THE USE OF QUANTITATIVE RISK ANALYSIS FOR PRIORITIZING FLOOD RISK MANAGEMENT ACTIONS IN THE NETHERLANDS

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ABSTRACT:
Almost two-thirds of the Netherlands is exposed to the risk of flooding, making the provision of flood safety a vital yet costly affair. To be able to make better informed decisions about flood risk management, the Dutch Ministry of Infrastructure and the Environment, the Association of Regional Water Authorities and the Association of Provincial Authorities commissioned a study to gain insight into the probabilities and consequences of large-scale floods. The resulting VNK2-project (VNK is the Dutch acronym for Flood Risk in the Netherlands) is a multi-million dollar, fully probabilistic quantitative risk analysis (QRA) for all fifty-three major levee systems in the Netherlands, as well as a number of embankments along the river Meuse. The outcomes of these analyses are used (i) to inform political debates about the acceptability of risks, (ii) to compare the effectiveness of alternative strategies for reducing risks (e.g. strengthening levees, reducing vulnerabilities, or improving crisis management capabilities), (iii) to set priorities within national levee reinforcement programmes, and (iv) to (re)direct research efforts towards important sources of uncertainty. This paper presents an overview of the methods and techniques used for quantifying flood risks in the Netherlands and focuses on the use of QRA for prioritizing flood risk management actions.

RÉSUMÉ:
Près des deux tiers du territoire néerlandais sont exposés à des risques d’inondation. En conséquence, la prévention des risques d’inondation est une priorité vitale, mais coûteuse pour le pays. Afin de prendre des décisions éclairées sur la gestion des risques d’inondation, le Ministère de l’Infrastructure et de l’Environnement néerlandais, l’Association des autorités régionales de l’eau et l’Association des collectivités provinciales ont conjointement commandé une étude de plusieurs millions d’euros pour acquérir une connaissance approfondie de la probabilité et des conséquences d’inondations majeures. Le projet VNK2 (VNK désignant les risques d’inondation aux Pays-Bas) est une étude quantitative d’analyse de risque portant sur chacun des 53 systèmes de digues des Pays-Bas ainsi que sur les berges le long du fleuve Meuse. Les résultats de ces analyses sont utilisés pour (i) éclairer les débats politiques concernant l’acceptabilité des risques, (ii) comparer l’efficacité des diverses stratégies de réduction de risques envisagées (par ex. : renforcer les digues, réduire leur vulnérabilité, améliorer les capacités de gestion de crise), (iii) établir des priorités au sein du programme national de renforcement des ouvrages de protection contre les inondations, et (iv) réorienter l’effort de recherche sur les principales sources d’incertitude. Cet article propose une vue d’ensemble des méthodes et techniques mises en œuvre pour évaluer les risques d’inondation aux Pays-Bas et met l’accent sur le potentiel d’utilisation de l’analyse de risque quantitative pour prioriser les actions liées à la gestion du risque d’inondation.
1 INTRODUCTION

The Netherlands is a low-lying, densely populated country. Some polders, such as the Alexander polder near Rotterdam, lie 6m below mean sea level. Amsterdam internal airport lies 4m below mean sea level. The flooding of such parts of the country could have catastrophic consequences, similar to the flooding of New Orleans in 2005 (Jonkman et al., 2005). The same holds true for the sizeable polders further upstream, that are at risk from flooding from the rivers Rhine and Meuse, and the polders along Lake IJssel.

A system of flood defenses protects the Netherlands from large-scale floods. The flood prone parts of the Netherlands are divided into over fifty major levee systems, also called dike ring areas. These cover about 60% of the Dutch territory. Each major levee system consists of a series of primary flood defenses. The word ‘primary’ is used to distinguish these flood defenses from the numerous secondary or regional flood defenses within each major levee system. The primary flood defenses are natural or man-made barriers such as dunes, levees, sea dikes, dams, and hydraulic structures (e.g. locks and drainage sluices). With over 3600 kilometers of primary flood defenses, flood risk management is a vital, yet costly affair. Annual expenditures on flood protection are in the order of USD 0.5-1 billion (e.g. Vellinga et al., 2006).

