Applications of VNK2, a fully probabilistic risk analysis for all major levee systems in The Netherlands

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ABSTRACT: The VNK2-project is a large-scale, fully probabilistic risk analysis for the low-lying parts of The Netherlands. It started in 2006 and draws upon decades of research and development. This paper presents a number of examples that illustrate the potential of VNK2, and quantitative risk analysis in general, to inform and improve flood risk management. These examples concern (i) prioritising investments on the basis of their cost-effectiveness, (ii) informing political debates about the acceptability of risks, and (iii) evaluating the impact of so-called delta levees on flood risks.

The results of VNK2 have various applications in the field of flood risk management. Here, we focus on three of these:

– Prioritising investments in flood protection. The outcomes of a VNK2-risk analysis can be used to rank investments on the basis of their cost-effectiveness. As such, the VNK2-project can be used to set priorities within levee reinforcement programmes, such as the multi-billion euro nHWBP (the Dutch acronym for the new Flood Protection Programme).

– Informing political debates about the acceptability of risks. The VNK2-project gives insight into economic and fatality risks. It thereby provides a basis for political debates about the acceptability of risks, and e.g. the adequacy of existing safety standards.

– Evaluating the impact of super levees on flood risks. In The Netherlands, so-called super or delta levees have recently gained popularity in policymaking circles. With the probabilistic techniques used within the VNK2-project, it is possible to evaluate the designs of super levees, and to show how such super levees would influence the risk of flooding in a particular levee system.

Each of these applications will be illustrated by means of an example. These are discussed in sections 3 to 5. But first, an overview of the technical backgrounds of the VNK2-project is given in section 2. The paper ends with conclusions and a discussion.

2 TECHNICAL BACKGROUND

In the VNK2-project, flood risk is treated as a set of triplets: a set of scenarios, scenario probabilities,
and consequences per scenario (see also Kaplan and Garrick, 1981):

\[ R = \left\{ \text{Scen}_i, P_{\text{Scen}_i}, q_{\text{Scen}_i} \right\} \]  

where \( R = \text{risk} \); \( \text{Scen}_i \) = identification or description of scenario \( i \); \( P_{\text{Scen}_i} \) = probability of scenario \( i \); \( q_i \) = consequences of scenario \( i \) (fatalities and economic damage). The VNK2-procedure for computing flood risks comprises the following steps (Fig. 1).

1. **Decompose levee system into statistically homogenous sections.** This is done to facilitate the failure probability calculations for the different parts of the levee system. Hydraulic structures, such as sluices and culverts, are treated as individual sections. Levee sections are generally about 750 meters long, though they can range from 150 meters to over two kilometres depending on circumstances.

2. **Calculate a failure probability for each section.** This is done using PC-Ring, a programme specifically developed for calculating the failure probabilities of (parts of) levee systems (e.g. Vrouwenvelder 2006). The probabilistic techniques used within the VNK2-project allow for an explicit and consistent treatment of the uncertainties related to loads, strength properties, and models (via stochastic model factors).

3. **Define scenarios.** The infinite range of potential flood scenarios is characterised by a limited set of mutually exclusive and collectively exhaustive scenarios. Each scenario is the result of a different (combination of) breach(es), in one or more groups of sections, called consequence segments.

4. **Calculate scenario probabilities.** This is done by combining the failure probabilities of the different sections. The water level that triggers a scenario is chosen on the basis of the design point obtained by the scenario probability calculation.

5. **Calculate the consequences for each scenario (economic damage, fatalities).** Consequence estimates are obtained by combining the outcomes of flood propagation models, land-use data, and dose-response functions. The possible success rates of preventive evacuation are included in the risk analysis by means of event trees.

6. **Combine the scenario probabilities and consequences per scenario to obtain risk estimates.** Risks can be presented in various forms, ranging from individual and societal risk to expected damages. Both economic and fatality risks are considered in VNK2.

3 APPLICATIONS OF VNK2 IN FLOOD RISK MANAGEMENT

3.1 Prioritising investments in flood protection

The multi-billion euro nHWBP-project (new Flood Protection Programme) aims to strengthen
the flood defences that failed to meet the most recent statutory safety assessment. Because of budget constraints and the efficient use of organisational capacities, not all flood defences can be strengthened simultaneously. Priorities thus have to be set.

The methods and outcomes of the VNK2-project can be used to identify the measures that would be most effective in terms of risk reduction. In cost-benefit 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 an intervention then equals the present value of the reduction of annual expected loss divided by the present value of the investment cost. From a purely economic perspective, only investments with a benefit-cost ratio greater than 1 should be taken.

