THE VNK2 PROJECT: A DETAILED, LARGE-SCALE QUANTITATIVE FLOOD RISK ANALYSIS FOR THE NETHERLANDS

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ABSTRACT: Quantitative risk analysis (QRA) is a powerful tool for evaluating and mitigating flood risks. The VNK2-project is a large-scale quantitative risk analysis for the low-lying parts of the Netherlands. It started in 2007 and draws upon decades of research and development. Flood probabilities are quantified in a Bayesian framework, taking into account the uncertainties related to loading conditions, resistances, physical models, and human behavior. Both economic and fatality risks are considered. These are expressed in various forms, ranging from population-averaged values to individual exposures. The project's results can be used to evaluate alternatives for mitigating risks, inform the political debate about new safety standards, prioritize interventions, and (re)direct research efforts to reduce important sources of uncertainty.

Key Words: Flood risk, (VNK2), quantitative risk analysis

1. INTRODUCTION

Flood safety is of paramount importance to the Netherlands. A large part of the country lies below sea level and almost ten million people, two-thirds of the Dutch population, live in flood prone areas. Although major floods have not occurred since 1953, the risk of flood is ever-present as shown by the high waters of 1993 and 1995 that triggered mass evacuations. As in other countries, there are various alternative strategies to mitigate this risk, ranging from flood defense and safety zoning to crisis management. Given the uncertainties related to, amongst other, the performance of flood defenses and emergency response organizations under extreme conditions, evaluating the effectiveness and efficiency of alternative risk management strategies is not an easy task. Quantitative risk analysis (QRA) provides a means for dealing with relevant uncertainties in an explicit and consistent way.

In 2006, the Dutch Ministry of Public Works and Water Management, the Dutch Provinces and the Union of Water Boards commissioned a study to gain insight into the probabilities and consequences of large-scale floods. The project Flood Risk in the Netherlands 2 (VNK 2 in Dutch) aims at quantifying flood probabilities and consequences for all dike rings in the Netherlands (a dike ring is an area that is protected from major floods by flood defenses). The project draws upon several decades of research and development in this field, following a course set out by the Dutch Technical Advisory Committee on Flood Protection (TAW, currently named the Expertise Network for Flood Protection or ENW).

The methods and instruments used within the VNK2-project have been developed and further refined following a number of case studies that focused, initially, on quantifying flood probabilities. The Picaso-study was a pilot in which the failure probabilities of flood defenses and the associated consequences were analyzed in conjunction (Van Manen & Brinkhuis, 2004). The VNK1-project was a first attempt to move from research to production. Sixteen dike rings were analyzed in the period between 2001 and 2005. Valuable lessons were learnt, and in 2006, the VNK2-project commenced. The first three years were spent on further improving the instruments and models. Nine risk analyses were completed by 2010. The project's objective is to provide detailed risk estimates for all 53 dike rings before the end of 2015.

In this paper, we discuss the methods and applications of the VNK2-project. The results of VNK2-project can be used to evaluate alternative solutions for mitigating risks, inform the political debate about new safety standards, prioritize interventions, and (re)direct research efforts to reduce important sources of uncertainty. This is illustrated by a number of practical examples.

2. METHODOLOGY

2.1 Overview

In the VNK2 project, flood probabilities are quantified in a Bayesian framework, taking into account the uncertainties related to loading conditions, resistances, and empirical models. The infinite range of potential flood scenarios is characterized by a limited set of mutually exclusive and collectively exhaustive scenarios. Probabilities are calculated for each of these scenarios on the basis of the flood probabilities per failure mechanism and dike section. The consequences per flood scenario are estimated using flood propagation models, land-use data, and probit-functions. The various possible outcomes of evacuation attempts are estimated on the basis of event trees. Economic and fatality risks are calculated by combining the probabilities of flood scenarios with the consequences associated with these scenarios. Various risk metrics are considered in the VNK2-project, ranging from expected values per dike ring to cumulative distributions and individual exposures.