All primary flood defenses are periodically tested against statutory safety standards. Flood defenses that fail to meet these standards have to be strengthened. The multi-billion euro nHWBP (new Flood Protection Programme) aims to strengthen all primary flood defences that failed the most recent statutory safety assessment. Due to the scale of the nHWBP, priorities have to be set. Yet present-day safety assessments only say which flood defences have to be strengthened (outcomes are binary: flood defences ‘pass’ or ‘fail’), they do not indicate where risks are highest, making it hard to distinguish between the hundreds of kilometers of flood defenses that failed the assessment.

In 2006, the Dutch Ministry of Infrastructure and the Environment, the Association of Regional Water Authorities and the Association of Provincial Authorities commissioned a study to gain insight into the probabilities and consequences of large-scale floods in the Netherlands. The so-called VNK2-project is a large-scale quantitative flood risk analysis for all major levee systems in the country, to be completed by the end of 2014 (Jongejan et al., 2012a). The methods and risk estimates of the VNK2-project are currently being used to support the prioritization of flood risk management actions within the nHWBP (new Flood Protection Programme).

The outcomes of the VNK2-project are also being used for informing the political debate about new flood safety standards, for choosing between alternative strategies for reducing flood risks (e.g. strengthening flood defenses, managing land-use and development and/or improving disaster preparedness), and for (re)directing research efforts towards important sources of uncertainty. While this may not be directly obvious, each of these applications of the VNK2-project also revolves around the prioritization of risk management actions.

Deciding where to raise, or lower, present-day flood safety standards is essentially about prioritizing a virtually infinite number of alternatives. And in cost-benefit analyses aimed at deriving economically optimal safety standards (i.e., maximum allowable probabilities of flooding), actions are ranked on the basis of their cost-effectiveness to ensure diminishing marginal returns. Deciding on a risk management strategy is also essentially a prioritization exercise, with the strategy that receives the most favourable score being implemented. Deciding which kinds of research to initiate or intensify is similarly about deciding where and how much to invest.

This paper is organized as follows. An overview of the methods and techniques for quantifying flood risks in the Netherlands is given in section two. Section three then shows how quantitative risk estimates can be used for prioritizing flood risk management actions. It will be shown how different, widely used criteria for prioritizing risk management actions may lead to very different outcomes. This is illustrated by means of a case study in section four. Finally, summary conclusions are provided in section five.
2 QUANTITATIVE RISK ANALYSIS IN THE NETHERLANDS: METHODS AND TECHNIQUES

2.1 Overview

The Dutch major levee systems and the areas they protect have wide-ranging characteristics. Some of these areas cover hundreds of square kilometres, others just a few; some have millions of inhabitants, others only a few thousand; some are heavily compartmentalized by (regional) flood defences or line infrastructures, others are relatively open; some are at risk from salt water floods, others from fresh water floods. Some levee systems consist exclusively of levees and structures, others also include dunes and sea dykes. Dyke materials and subsoil characteristics vary strongly throughout the country, as do hydraulic loading conditions. Each major levee system is thus unique, requiring a separate risk assessment.

The consequences of the failure of a major levee system depend, amongst other, on the number of breaches, the breach location(s), the hydraulic boundary conditions, the area’s topography, the vulnerability of impacted sites, and the effectiveness of crisis management operations such as preventive evacuation. The risk of flooding thus cannot be calculated by ‘simply’ calculating the probability of flooding (the occurrence of a breach), and by combining this probability with ‘the’ consequences of flooding. In the VNK2-project, the risk of flooding is therefore calculated by quantifying the probabilities and consequences of a set of flood events, called flood scenarios. The probabilities of these scenarios depend on the probabilities of failure (i.e. breaching) of the different parts of the levee system and the relations between these failures. A multiple-breach-scenario is relatively unlikely, for instance, when hydraulic loads drop markedly after the occurrence of the first breach.

The VNK2-procedure for quantifying flood risks comprises the following steps (Jongejan et al., 2012a):

1. Screening. During the screening phase, which is essentially about hazard identification, the analysts work towards a deeper understanding of the levee system and its components, and decide which failure mechanisms and parts of the levee system ought to be studied in greater detail. Probabilistic reliability analyses are only carried out for these failure mechanisms and parts of the levee system to save time and energy (steps 2-3).