For illustrate purposes, Figure 2 shows the probabilities and consequences of failure per section (i.e. a part of a levee system with statistically homogeneous characteristics, see section 2), for levee systems no. 12 Wieringen and no. 36 Land van Heusden/de Maaskant The higher the probability of failure and the higher the consequences of the failure, the greater the expected value of economic damage.

In a world without sea level rise, subsidence, or economic growth, and without strong correlations between the failures of different sections/structures, the benefit-cost ratio of strengthening a section/structure could be calculated as follows:

$$\frac{B}{C} = \frac{P_0 Q_0 - P_1 Q_1}{\gamma C}$$

(2)

where $B =$ present value of annual benefit (risk reduction); $C =$ investment cost; $P_0 =$ failure probability before the investment; $Q_0 =$ expected consequences in case of flooding before the investment; $P_1 =$ failure probability after the investment; $Q_1 =$ expected consequences in case of flooding after the investment; $\gamma =$ discount rate.

When an investment strongly reduces the probability of failure ($P_1 << P_0$) while leaving the expected consequences in case of flooding largely unchanged ($Q_0 \approx Q_1$), Equation 2 reduces to:

$$\frac{B}{C} = \frac{P_0 Q_0}{\gamma}$$

(3)

Using crude estimates of the costs of levee strengthening (5.10$^6$ euro/km for green levees, 12.10$^6$ euro/km for levees in urban areas), and assuming a discount rate of 2.5% per year, benefit-cost-ratios were calculated for strengthening the sections/structures shown in Figure 2. Results are shown in Figure 3. In only 31 out of 81 cases would the benefit-cost ratio be greater than one.

All major levees systems in The Netherlands are periodically tested against safety standards. A total of 39 sections/structures in levee systems no. 12 and 15 failed to meet these standards in the most recent statutory assessment, implying 39 sections/structures have to be strengthened. Estimates of the benefit-cost ratios of strengthening these sections/structures are shown in Figure 4.

Figure 4 shows that only positive 4 out of 39 cases have benefit-cost ratios greater than 1. Notwithstanding the crude assumptions on which these benefit-cost ratios rest, the gross disproportionalities between benefits and costs for a
majority of cases imply that present-day standards and statutory safety assessment methods could lead to an inefficient allocation of resources (note that a benefit-cost ratio of 0.1 implies that costs outweigh gains by a factor 10). This lends support to the thesis that a truly risk-informed approach to flood risk management could bring significant efficiency gains.

3.2 Informing political debates about the acceptability of risks

Present-day safety standards for the Dutch primary flood defences date back to the Flood Defence Act of 1996 (later turned into the Water Act). Evaluations of the benefits and costs of strengthening flood defences played an important role in defining the stringency of these standards (e.g. Van Dantzig 1956). The balance between costs and benefits has gradually changed due to population growth and economic development. These changes have led the Dutch government to re-evaluate the stringency of present-day safety standards.

In the so-called Delta Programme, the national government cooperates with regional water authorities, provinces and other stakeholders to work out plans and decisions to protect The Netherlands from floods, taking both a short and long-term perspective. As part of the Delta Programme, a Delta Decision on Flood Safety will be made in 2014. This decision concerns a proposal for new flood safety standards, as well as a choice for the regional strategies to implement these (Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, Agriculture and Innovation 2011).

Apart from the outcomes of a cost-benefit analysis (Kind 2008; Deltares 2011), the Dutch government explicitly considers fatality risks in the debate about new flood safety standards, as indicated by the National Water Plan (Ministry of Infrastructure and the Environment, 2009). To support the policymaking process, a number of studies have been carried out to provide preliminary estimates of fatality risks in The Netherlands (e.g. Jonkman et al. 2010; Deltares 2011). The results of the VNK2-project can be used for refining and verifying these.

To reduce flood risks to acceptable levels, prevention is not the only option. The various types of measures to reduce flood risks can broadly be grouped into two categories:

- Measures that influence the probabilities of flooding. Measures include: levee strengthening, beach nourishment, and widening rivers to increase their runoff capacities. Note that each of these measure can also influence, to some extent, the consequences of floods. Strengthening levees could, for instance, also favourably influence breach widths and thereby lead to lower consequences.

- Measures that influence the consequences in case of flooding. Measures include: implementing land-use planning restrictions, flood proofing vulnerable objects, and improving the opportunities for evacuation (early warning, shelters, etc.). Note that e.g. crisis management operations can fail, so that the impact of greater disaster preparedness on the consequences of a particular flood event is by no means certain.

In policymaking circles in The Netherlands, the term ‘multi-layered safety’ is often used to refer to the fact that (combinations of) different types of measures can be taken to reduce flood risks (e.g. Kolen & Kok 2011). These different ‘layers’ are flood prevention, spatial planning, and crisis management.