2.2 Quantifying failure probabilities per failure mechanism and section

To quantify failure probabilities, every dike ring is first divided into statistically homogeneous sections. A typical section has a length of 200-1000m. Hydraulic structures, such as sluices and culverts, are treated as individual sections. The failure mechanisms that are expected to be dominant are considered in the VNK2-project (other failure mechanisms are treated qualitatively):

1. Levees: overtopping, overflow, piping, slope instability, revetment failure and erosion

2. Hydraulic structures: overtopping, overflow, non-closure, piping, structural failure (collapse)

3. Dunes: dune erosion

A section will fail when an event, such as a storm surge extreme river discharge, causes a load that exceeds the section's resistance against a particular failure mechanism. Both resistances and hydraulic loads are typically uncertain. The probability that a section will fail due to a particular failure mechanism thus depends on the probability density functions of the loading conditions and the section's resistance against the failure mechanism under consideration:

$$P_{f_{ij}} = P(Z_{ij} < 0) = P(R_{ij} - S_{ij} < 0) = \int_{-\infty}^{+\infty} \int_{-\infty}^{s_{ij}} f(r_{ij}, s_{ij}) dr_{ij} ds_{ij} \qquad [1]$$

where Pf_{ij} [yr^{-1}] is the failure probability of section i due to failure mechanism j, Z_{ij} is the limit state function of section i due to failure mechanism j, R_{ij} is the lowest resistance present in section i against failure mechanism j, and S_{ij} is the highest load on section i associated with failure mechanism j in a one-year period.

To deal with the effect of spatial variability within sections efficiently, failure probabilities are first computed for an effective width, which may be thought of as the width involved in a failure. This failure probability is then scaled to a failure probability for the entire section, taking into account the effect of spatial correlations. This procedure rests on a level-crossing analysis: the probability of the limit state being less than zero increases with length and decreases when spatial correlations are strong (see e.g. VanMarcke, 2011). The correlation structure of each stochastic variable X_k is described by a one-dimensional correlation function $\rho_k(\Delta x)$ with a standard form:

$$\rho_k(\Delta x) = \rho_{x,k} + (1 - \rho_{x,k}) e^{-\frac{\Delta x^2}{d_{x,k}^2}} \qquad [2]$$

where Δx is the distance between two cross-sections, $\rho_{x,k}$ is a constant (the lower limit of $\rho_k(\Delta x)$), and $d_{x,k}$ [m] is the correlation length. In the slope stability analysis, the vertical spatial correlations are also considered (Vrouwenvelder, 2006).

Correlations in the time domain are taken into account using the model of Ferry-Borges & Castanheta (1971), according to which continuous stochastic processes are discretized into intervals. Within intervals, correlation is perfect; between intervals, it is constant and less than one (often zero). For the river Rhine, the intervals have a length of about 8 days for small discharges and 2 days for extreme discharges. For a more detailed description of the treatment of correlations in the VNK2-project, the reader is referred to Vrouwenvelder (2006).

The probability calculations within the VNK2-project are made using PC-Ring version 5.3.2 or higher (with the exception of the failure probability calculations for slope instability which are made with MProStab). A wide range of probabilistic techniques is available in PC-Ring: FORM, SORM, directional sampling, Monte Carlo simulation, and numerical integration (Steenbergen and Vrouwenvelder, 2003). The relatively efficient FORM-algorithm (after Hasofer and Lind, 1974) generally yields satisfactory results. Directional sampling is typically used in case of non-convergence or suspected errors.

2.3 Combining failure probabilities and quantifying scenario probabilities

The failure probabilities per failure mechanism and section have to be combined per section, as well as per failure mechanism, to quantify the probability of a failure for a (particular part of a) dike ring. In PC-Ring, sections (as well as failure mechanisms) are combined in a pair-wise manner. The failure probability of a pair of sections (a series system of two elements) is given by:

$$P_{12} = P(Z_1 < 0 \cup Z_1 < 0) = P(Z_1 < 0) + P(Z_2 < 0) - P(Z_1 < 0 \cap Z_2 < 0) \qquad [3]$$

Note that $P(Z_1<0 \cap Z_2<0)$ does *not* equal $P(Z_1<0) \cdot P(Z_2<0)$ when the limit state functions Z_1 and Z_2 are correlated. Correlations should thus be considered when combining sections.

The algorithm that is used for combining sections rests on the first-order method by Hohenbichler-Rackwitz (1983) for calculating the failure probability of a series system of two correlated elements. A FORM-analysis yields a reliability index (β_i) and influence coefficients (α_{ik}) per stochastic variable X_k (k=1..k_{tot}) for a limit state function of a section (Z_i), such that:

$$Z_i = \beta_i + \sum_{k=1}^{k_{tot}} \alpha_{ik} u_{ik} \qquad [4]$$

where u_{ik} is a standard normally distributed variable.