2. Decompose the levee system into statistically homogeneous sections. This is done to facilitate probabilistic reliability analyses.

3. Calculate failure probabilities for each relevant failure mechanism, for each section. These can then be combined to failure probabilities of groups of sections.

4. Define scenarios. The infinite range of possible flood events is characterised by a limited set of mutually exclusive and collectively exhaustive scenarios. Each scenario is the result of breach in a so-called consequence segment (which comprises one or more sections), or a series of breaches in different consequence segments during the same high water event. A consequence segment is a part of the levee system in which breaches would have largely similar consequences (on average, a levee system is decomposed into 10 consequence segments, each consisting of 1-10 sections). The number of scenarios can be up to \(2^n-1\) in which \(n\) is the number of consequence segments; for \(n = 10\) there could already be 1023 scenarios.

5. Calculate scenario probabilities. This is done by combining the failure probabilities of the different sections, taking into account their interdependencies.

6. Calculate the consequences of each flood scenario. Consequence estimates are obtained by combining the outcomes of flood propagation models, land-use data, and dose-response functions. The various possible success rates of preventive evacuation are included in the analyses via event trees.

7. Combine the scenario probabilities and the consequences per scenario to obtain risk estimates.

Steps 3-7 will be discussed in greater detail in the following sections.

Throughout each risk analysis, analysts meet frequently with experts from regional water authorities and provincial authorities. Their involvement is essential for avoiding misinterpretation and errors. An elaborate system of quality control, involving regular exchanges between risk analysts, training, and internal and external reviews, ensures all risk analyses are carried out correctly and consistently.
2.2 Quantifying failure probabilities and scenario probabilities

In the VNK2-project, the failure probability of a statistically homogeneous section is obtained by first calculating a failure probability for a representative cross section and by subsequently scaling this cross-sectional failure probability to the length of the entire section via an outcrossing approach (Vrouwenvelder, 2006). This is done for all relevant failure mechanisms. The results are then combined, taking into account the correlations between the different failure mechanisms. Each cross-sectional failure probability is calculated by evaluating a limit state function. Although these functions are different for each failure mechanism, they all share the same format:

\[ Z = R - S \]  

where \( Z \) is the limit state function (\( Z < 0 \) indicates failure), \( R \) is resistance, and \( S \) is load. Because \( R \) and \( S \) are stochastic (uncertain) variables, so is \( Z \). The probability of failure equals the probability that load exceeds resistance or, equivalently, that the limit state function is smaller than zero:

\[ P_f = P(S > R) = P(Z < 0) \]  

The probability of failure of a section depends on its length when load and/or resistance are not perfectly spatially correlated: in case of spatial variance, the probability of observing some extreme value increases with distance (see e.g. VanMarcke, 1977; 1988; 2011). The autocorrelation function of \( Z \) depends on the autocorrelation functions of its constituent components (i.e., the stochastic variables that define \( R \) and \( S \)), as well as their relative importance. Note that the failure probability of a section can still be written as \( P(Z < 0) \), albeit with different (extreme value) distributions of \( R \) and \( S \).

To obtain the failure probability of a section (for a group of failure mechanisms) or the failure probability of a consequence segment (a group of sections), failure probabilities have to be combined. In the VNK2-project, this is done in a pair-wise manner. Each pair can be conceptualized as a series system of two components. Such a system’s failure probability can be calculated as follows:

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

The probabilities \( P(Z_1 < 0 \cup Z_2 < 0) \) and \( P(Z_1 < 0 \cap Z_2 < 0) \) depend on the correlations between \( Z_1 \) and \( Z_2 \). The method that is used in the VNK2-project for combining elements with correlated limit state functions rests on a first-order method developed by Hohenbichler-Rackwitz (1983) that relies on the correlation coefficient between the normalized and linearized limit state functions of \( Z_1 \) and \( Z_2 \).

