1/100 a year, which is much higher than the tolerable 10^{-3}.

In the reference situation, the societal risk of the riverrine area is dominated by events with high river discharges and flooding in the transition area and central river area. Both potential numbers of flood fatalities and flood probabilities are relatively high in those areas. In the strategies A and B, the flood protection standards in the non-tidal and transition area have decreased signficantly. Therefore, events in the tidal and transition area, caused by storm surges determine to a large extent the societal risk in those strategies. Defence sections which contribute most in those strategys are located along the Nieuwe Maas near Rotterdam and in the transition area.

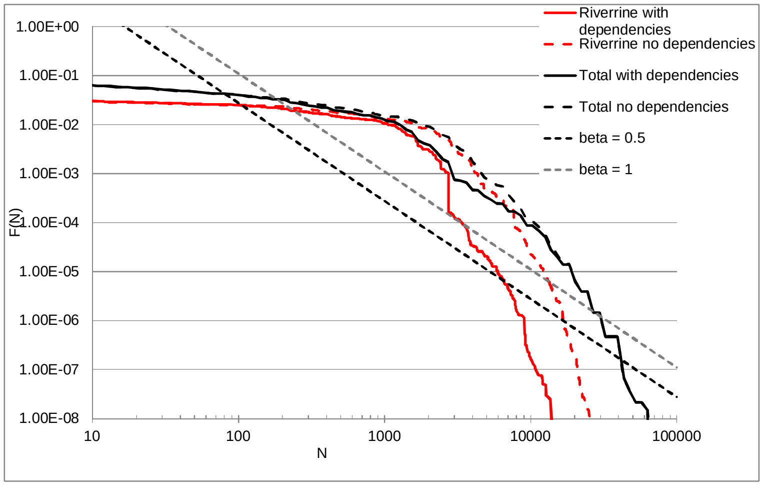


Figure 5: FN curve for the reference situation for the Netherlands as a whole and for the riverine area calculated with and without taking into account ‘hydrodynamic interdependencies’, i.e. the reducing effect of breaching on downstream water levels. Two orientation lines (with β = 0.5 and 1) are also shown.

Figure 6 shows the FN curve for four situations: the reference situation, the economic optimal flood protection standards, and the flood protection levels corresponding with strategies A and B. Strategy A and B are elaborated in such a way that the national curve lies just below the β = 1 line. The figures clearly illustrate the effect of the flood risk strategies: the three FN curves of the strategies are significantly lower than the curve corresponding with the reference situation.

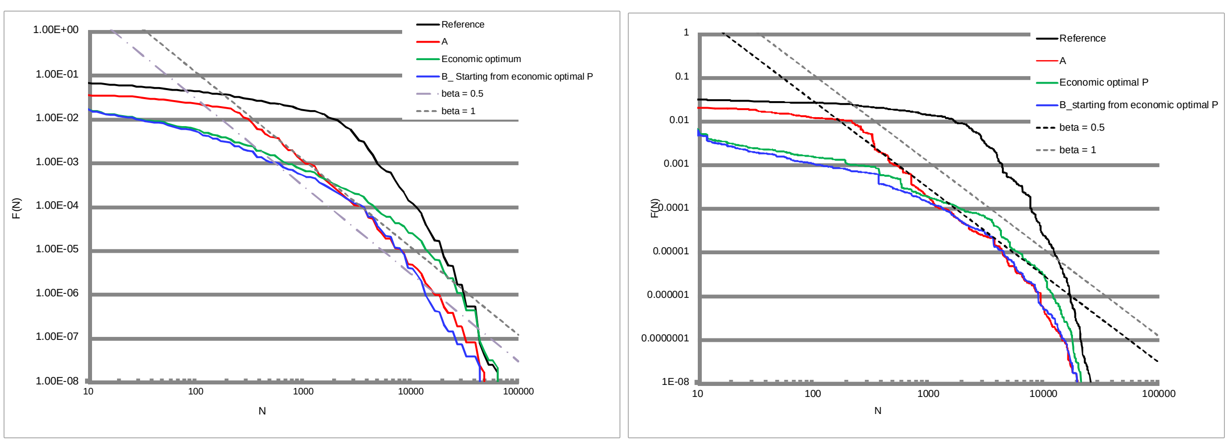
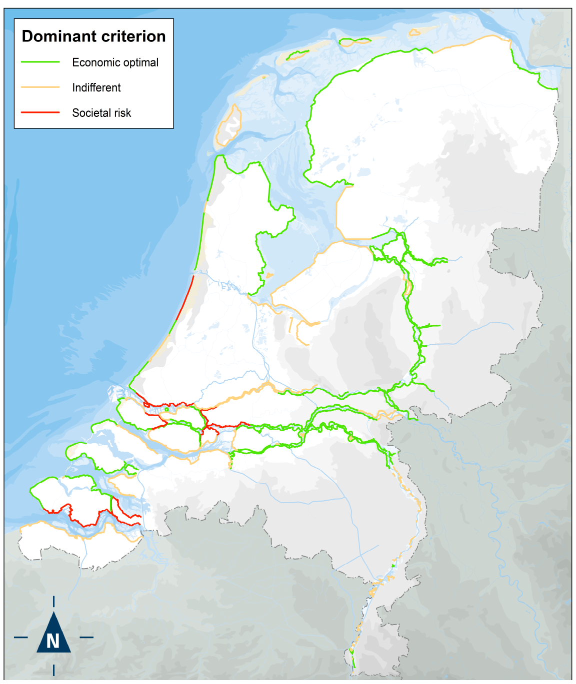


Figure 6: The FN curves corresponding with: the reference situation, the economic optimal flood protection standards and strategies A and B for the riverine area (left) and for the Netherlands as a whole (right) (all without taking into account breach outflows)

Strategy A results in higher societal flood risks than strategy B, since in strategy A only defence sections of which a breach would cause many fatalities have obtained strict protection standards (see table 1). The resulting flood risk in fatalities per year is, therefore, also higher than in strategy B (3 instead of 9 fatalities per year).