Each time sections (or failure mechanisms) are combined, an equivalent limit state function is computed, taking into account the correlations between these sections (Vrouwenvelder, 2006):

$$Z_{12}^e = Min(Z_1, Z_2) = \beta_{12}^e + \sum_{k=1}^{k_{tot}} \alpha_k^e u_k \qquad \text{with} \quad \beta_{12}^e = -\Phi^{-1}\left(P\left(Z_{12}^e < 0\right)\right) \qquad [5]$$

where Z_{12}^e is the equivalent limit state function for the two sections combined; β_e is the equivalent reliability index, α_k^e is an equivalent FORM-influence coefficient, and u_k is a standard normally distributed variable for stochastic variable X_k.

The correlation between two sections $i=1$ and $i=2$ (ρ_{12}) can be computed on the basis of the FORM-influence coefficients and the assumed correlation per stochastic variable (ρ_k, see [eq.2]).

$$\rho_{12} = \sum_{k}^{k_{tot}} \alpha_{1,i}\alpha_{2,k}\rho_k \qquad [6]$$

On the basis of this combinatory process, flood probabilities can be computed for (a particular part of) a dike ring and a particular set of failure mechanisms. It can also be used to compute scenario probabilities. A flood scenario is a unique sequence of events following the failure of a flood defense at one of more locations under specific high water conditions. In reality, the number of potential flood scenarios is infinite. In the VNK2-project, the infinite range of potential flood scenarios is characterized by a limited set of representative scenarios. To define these scenarios, every dike ring is first divided into segments, each comprising one or more sections. Within a segment, the flood pattern should be insensitive to the precise breach location. An equivalent limit state function can be computed for each segment.

Depending on the effect of a failure in a segment on the hydraulic loading conditions on the other segments, the possibility of multiple failures should be considered. In the VNK2-project, three cases are distinguished (Table 1) (Thonus et al., 2008).

Table 1: Scenario definition

The effect of a failure of a segment on the loads on the other segments	Number of scenarios	Scenario probabilities (for m=2)
No unloading	$2^{m_{tot}} - 1$ where m_{tot} is the total number of segments (for m_{tot}=13, there are 8.191 scenarios)	$P_{Scen,1} = P(Z_1^e < 0 \cap Z_2^e > 0)$ $P_{Scen,2} = P(Z_1^e > 0 \cap Z_2^e < 0)$ $P_{Scen,3} = P(Z_1^e < 0 \cap Z_2^e < 0)$ where $P_{scen,a}$ [yr^{-1}] is a scenario probability, and Z_m^e is the equivalent limit state function of segment *m*
Unloading: weakest segment fails first	m_{tot}	$P_{Scen,1} = (Z_1^e < 0 \cap Z_1^e < Z_2^e)$ $P_{Scen,2} = P(Z_2^e < 0 \cap Z_2^e < Z_1^e)$
No unloading: first loaded segment fails first	m_{tot}	$P_{Scen,1} = P(Z_1^e < 0)$ $P_{Scen,2} = P(Z_2^e < 0 \cap Z_1^e > 0)$

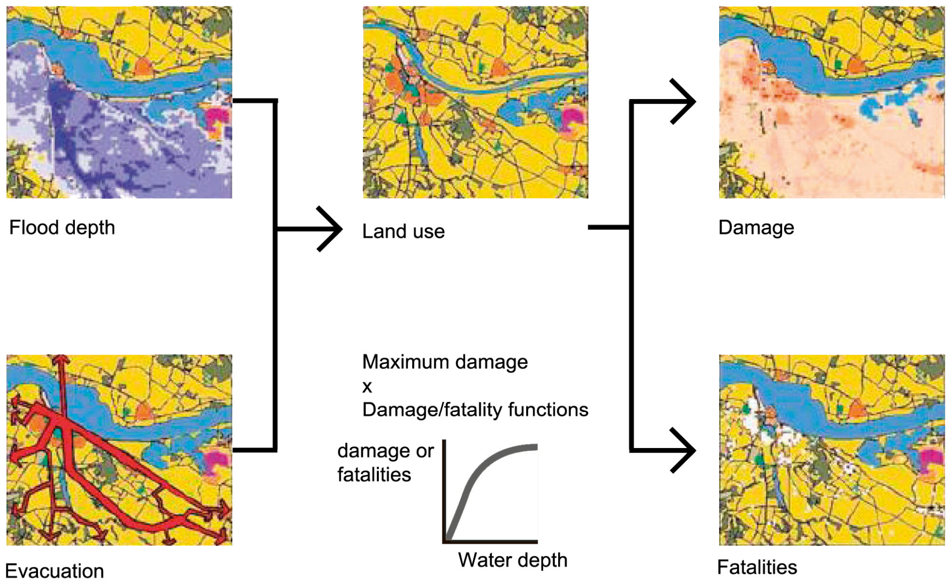
2.4 Quantifying the consequences of floods

The consequences of floods will vary per scenario, depending on the vulnerability of the affected area and the characteristics of the flood itself, such as water depths and rise rates. The latter characteristics depend on the area's hydraulic roughness, as well as the conditions under which the flood scenario is likely to take place (water level, wave length). Estimates of these conditions are based on the design point values for each scenario, see paragraph 2.3.