After combining two elements, an equivalent limit state function is computed for the two-component-series-system (Vrouwenvelder & Steenbergen, 2003; Vrouwenvelder, 2006). This equivalent limit state function is then be combined with the limit state function of the next element, following the same procedure. This combinatory procedure has been implemented in PC-Ring, the software programme that is used in the VNK2-project for calculating failure probabilities for (groups of) sections, as well as scenario probabilities (Vrouwenvelder & Steenbergen, 2003).

For a levee system composed of only two consequence segments with (equivalent) limit state functions \( Z_1 \) and \( Z_2 \), the scenario probabilities are as follows when there is no relief (a drop in hydraulic loads) after the first breach: \( P_1 = P(Z_1 < 0) \cap Z_2 < 0 \), \( P_2 = P(Z_2 < 0) \cap Z_1 < 0 \), and \( P_{12} = P(Z_1 < 0 \cap Z_2 < 0) \) (Thonus et al., 2008). When relief is likely to occur, the scenario definitions are as follows: \( P_1 = P(Z_1 < 0 \cap Z_2 < 0) \) and \( P_2 = P(Z_2 < 0 \cap Z_1 < 0) \) (only the weakest section fails), or \( P_1 = P(Z_1 < 0) \) and \( P_2 = P(Z_2 < 0) \) (loading sequence, only one section fails). Note that all scenario definitions satisfy the total probability theorem: the sum of the scenario probabilities always equals \( P(Z_1 < 0 \cup Z_2 < 0) \).
2.3 Quantifying the consequences of failure

For each scenario, the economic damage and the number of fatalities are estimated on the basis of flood simulations (which provide maximum water depths, rise rates, and flow velocities), land use data (value and population at risk), estimates of evacuation effectiveness and dose-response functions. The whole procedure for calculating the consequences per scenario is graphically illustrated in Figure 1.

![Figure 1: Procedure for quantifying the consequences associated with a flood scenario](image)

The flood simulations are made with integrated 1D/2D-models, using a grid size of 100x100m to 25x25m (e.g. Verwey, 2001). An example of the end-result of such a simulation is shown in Figure 2. For more details about the probabilistic evacuation analyses rates, the reader is referred to Maaskant et al. (2009a). More information about the dose response functions that are used to link flood characteristics to damages and mortality rates, the readers is referred to Jonkman (2007) and Maaskant et al. (2009b).

![Figure 2: The result of a flood simulation for a breach in levee system no. 36 Land van Heusden/de Maaskant. The breach location is marked by a black circle.](image)
2.4 Combining scenario probabilities and the consequences per scenario to risk estimates

The scenario set characterizes all possible flood events. Each scenario contributes to the risk of flooding in a levee system. Since scenarios are mutually exclusive and collectively exhaustive (see also section 2.2), their contributions add up to the total risk of flooding in a levee system. This risk can be expressed in various ways: in numbers (e.g. annual expected values), graphs (e.g. FN-curves, showing the cumulative distribution of the number of fatalities) or plotted on maps showing the spatial distribution of expected loss or potential loss of life. Examples are provided in section 4.

3 PRIORITIZING RISK MANAGEMENT ACTIONS

3.1 Setting priorities: a value-laden activity

Prioritizing risk management actions is a value-laden activity, as any ranking mechanism inevitably involves value-laden assumptions that influence the outcomes of a ranking exercise (see also Arrow, 1963; Fischhoff et al., 1981; Fischhoff et al., 1984; Slovic et al., 1999). Defining risk as the annual expected value of economic damage or the weighted sum of different attributes may strongly influence the ranking of alternatives. Also, ranking procedures need not be based on ‘scientific’ methods such as multi-criteria analysis, cost-effectiveness analysis or cost-benefit analysis. They could also be based on voting procedures to aggregate individual preferences (e.g. Arrow, 1963). Each procedure may yield different outcomes.

The fact that all prioritization procedures can be criticized on subjectivist grounds need to lead to mindless relativism. In practice, ranking procedures, based on agreed upon criteria, can help decision makers to identify cases that warrant attention. It may also depoliticize/rationalize investment decisions by laying down transparent ‘rules of the game’. The latter is especially important when costs and gains are unevenly distributed, as is the case in the Netherlands: the costs of strengthening flood defenses are partly borne by the national government and partly shared by the different regional water authorities. Only a small percentage of the costs of strengthening a flood defense is paid by its local beneficiaries.