If the economic optimum flood probabilities would be implemented, the societal flood risks would still lie above the potential orientation line β = 1. Especially the probability of events with more than 1000 fatalities would be too high. By strengthening six sections of defences (about 130 km) the probability of events with many fatalities reduces significantly as is seen from differences between the FN curve of strategy B and the curve corresponding with economic optimal flood probabilities. The reduction in the riverine area is significant, but less pronounced than the effect on the FN curve of the Netherlands as a whole (two sections with many fatalities in the southern coastal areas were strengthened as well). Figure 7 shows where the flood protection standards following from approach A are less severe than the economic optimal flood probabilities and which sections were strengthened further than the economic optimum requirements in strategy B.

The requirements from an economic viewpoint and from a societal flood risk thus differ, although in densely populated areas flood damages and fatality rates may both be high. Economic optimal flood protection standards are more strict than those in strategy A for defence sections which are relatively inexpensive to strengthen, or for defence sections which protect densely populated or industrial areas with small inundation depths. If such defence sections break, damages will be high, while fatality rates will be low. Reversely, requirements based on flood fatalities are more strict than economic flood probabilities for defence sections which protect small deep polder areas which are rather dangerous: many fatalities may occur when those break. These areas are found in the tidal riverine area near Rotterdam. Requirements based on flood fatalities are also more strict than the economic optimal flood protection standards for defence sections which are relatively expensive to strengthen.



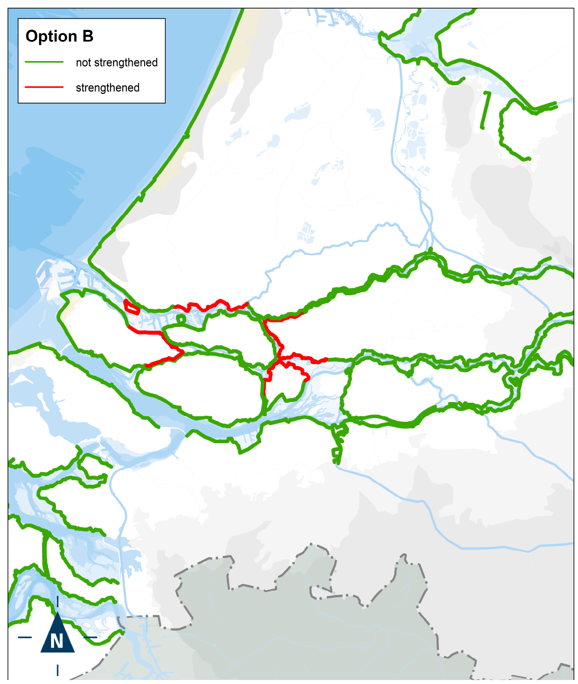


Figure 7: Location of dike sections for which strategy A results in more strict, equal or less strict requirements than economically justified (left side) and the dike sections which were strengthened beyond the economic optimal flood probabilities in strategy B (right side).

5. DISCUSSION

The results of the analyses give insight in societal risk in the riverine area of the Netherlands. They show that the societal flood risk can be reduced in different ways. The method shows the effect of the strategies, the most important events and the most relevant defence sections. The uncertainties in the input data, such as the fragility curves, probability distributions, fatality figures related to dike breaches and in the model schematisation contribute to the uncertainties in the outcomes. Sensitivity analyses have shown that although the absolute height of the FN curve is sensitive to the input data, the identification of the most contributing defence sections is robust (De Bruijn et al., 2014).

The analysis shows that using societal risk as a separate criterion does yield new insights which may add to the insights obtained from a cost benefit analysis or individual risk analysis. It shows that if economic optimal flood protection standards are implemented, the probability of disrupting events with many fatalities is still high. If one aims to reduce the probability of events with many fatalities those defence sections which contribute most to the probability of such catastrophic events should be strengthened beyond what is economically efficient.

In the Netherlands no decision has been made yet for future flood protection standards (see for more discussion Van der Most et al., 2014 and Van Alphen et al., 2014). Societal flood risk information is used in the discussion. To obtain tolerable levels for societal risk the framework of the TAW (Vrijling et al., 1998) is often used, as discussed in section 2. However, if a risk neutral instead of risk averse orientation line with a slope of minus 1 would be used (such as used by the US Department of the Interior (2011)) than possibly other locations would be selected for strengthening (see Klijn et al., 2013).

In the current discussion on future flood protection standards, most attention goes to embankment strengthening. However, also improvement of the storm surge barrier near Rotterdam could be considered. Furthermore, in some areas where flood extents are small or where warning time or arrival time is longer, it may be worth considering options to improve evacuation or to raise buildings or take other measures to reduce the number of fatalities, instead of the probability of flooding.

The analysis on societal flood risk was initiated to quantify the disrupting effects of floods. We acknowledge that societal disruption can also occur when critical infrastructure is affected, high damages occur, or large areas are flooded during long periods of time. These aspects should be considered in flood risk management too.

6. CONCLUSIONS

Flood fatality risks play an important role in flood risk management. In the discussion on new flood protection standards in the Netherlands flood fatality risks are considered both from an individual and societal viewpoint. From a societal viewpoint, societal flood risks, or the probability of events with more than N fatalities is assessed. This paper presented a method which allows calculation of societal flood risks in riverine areas and shows that the insights obtained are relevant for the discussion on future flood protection standards. The results added to information obtained from a cost-benefit analysis and an analysis of individual flood risks.

7. ACKNOWLEDGEMENTS

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