In case of no unloading after a failure, the number of potential scenarios will be considerable (Table 1).To avoid having to simulate thousands of flood scenarios, flood simulations are only made for the m_{tot} single-breach scenarios. The characteristics of the multiple-breach scenarios are approximated by combining single-breach scenarios, correcting for any overlap between them. Computing the consequences for each simulated (or approximated) flood scenario is also time-consuming, which is why this is only done for the 50 scenarios with the highest probabilities (exceptions apart). For all other scenarios, the maximum consequences are assumed. Flood risks are however hardly overestimated since the probabilities of the 50 most likely scenarios typically add up to over 99% of the sum of all scenario probabilities.

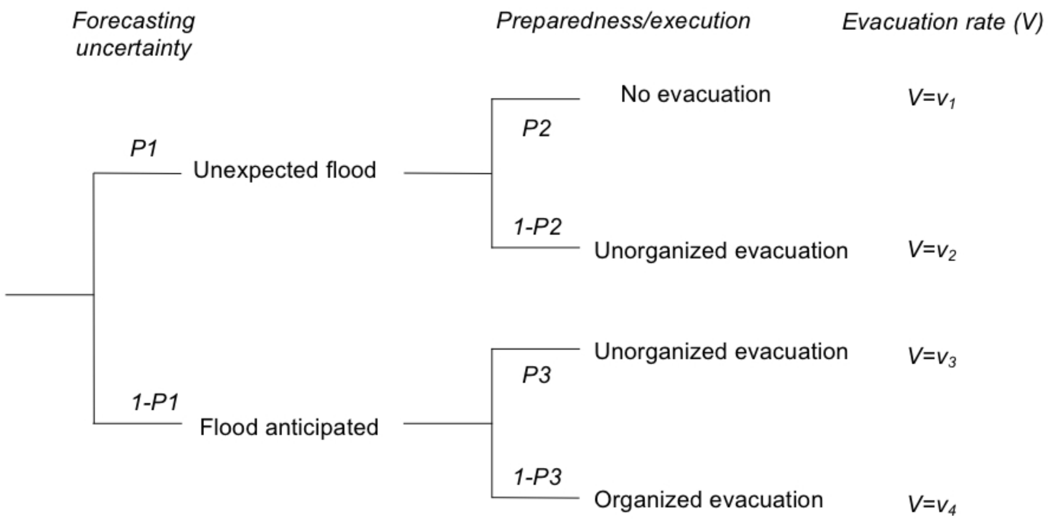
The extent of economic damage and the number of fatalities per flood scenario are estimated on the basis of flood simulations (which yield water depths, rise rates, and flow velocities), land-use data (economic value and population density), and probit-functions. The procedure is graphically illustrated by Figure 1. A probit-function relates the extent of damage or flood mortality to flow velocities, rise rates, and water depths. The impact on the Dutch economy is estimated on the basis of the direct damages, with adjustments for indirect damages and the opportunities for substitution. For further details about probit-functions in general and the functions that are used to compute flood mortality in the VNK2-project, the reader is referred to Jonkman (2007).

Figure 1: Quantifying the consequences of a flood scenario.



Preventive evacuation can significantly reduce loss of life and should therefore be considered in a flood risk analysis. Note however that it would be incorrect to assume that evacuation will always be successful. The (un)reliability of long-term forecasts of high waters and the uncertainty related to the resistance of flood defenses imply that floods cannot be perfectly predicted: floods might occur without warning. Also, politicians might also decide not to evacuate a polder. But even when the public is timely warned and an evacuation is decided upon, people might be reluctant to leave, or the evacuation attempt might fail due to congestion. The evacuation rate, expressed as the percentage decrease of the exposed population, is therefore uncertain. An event tree is used to model this uncertainty (Figure 2).

Figure 2: Modeling the effectiveness of evacuation



The conditional probabilities and evacuation rates in Figure 2 are based on expert judgment, traffic management studies, data on weather and water forecasting uncertainties, and historic events. The probabilities of timely warning and preparedness vary by region, as do the evacuation rates. The probability of timely warning is for instance assumed to be lower along the coast (storm surges) than far upstream (extreme river discharges). Lower evacuation rates are also to be expected in densely populated dike rings with relatively few exits to higher grounds.