Two popular ranking procedures will be discussed in the following sections. They both rest on information that can be obtained via quantitative risk analyses such as the VNK2-project:

1. risk-risk comparison
2. benefit-cost comparison

Since risk can be defined in a myriad of ways, it will be shown how different definitions of risk influence rankings based on risk-risk comparison. The following definitions of risk will be considered:

1. risk defined as annual expected value of economic loss
2. risk defined as the annual expected value of the number of fatalities
3. risk defined as group risk (i.e., the annual expected value of a non-linearly weighted number of fatalities)

Note that risk is defined as probability times consequence in each of these definitions, albeit with consequences defined differently

There are numerous types of group risk measures (Jonkman et al., 2003). Despite their different appearances, a shared feature is that they place disproportionately greater weight on greater numbers of fatalities, giving rise to a phenomenon called risk aversion (see e.g. Chavas, 2004). Here, one of the simplest types of group risk measures will be considered: the annual expected value of the squared number of fatalities. It should be noted that the use of a quadratic weighting function (or disutility function) corresponds to relatively strong risk aversion. This highlights the differences between group risk and the annual expected value of the number of fatalities, the latter being conceptually similar to a group risk measure based on a linear (risk neutral) weighting function.
Benefit-cost comparison is essentially a special instance of cost-effectiveness comparison, with the effectiveness of risk management actions measured in money terms. In principle, the effectiveness of risk management actions could be defined in as many ways as risk itself. Since the dilemmas related to the definition or risk will already be discussed within the context of risk-risk comparison, and because benefit-cost comparisons are widely used as a basis for prioritization procedures, only benefit-cost comparison will be discussed hereafter.

For reasons of simplicity, all examples hereafter will concern flood protection only, i.e. the strengthening of parts (sections) of levee systems. In practice, risk management actions could also concern other types of measures, such as flood proofing vulnerable objects or improving disaster preparedness. Any of such measures could be ranked using the same prioritization procedures. In that sense, quantitative risk analysis provides a basis for comparing, or ranking, the seemingly incomparable (e.g. Jongejan et al., 2012a, 2012b).

### 3.2 Risk-risk comparison

A ranking procedure based on risk-risk comparison gives greatest priority to actions where risks are highest. Deciding which parts of a major levee system ought to strengthened first thus requires us to differentiate between the risks associated with each of the system’s parts. Yet there might be numerous sections that contribute to the risk in a (particular part of a) major levee system so that the criterion ‘where risks are highest’ could correspond to a large number of actions. This non-uniqueness issue could be addressed in two different ways.

First, the risk-risk comparison could be based on the ‘risks per section’, with the ‘risk per section’ being the product of a section’s failure probability and the consequences if it were to fail. This is equal to the risk of flooding if all other sections would be perfectly safe. While pragmatic, the concept of ‘risk per section’ has its limitations due to the effects of spatial correlations. Consider for instance a consequence segment composed of two sections with identical and perfectly correlated limit state functions $Z_1$ and $Z_2$. The failure probability of the consequence segment then equals $P(Z_1<0 \cup Z_2<0) = P(Z_1<0)P(Z_2<0)$ and the ‘risks per section’ are $P(Z_1<0)q$ and $P(Z_2<0)q$ respectively (with $q$ being the consequences of flooding). Reducing the risk of only one of these sections to zero (by reducing $P(Z_1<0)$ or $P(Z_2<0)$ to zero) will not change the failure probability of the consequence segment or the risk of flooding.

Second, the risk-risk comparison could be based on ‘contributions to the risk of flooding’. Rather than assuming all other sections are perfectly safe, the failure probabilities of the other sections are now treated as a given. This, however, means that high-risk cases might go unnoticed. Consider, again, a consequence segment composed of two sections with identical and perfectly correlated limit state functions. The contribution of each individual section to the failure probability of the consequence segment, and hence the risk of flooding, would be equal to zero, even if these sections would have very high failure probabilities.