By measuring the effectiveness of investments in terms of their impact on flood risk, it becomes possible to directly compare the effectiveness of different types of measures: the effectiveness of prevention, spatial planning and crisis management can all be expressed in terms of their impact on economic and fatality risks. The quantitative risk analyses of the VNK2-project thus provide a ‘level playing field’ for evaluating the effectiveness of investments in the different ‘layers of protection’.

Figure 5 and Figure 6 illustrate how the different ‘layers of protection’ influence fatality risks, for two widely used individual risk metrics: societal risk and individual risk. Figure 5 shows the effect of a number of levee reinforcements on the individual risk (excluding the effect of preventive evacuation) in levee system no. 5 Texel island. These
reinforcements lower the individual risk in the different parts of the levee system. Figure 6 shows the effect of preventive evacuation on the FN-curve for levee system no. 36 Land van Heusden/de Maaskant (Havinga 2010).

An example of the potential of quantitative risks analysis to provide insight into the effectiveness of investments in different ‘layers of protection’, concerns a recent case study for levee system no. 36 Land van Heusden/de Maaskant (Oranjewoud & HKV Consultants 2011). This case study considered the situation in the year 2040, on the grounds that implementing large-scale measures takes many years. Based on historic trends, an economic growth rate of 1.9% per year was assumed; the number of inhabitants was assumed to remain constant. The following strategies were evaluated:

1. Do nothing. The failure probabilities of the different levee sections were assumed to stay the same as the outcomes of the VNK2-analysis.
2. Reduce the probability of flooding for the entire levee system from >1/100 per year to 1/1,250 per year. The probability of failure per kilometre was assumed constant.
3. Improve the potential for preventive evacuation and shelter. Flood mortality was reduced by a factor 5 and the expected evacuation rate was increased from 75% to 88%. This increase was based on estimates of Maaskant et al. (2009) and an EvacuAid-analysis (Kolen et al. in press), using best case assumptions for key parameters (‘response of authorities’, ‘citizen response’ and ‘adaptive use of the environment and infrastructure’) and by adding half a day to the forecasting horizon.
4. A combination of different types of measures, aimed at reducing flood risks in the most vulnerable area: the densely populated area around the city of ‘s-Hertogenbosch in the western part of the dike ring area. These measures are: strengthening the weakest 35 km of levees (giving them a combined failure probability of 1/5,000 per year), and improving the potential for preventive evacuation and shelter in the ‘s-Hertogenbosch region (assuming the parameter values of strategy no. 3).
The results for the abovementioned strategies are shown in Table 1 and Figure 7.

Table 1 illustrates the fact that investing in the opportunities for preventive evacuation and shelter can strongly influence fatality risks (albeit not as strongly in levee systems along the coast, where warning times are considerably shorter), but that it hardly influences economic risks. Strengthening flood defences reduces both fatality and economic risks.

3.3 Evaluating the impact of super levees on flood risks

The Dutch National Water Plan mentions the introduction of so-called super or delta levees as a possible, innovative means to protect The Netherlands from floods (Ministry of Infrastructure and the Environment 2009). According to the National Water Plan, delta levees are ‘so high, wide or strong that the probability of a sudden and uncontrollable flood is almost nil’ (Ministry of Infrastructure and the Environment 2009: p.72). This description allows for a wide range of interpretations as to the exact, defining characteristics of delta levees.

One might argue that a negligible probability of a sudden and uncontrollable flood implies a relatively low probability of geotechnical failure and an ability to withstand high overtopping discharges (e.g. Oranjewoud & HKV Consultants 2011; Knoeff & Ellen 2011). When an existing levee is upgraded to a delta levee with these characteristics, its probability of failure (i.e. the probability of a breach, or ‘uncontrolled flooding’) will be significantly reduced. Note that the fact that failure due to overtopping only occurs at relatively high overtopping discharges means that damages due to massive overtopping (without breaching) should now be taken into account.

Oranjewoud & HKV Consultants (2011) studied the effect of implementing delta levees in levee

<table>
<thead>
<tr>
<th>Case/strategy</th>
<th>Expected value of economic damage [Million euro/yr]</th>
<th>Expected value of the number of fatalities [yr⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNK2-estimate (2006)</td>
<td>30.9</td>
<td>0.59</td>
</tr>
<tr>
<td>1. Do nothing (2040)</td>
<td>54.4</td>
<td>0.59</td>
</tr>
<tr>
<td>2. Reduce the probability of flooding to 1/1,250 per year (2040)</td>
<td>8.9</td>
<td>0.11</td>
</tr>
<tr>
<td>3. Improve the potential for shelter and preventive evacuation (2040)</td>
<td>54.4</td>
<td>0.04</td>
</tr>
<tr>
<td>4. A combination of measures, focused on the ‘s-Hertogenbosch region (2040)</td>
<td>10.2</td>
<td>0.07</td>
</tr>
</tbody>
</table>
system no. 36 Land van Heusden/de Maaskant, assuming:

- a probability of a levee breach (‘uncontrolled flooding’) of 1/125,000 per year for the entire levee system, with a constant failure probability per kilometre.
- a probability of 1/12,500 per year of an average overtopping discharge of 10 l/s/m during a period of 12 hours over the full length of the primary flood defence. This overtopping discharge could be interpreted, more or less, as ‘a conditional expected value’, since overtopping discharges could be higher and lower, depending on the hydraulic loading conditions.

It should be noted that these assumptions imply a drastic (and very costly) upgrade of the existing flood defences. The benefit-cost ratio of implementing delta levees along the full length of the levee system would be considerably lower than one.

Figure 8 shows the effect of an average overtopping discharge of 10 l/s/m during a 12 hour period over the full length of the primary flood defence of levee system no. 36 Land van Heusden/de Maaskant. The water depths in the affected areas would mostly be 0 to 0.5 m, although they could reach up to 2 m.

Table 2 shows the risk of flooding in levee system no. 36 after upgrading the entire primary flood defence to a delta levee. As a reference, the table also shows the risk for two strategies discussed in section 3.2: ‘do nothing’ and ‘reduce the probability of flooding to 1/1250 per year’. Furthermore, the table shows the risk of flooding in case the probability of flooding is reduced to 1/125,000 per year, just like the delta levee, but with a ‘traditional design’ with a lower critical discharge (i.e. a higher crest rather than a more gentle overtopping resistant inner slope).

Table 2 illustrates the following points:

- When levees are designed such that their critical overtopping discharges (i.e. the discharges that cause failure, or ‘uncontrolled floods’) are relatively high, the consequences associated with large-scale over-topping should be taken into account.
- The failure probability of a levee due to overtopping can be reduced by raising its critical overtopping discharge, or by lowering the probability of a high overtopping discharge by raising its crest height or by constructing a berm. While allowing existing levees to withstand higher overtopping discharges might be a cost-effective strategy to reduce their failure probabilities, a similar failure probability reduction obtained differently (i.e. by not raising the critical discharge but by lowering the probability of an extreme overtopping discharge) would be preferable from the perspective of risk reduction. Given a probability of failure (or: given a probability of an ‘uncontrolled flood’), lower critical discharges are preferable over higher ones.

The above shows how VNK2’s risk analysis methods and techniques can be used to gain

<table>
<thead>
<tr>
<th>Case/strategy</th>
<th>Expected value of economic damage [Million euro/yr]</th>
<th>Expected value of the number of fatalities [yr⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implement delta levee (2040)</td>
<td>0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>Do nothing (2040)</td>
<td>54.4</td>
<td>0.59</td>
</tr>
<tr>
<td>(strategy 1 in section 3.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduce the probability of flooding to 1/1250 per year (2040) (strategy 2 in section 3.2)</td>
<td>8.9</td>
<td>0.11</td>
</tr>
<tr>
<td>Reduce probability of flooding to 1/125,000 per year (2040)</td>
<td>0.0089</td>
<td>0.00011</td>
</tr>
</tbody>
</table>
insight into the effect of design changes to existing levees. Such insights are valuable for (re)formulating design standards and for designing tailor-made solutions.

4 CONCLUSIONS AND DISCUSSION

The VNK2-project is a large-scale quantitative flood risk analysis for all major levee systems in The Netherlands. Amongst other, the project’s results can be used to prioritise interventions, inform political debates about new safety standards, evaluate alternative strategies for reducing risks, assist the development of new statutory safety assessment techniques, and (re)direct research efforts to reduce important sources of uncertainty.

In this paper, three applications were discussed in somewhat greater detail. These concerned the (potential) use of VNK2's methodology and outcomes to (i) set priorities within the new Flood Protection Programme (nHWBP), (ii) inform the policymaking processes that are taking place within the context of the Dutch Delta Programme, and (iii) evaluate the design of super, or delta levees and assess their impact on flood risks.

Apart from providing insight into the risks of flooding in The Netherlands, the VNK2-project has two important by-products. The first is a database with detailed statistical data for over 150 stochastic variables about the Dutch flood defences. This database will provide a valuable basis for future research and development, as well as policy analyses. The second important by-product is the build-up of experience and expertise with a truly risk-informed approach to flood risk management. The project thereby paves the way towards new and more efficient ways to protect The Netherlands against floods.

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