2.5 Quantifying flood risks

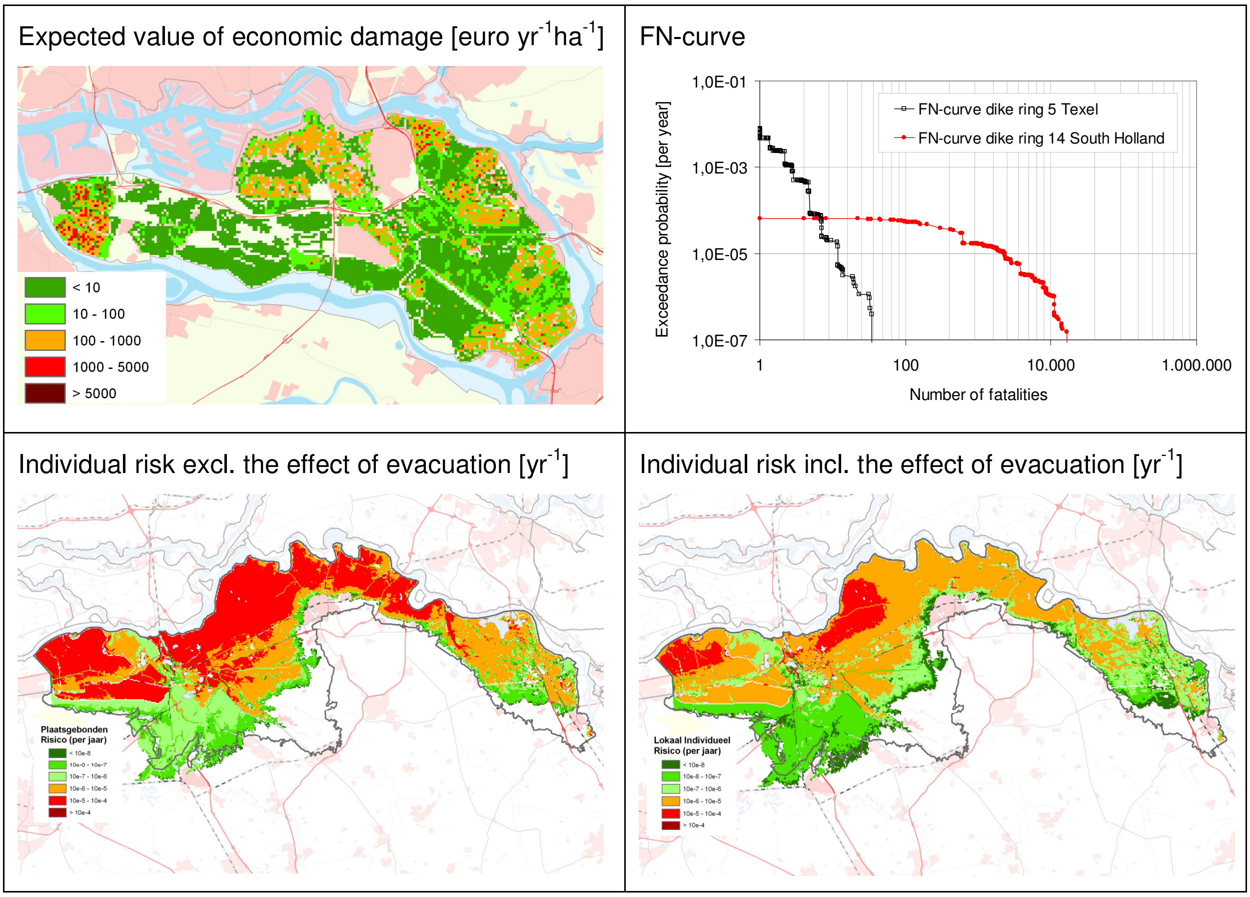
Flood risks can be expressed in various ways: e.g. by (spatial distributions of) expected loss, or loss distributions. An overview of the risk metrics that are used within the VNK2-project is given by Table 2. Examples are shown in Figure 3.