Considering the above, a risk-risk ranking procedure based on the ‘risk per section’ was applied to VNK2-data. Note that rankings based on the ‘risks per section’ and the ‘contributions to the risk of flooding’ yield identical results when section failures are disjoint events. This presupposes, at a minimum, statistical independence. At least in the Netherlands, this will rarely be the case.

Figure 3 shows plots of the failure probabilities and consequences (economic loss, number of fatalities, number of fatalities squared) for 1672 sections with a combined length 1375 kilometers (22 major levee systems). The dashed lines in each plot show where the ‘risk per section’ (probability times consequence) is the same. To show how different definitions of risk would influence the outcomes of a ranking exercise, the sections of levee system no. 36 (Land van Heusden/de Maaskant, along the river Meuse) are highlighted. When the ranking is based on economic risk, 15 sections of levee system no. 36 appear in the top 100, 13 when the ranking is based on fatality risk, and 14 when it is based on group risk.
Ranking based on the annual expected value of economic loss

Ranking based on the annual expected value of the number of fatalities

Ranking based on group risk

Figure 3: Consequences and failure probabilities per section, for different types of consequences: economic loss (top, left), number of fatalities (top, right), and the number of fatalities squared (bottom); black squares: sections belonging to levee system no. 36; grey circles: all other sections.

3.2 Benefit-cost comparison

In economic analyses, flood risk is typically defined as valued at the expected value of economic damage (the actuarially fair insurance premium), see e.g. Van Dantzig (1956). The benefit-cost ratio of a risk management action then equals the present value of the reduction of annual expected loss divided by the present value of the cost of the action. Only when benefit-cost ratios are greater than 1 do benefits outweigh costs. The higher an action’s benefit-cost ratio, the greater is its net present value. A ranking based on benefit-cost comparison thus gives greatest priority to the actions with the greatest net present values.
When quantifying the benefits of strengthening individual sections, the same methodological issue arises that was discussed in the previous section: due to spatial correlations, the benefit of strengthening a particular section may depend on whether other sections are strengthened as well. Here, again, each section was treated in isolation, i.e. the benefit of strengthening a section were quantified assuming all other sections are perfectly safe. In that case, the benefit-cost ratio of strengthening a section can be calculated as follows (assuming, for reasons of simplicity, the absence of sea level rise, subsidence, and economic development):

\[
\frac{C}{P_f} \frac{q_f}{100} \frac{P}{\gamma} = \frac{P_f q_f - P_f q_i}{\gamma} / C
\]

(4)

where \(C\) is the (present value) of the cost of the risk management action (i.e., the cost of strengthening a section), \(P_f\) the annual probability of failure of the section before the action, \(q_0\) the expected economic loss in case of flooding (conditional expected value) before the action, \(P_f\) the annual probability of failure after the action, \(q_i\) the expected economic loss in case of flooding after the action, and \(\gamma\) the discount rate.

When an investment strongly reduces the probability of failure \((P_f << P_f)\) while leaving the economic impact of flooding largely unchanged \((q_0 \approx q_i)\), equation (4) reduces to:

\[
\frac{C}{P_f} \frac{q_f}{100} \frac{P}{\gamma} = \frac{P_f q_0}{\gamma C}
\]

(5)

Using equation (5), benefit-cost ratios were calculated for all sections in 22 major levee systems. The discount rate was set at 2.5% per year, the Dutch official risk-free rate for government project appraisal. Crude estimates were used for the costs of strengthening levees (for illustrative purposes only): 12 million euro/km for levees in urban areas, 5 million euro/km for levees in rural areas, 2.5 million euro/km for levees in rural areas along the river IJssel, and (a somewhat arbitrary) 0.25 million euros per hydraulic structure. Dunes were left aside because of their relatively low probabilities of failure. Results are shown in Figure 4. Eighteen sections of levee system no. 36 appear in the top 100 sections with the highest benefit-cost ratios.