Table 2: Risk metrics

Type of risk	Risk metric	Potential use of risk metric (indication)
Economic risk	Expected value of economic damage [yr^{-1}]	Provides an indication of the cost of risk bearing for cost-benefit analyses (the expected value is the actuarially fair insurance premium)
	Spatial distribution of the expected value of economic damage [euro $yr^{-1}ha^{-1}$]	Idem; potentially useful for cost-benefit analyses that deal with local investments
	Cumulative probability density function of economic damage	Provides insight in the probability of a severe economic impact

Table 3 continued		
Type of risk	Risk metric	Potential use of risk metric (indication)
Fatality risk	Expected value of the number of fatalities [yr^{-1}]	Useful for cost-benefit analyses when loss of life is monetized and included in the financial balance
	Spatial distribution of the expected value of the number of fatalities [$yr^{-1}ha^{-1}$]	Idem; potentially useful for cost-benefit analyses that deal with local investments
	FN-curve/societal risk	Provides insight in the probability of floods with severe social impacts
	Individual risk excluding or including the effect of evacuation [yr^{-1}]	Provides insight in the distribution of exposures over a region/population.

Figure 3: Examples of risk metrics from the VNK2-project (from VNK2-reports: Havinga, 2010, Jongejan, 2010, Maaskant, 2010, Ter Horst, 2010)



Each of the risk metrics shown in Table 2 can be quantified on the basis of the scenario probabilities and the consequences per scenario. Consider for instance the expected value of economic damage, which equals the sum of the probability-weighted consequences per scenario:

$$E(Q) = \sum_{m=1}^{m_{tot}} P_{scen,m} \cdot q_m \qquad [7]$$

where $E(Q)$ [euro/yr] is the expected value of economic damage; $P_{scen,m}$ [yr^{-1}] is the probability of scenario k, and q_m [euro] is the extent of economic damage if scenario m were to occur.

The cumulative distribution of the number of fatalities (or economic damage) is typically depicted as an FN-curve, showing the exceedance probabilities of the numbers of fatalities on double-log scale. To draw an FN-curve, the scenarios first have to be sorted by the number of fatalities. The sliding aggregate of the scenario probabilities then yields the exceedance probabilities.

For obtaining a spatial distribution of flood risk/a risk map, the economic of fatality risk should be shown per grid cell. Consider for instance the spatial distribution of the expected number of fatalities:

$$E(N_d(x,y)) = N_{par}(x,y) \cdot (1 - E(V)) \cdot \sum_{m=1}^{m_{tot}} P_{d,m}(x,y) \cdot P_{scen,m} \qquad [8]$$

where $E(N_d(x,y))$ [yr^{-1}] is the expected number of fatalities in a gridcell with coordinate (x,y), $N_{par}(x,y)$ is the number of people at risk in that gridcell, $E(V)$ is the expected value of the evacuation rate, $P_{d,m}(x,y)$) is the probability of death per individual in that gridcell for scenario m, $P_{scen,m}$ [yr^{-1}] is the probability of scenario m, and m_{tot} is the total number of scenarios. Individual risk, i.e. the probability of death at a specific location, can be calculated by assuming $N_{par}(x,y)=1$ (to exclude the effect of preventive evacuation, $E(V)$ should be taken equal to zero).

3. APPLICATIONS

3.1 Evaluating alternatives for risk mitigation

Broadly speaking, there are three types of strategies to mitigate flood risks:

1. Reducing flood probabilities. Measures include dike strengthening, beach nourishment, and widening rivers to increase their runoff capacities.

2. Reducing the consequences of floods. Measures include implementing land-use planning restrictions, flood proofing vulnerable objects, and improving the opportunities for evacuation (early warning, shelters, etc).

3. A mixture of the above.

Investments in e.g. prevention, crisis management, spatial planning, or resilience can all reduce economic and fatality risks. But faced with budget constraints, difficult choices have to be made. Comparing the effectiveness of different options is difficult without a common denominator. The effect of prevention, crisis management, spatial planning, and other strategies can all be expressed in terms of their impact on the level of flood risk, however defined. QRA thus provides a 'level playing field' for evaluating alternative strategies for risk mitigation. Figure 4 and Figure 5 illustrate how different types of interventions influence flood risks.

Figure 4: The effect of evacuation on the FN-curve for dike ring 36 (Havinga, 2010) .

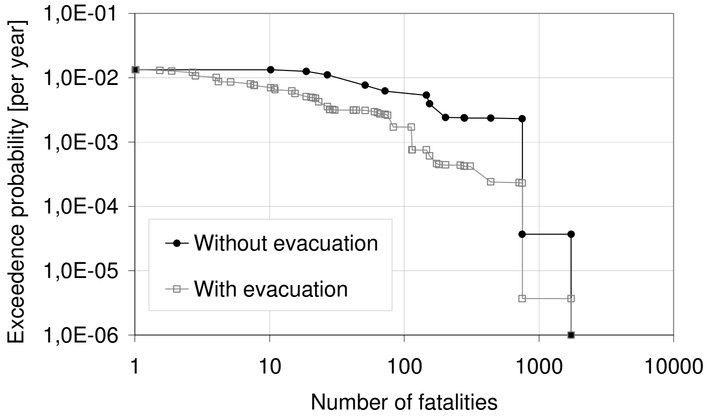
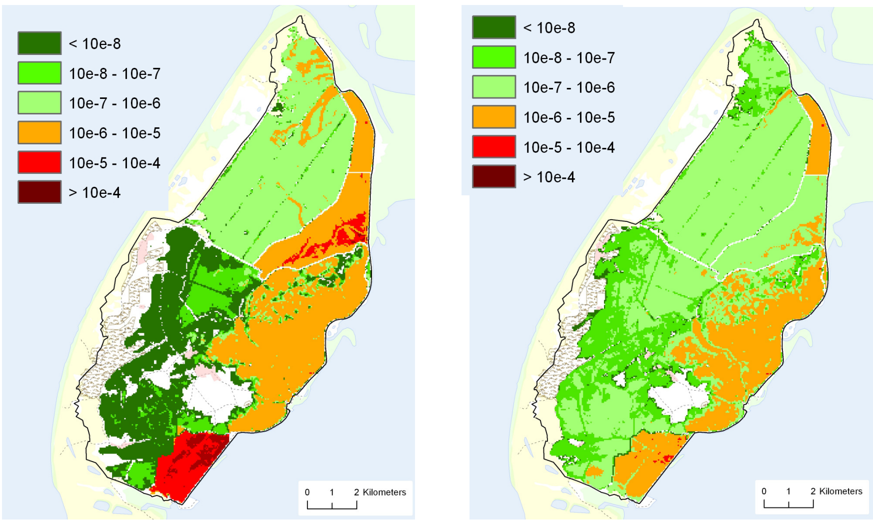


Figure 5: The effect of dike strengthening: individual risk (excluding the effect of evacuation) [yr^{-1}] for dike ring 5, before (left) and after (right) the strengthening of ten dike sections (Maaskant, 2010).



3.2 Informing the political debate about flood safety standards

As discussed in section 3.1, a quantitative risk analysis can provide valuable information for informing a political debate about ways to improve flood safety. It should therefore come as no surprise that VNK2 plays an important role in the current process of updating the Dutch flood safety standards.

The foundations of the present Dutch flood safety policy were laid by the so-called Delta Committee that was installed after the Big Flood of 1953. The committee explicitly balanced the costs of periodically strengthening flood defenses against the reduction of flood risks, thereby introducing a risk-based design philosophy (Van Dantzig, 1956). But because flood probabilities proved difficult to quantify, exceedance probabilities were defined of the water levels that the primary flood defenses should be able to safely withstand. Nowadays, policymakers are exploring a move towards standards that are defined as flood probabilities.

The debate about the stringency of these new flood safety standards relies heavily on the outcomes of cost-benefit analyses (taking into account the economic risk), and the projected levels of individual and societal risk. Detailed estimates for each of these risk metrics can be, and are, provided by the VNK2-project.

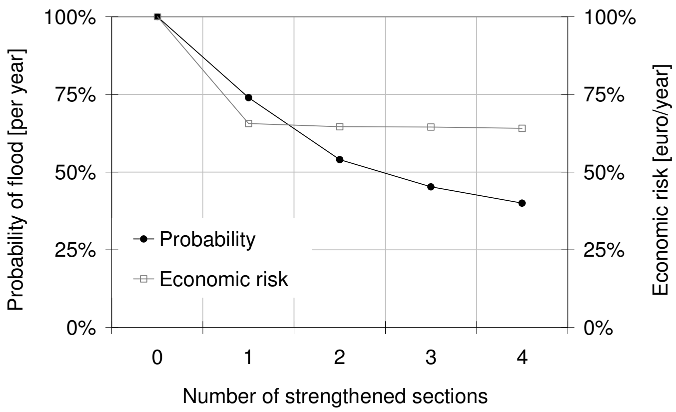
3.3 Prioritizing interventions

The present-day legal set of instruments for evaluating the safety of flood defences only shows whether a flood defence needs to be strengthened or not. But because budgets are limited, priorities have to set. The results of the VNK2-project can be used for informing the political process of prioritizing interventions. As discussed in section 3.1, the effectiveness of an investment in flood safety can be measured in terms of its impact on the level of risk. After completing a risk analysis for a dike ring, the effectiveness of a wide range of interventions can be quantified by modifying parameter values.