Figure 4: Benefit-cost ratios per levee section; benefit-cost ratios smaller than 0.001 not shown
It is emphasized that the benefit-cost ratios shown in Figure 4 rest on cost estimates that are highly inaccurate. This, however, does not render the outcomes shown in Figure 4 useless. Benefit-cost ratios easily vary of orders of magnitude, implying crude cost estimates will often suffice for identifying the most cost-effective risk management actions. Moreover, the absolute values of the cost estimates are irrelevant for a ranking exercise: for prioritization purposes, only cost differentials matter. Analyses similar to the one presented here may thus serve as a useful preliminary to more detailed analyses, to ensure time and energy are spent efficiently.

4 HOW ALTERNATIVE PRIORITIZATION PROCEDURES INFLUENCE THE RISK OF FLOODING: A CASE STUDY

Different prioritization procedures place different weights on the different attributes of flood risk management actions and/or the risks they are supposed to address. This means that different prioritization procedures may lead to different orderings of risk management actions. In practice, such differences not only influence how resources are allocated, but also how the risk of flooding is impacted.

Prioritization procedures based on risk-risk comparison can have unexpected and/or unintended outcomes. An investment strategy based on benefit-cost comparison may, for instance, lead to lower levels of economic risk when risk is defined as the annual expected value of the number of fatalities than when it is defined as the annual expected value of expected loss. This is because the effectiveness and the costs of risk management actions are ignored in risk-risk comparisons: ineffective, costly actions may consume a sizeable portion of the available budget, leaving little room for more effective actions.

To illustrate how different prioritization procedures influence the risk of flooding Table 1, Figure 5 and Figure 6 show how an investment of 100 million euros (USD 130 million) would impact the risk of flooding in levee system no. 36 (Land van Heusden/de Maaskant). The risk of flooding is expressed in various ways. Table 1 shows annual expected values, Figure 5 cumulative distributions of the number of fatalities (FN-curves), and Figure 6 individual risk maps. Clearly, the risk of flooding in levee system no. 36 is strongly influenced by the way in which priorities are set. The investment strategy based on benefit-cost comparison appears to outperform the other investment strategies on every measure: it leads to the lowest levels of economic risk, fatality risk, group risk and individual risk.

<table>
<thead>
<tr>
<th>Case</th>
<th>Annual expected value of economic loss</th>
<th>Annual expected value of the number of fatalities</th>
<th>Annual expected value of the squared number of fatalities (group risk)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status quo (before spending EUR 100 million)</td>
<td>EUR 30.3 million</td>
<td>0.58</td>
<td>174.7</td>
</tr>
<tr>
<td>Risk-Risk-comparison</td>
<td>EUR 5.1 million</td>
<td>0.08</td>
<td>6.6</td>
</tr>
<tr>
<td>After spending EUR 100 million with prioritization based on economic risk (i.e., the annual expected value of economic loss)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After spending EUR 100 million with prioritization based on fatality risk (i.e., the annual expected value of number of fatalities)</td>
<td>EUR 4.5 million</td>
<td>0.07</td>
<td>5.1</td>
</tr>
<tr>
<td>After spending EUR 100 million with prioritization based on group risk (i.e., the annual expected value of the squared number of fatalities)</td>
<td>EUR 7.9 million</td>
<td>0.11</td>
<td>5.6</td>
</tr>
<tr>
<td>Cost-effectiveness comparison</td>
<td>EUR 3.0 million</td>
<td>0.04</td>
<td>1.9</td>
</tr>
<tr>
<td>After spending EUR 100 million with prioritization based on benefit cost comparison</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Figure 5. FN-curves before and after spending EUR 100 million on preventive measures, using different prioritization methods.