In cost-benefit analyses, flood risk is typically defined as the expected value of economic damage. The net present value of an intervention thus equals its cost minus the present value of the reduction of flood risk. From a purely economic perspective, the interventions with the highest net present values should be taken first (in a world without budget constraints, all interventions with positive net present values should be taken).

Note that measuring the effectiveness of interventions on the basis of their impact on the probability of flood rather than flood risk need not yield the same results. This is illustrated by Figure 6. The figure shows, for dike ring 17, how the probability of a flood in a dike ring (the probability that at least one section fails) and economic risk (defined as the expected value of economic damage) decrease as a function of the number of sections that are strengthened. Every successive intervention was selected so as to minimize the probability of food. After the first intervention, the economic risk stays almost the same. This is because sections that contribute most strongly to the probability of flood need not be the sections where the consequences of a failure are most severe.

Figure 6: The difference between prioritizing interventions on the basis of their impact on the probability of flood for dike ring 17 (data from Ter Horst, 2010).



3.4 Highlighting important sources of uncertainty

Some uncertainties, such as the uncertainties caused by natural variability in the time domain (e.g. river discharges, wind speeds, water levels) often cannot be reduced through research and/or data collection. The opposite holds true for model uncertainties and the uncertainties about local soil properties (permeability, grain diameters, cohesion, etc.) that arise from spatial variability combined with limited observations (sparse geotechnical data). But which uncertainties are most important?

The FORM-influence coefficients indicate the importance of the uncertainty related to a stochastic variable, see also eq. [4]. An inspection of FORM-influence coefficients thus provides useful information about the dominant sources uncertainties. In the VNK2-project, the model uncertainties often appear to be relatively unimportant compared to the uncertainties related to soil properties and hydraulic boundary conditions. This indicates that the collection of geotechnical data, rather than research and development (model improvement), is most likely to influence the outcomes of flood probability calculations in VNK2.

Some uncertainties, such as the uncertainties related to the presence of low permeability top layers in a flood plain or the quality of the foundation of centuries-old hydraulic structures, cannot be included in the probability calculations of the VNK2-project. In these cases, sensitivity analyses are performed to evaluate the importance of these missing data (the most likely schematization is selected on the basis of historical and geological data, combined with expert judgment).

Although soil properties are typically deterministic, their values remain uncertain until they are actually measured. The uncertainty related to the soil conditions at a cross section that is location at some distance from a measurement location depends on the spatial correlation structure. When the correlation distance is small and variance is large, the probability of flood will increase strongly with unit length. Correlations in space are explicitly addressed in the VNK2-project (see section 2.2). The probability calculations of the VNK2-project clearly demonstrate the importance of moving away from purely cross-sectional evaluations of the strength of flood defenses to approaches that explicitly address the third, longitudinal dimension as well. While this issue has been known for decades (e.g. VanMarcke, 1977; 1988), several design codes for flood defenses are still based on purely cross-sectional analyses. The VNK2-project raised awareness for the importance of the third dimension, leading to debate about the stringency of the current (semi-probabilistic) rule for assessing the safety of levees against piping (Vrijling et al., 2011).

4. CONCLUSIONS AND DISCUSSION

The VNK2-project is a large-scale quantitative flood risk analysis (QRA) for the Netherlands. Within the project, advanced techniques are used to quantify the probabilities of flood scenarios and the consequences of these scenarios. The results of the VNK2-project can be used to inform the political debate about the acceptability of risks and to compare the effectiveness of alternative strategies or interventions to reduce risks. The project's results can also be used to identify important sources of uncertainty, to (re)direct research efforts.

A by-product of the risk analyses is a database with detailed statistical data about the Dutch flood defenses. This database will prove invaluable for future research and development, as well as policy analyses. An important side-effect of the VNK2-project is that it familiarizes people at the national government, water boards, provinces and engineering consultancies with probabilistic, risk-based approaches to evaluate the safety of flood defenses. The project thereby paves the way towards new and more efficient ways to protect the Netherlands against floods.

There are 57 dike rings in the Netherlands. By the end of 2012, quantitative risk analyses will be completed for 17 of them. By the end of 2015, risk analyses will be completed for 55 dike rings, as well as a number of embankments along the river Meuse. Detailed, quantitative flood risk estimates will then be available for an area that spans roughly two-thirds of the Dutch territory.

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