The FN-curve shown in Figure 5 for the case in which priorities are set on the basis of benefit-cost comparison lies below all the other FN-curves. This implies that the level group risk will be the lowest when prioritise are set on the basis of benefit comparison (in this particular case), regardless of the exact weighting function that is used for computing/defining group risk (see also section 3.1). Every risk-averse decision maker would opt for the lowest FN-curve in Figure 5, regardless of his or her exact risk preferences (i.e., regardless of the type and degree of risk aversion).
<table>
<thead>
<tr>
<th>Prioritization Method</th>
<th>Before Spending EUR 100 million</th>
<th>After Spending EUR 100 million</th>
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<td>Base case (status quo)</td>
<td><img src="image" alt="Base case" /></td>
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<td>After spending EUR 100 million, with priorities based on the annual expected value of economic loss</td>
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<td>After spending EUR 100 million, with priorities based on the annual expected value of the number of fatalities</td>
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<tr>
<td>After spending EUR 100 million, with priorities based on societal risk</td>
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<tr>
<td>After spending EUR 100 million, with priorities based on benefit-cost ratios</td>
<td><img src="image" alt="Benefit-Cost" /></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: Individual risk maps before (top row) and after spending EUR 100 million on preventive measures, using different prioritization methods.
5 CONCLUSION AND DISCUSSION

Setting priorities is a vital part of flood risk management as decision makers are routinely confronted with budget and organizational constraints. Prioritization procedures are widely used for structuring and rationalizing decision making processes. This paper showed how the results of quantitative risk analyses can be used for prioritization purposes. It also explored some of the dilemmas that arise when developing procedures for prioritizing flood risk management actions. While this paper focused on experiences from the Netherlands, its conclusions are more widely applicable.

First, the outcomes of prioritization procedures based on risk-risk comparisons or cost-effectiveness analyses depend critically on how risk (and hence effectiveness) are defined. When stakeholders cannot reach consensus on the risk attributes on which the ordering of risk management actions is to be based, sensitivity analyses could be carried out to demonstrate to what extent the definition of risk influences the outcomes of a prioritization exercise.

Second, prioritization procedures based on risk-risk or benefit-cost comparison can only be unambiguously applied when cases or actions can be uniquely linked to particular risks. In case of strong correlations between the contributors to the risk of flooding, the impact of removing a single contributor might be small, but the impact of removing a group of contributors considerable. This is not merely a hypothetical issue, since the loads on the different parts of a flood protection system are often strongly correlated. Considering contributors in isolation, assuming all other contributors are absent or perfectly safe, ensures that high-risk cases will be identified. It may, however, lead to ineffective actions being given high priority.

Third, prioritization procedures based on risk-risk comparison may yield unexpected outcomes. For instance, targeting places where economic risks are highest may be less effective in reducing economic risks than targeting places where fatality risks are highest. This is because the places where (particular types of) risk are highest are not necessarily the places where actions are most cost-effective. Costly and/or ineffective actions in places where risk are highest may leave little room for effective actions elsewhere. Prioritization procedures based on cost-effectiveness do not suffer from such drawbacks and yield more predictable results.

While this paper discussed prioritization procedures that rely on the outcomes of quantitative risk analyses, such complex analyses are not always needed to be able to distinguish between groups of cases. A layered approach, starting with relatively simple qualitative criteria and then gradually moving towards ever more detailed quantitative analyses, might save precious time and energy. The USACE Levee Safety Program, for instance, assigns each levee a Levee Safety Action Classification (LSAC) based on inspection results. These LSACs are then used to decide whether more detailed analyses are needed. A similar, albeit less strong ‘layered-ness’ can be found in Dutch levee safety assessment guidelines.

The present-day Dutch levee assessment guidelines do not (yet) allow for probabilistic assessments: they rely on a partial safety factor approach and only indicate whether a flood defense should be strengthened. This is why the analyses presented in this paper relied on probability and consequence estimates from the VNK2-project, a large-scale quantitative risk analysis for all major levee systems in the Netherlands. Unfortunately, the outcomes of the VNK2-project and the most recent statutory assessment sometimes point in opposite directions. This means that relatively high risk cases (according to VNK2) may not be part of the new Flood Protection Programme, and vice versa (note: the outcomes of the VNK2-project are not linked to legal standards and thus cannot lead to a legal obligation to strengthen a flood defence).

While the abovementioned differences complicate the use of VNK2-outcomes within the new Flood Protection Programme, they are irrelevant to the discussion of prioritization procedures presented in this paper. These differences will also disappear with the introduction of new, risk-based safety standards, together with probabilistic assessment methods. Both are expected by 2017. The VNK2-project is not here to stay, but it does give an impression of the future of flood risk management in the Netherlands.
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