Flood Risk in the Netherlands

The method in brief
FLOOD RISK IN THE NETHERLANDS

VNK2: THE METHOD IN BRIEF

TECHNICAL BACKGROUND
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The Flood Risk in the Netherlands 2 project (in Dutch: Veiligheid Nederland in Kaart 2, or VNK2) is aimed at estimating flood risks for all major levee systems, also called dike rings, by calculating both the probabilities of flooding and the associated consequences. The results from a VNK2 analysis can be used to answer questions such as: Where is the risk of flooding high or low? What are the most vulnerable areas? What failure mechanisms are most likely to play a role in a levee breach? How can we effectively reduce the risk of flooding?

But how are these results computed? We regularly receive questions about how VNK2 determines flood risk, ranging from the very general to the highly specialised. This document explains, in various levels of detail, how flood risk is calculated in the VNK2 project.

This report has been structured in such a way that the broad outline and basic principles of the method are first introduced, followed by gradually more in-depth explanations of the underlying computational techniques. A certain level of background knowledge in risk concepts is therefore required. The bars on the edge of each page indicate the different sections of the report by target audience as follows:

- Administrators and policymakers: no technical knowledge required
- Flood protection experts with no background in quantitative risk analysis
- Flood protection experts with some knowledge of quantitative risk analysis
- Flood protection experts with a thorough understanding of quantitative risk analysis

Unfortunately, it is not possible in a short document such as this to go into all details of the methods and techniques used in the VNK2 project. For more detailed information on the models and techniques, the reader is referred to VNK2’s theoretical guides and scientific papers.

The document ends with a list of recommended reading on each subject. This list is intended for readers who are interested in learning more about particular issues. The VNK2 Project Office is also available to answer any questions readers may have.
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VNK2 IN PRACTICE: A COMMON CHALLENGE

2.1 Organisational structure of the VNK2 project

The VNK2 project is an initiative of the Ministry of Infrastructure and the Environment (I&M), the Association of Regional Water Authorities (UvW) and the Association of Provincial Authorities (IPO). A project office has been set up to oversee implementation of the project. The VNK2 Project Office works with the regional water authorities, also known as water boards, and provincial authorities, with the support of engineering consultancies and research institutes.

The VNK2 Project Office oversees and reviews the work carried out by the engineering consultancies, provides technical support, and disseminates the results of the risk analyses. The water boards make a vital contribution to the project by supplying data, and discussing the plausibility of model input and output. The provincial authorities provide a basis for estimating the consequences of the individual flood scenarios by making their flood propagation models available to the VNK2 project. Many parties are thus involved in a risk analysis of a levee system (Figure 1).

During the process of risk analysis, regular ‘levee system team’ talks are held between the VNK2 Project Office, the engineering consultancies, and the water boards and provincial authorities concerned. This communication is vital for the quality and consistency of the risk analyses.

In practice, it is impossible to know beforehand what circumstances one is likely to encounter during a risk analysis of a levee system. The VNK2 Project Office devotes a great deal of time and energy to sharing knowledge and experience in order to guarantee the consistency and quality of the products. Weekly Technical Meetings are held, where attendees discuss relevant experiences and problems. A Helpdesk manned by specialists answers the more difficult questions. Experts from research institutes can be brought in to answer highly specialised questions.

The risk analyses are reviewed both internally and externally. All analyses are reviews internally by the project managers and their peers. The technical specialists of the VNK2 Project Office also review the completeness and content of all interim products. Checks are also carried out to ensure that all the steps in the process comply with the requirements. Finally, the results of the risk analyses are reviewed by an independent, expert reviewer, and discussed with the Expertise Network for Flood Protection (ENW), which also randomly selects a number of reports for review.
Figure 1. Parties involved in risk analysis of a levee system. The actors shown in blue are part of the VNK2 Project Office.
2.2
The work process
Figure 2 summarises the various activities involved in executing the VNK2 risk analysis process on a levee system. Regular talks are held between the parties concerned throughout the process. The process and quality of the interim products are also tested throughout, so that necessary adjustments can be made in good time. A VNK2 risk analysis takes approximately seven months to complete.
**Screening** (approx. 1.5 months): cataloguing available data, defining focal points with water boards and provincial authorities, dividing dike ring into appropriate sections

**Schematisation** (approx. 2.5 months): calculating failure probability for each dike ring section/hydraulic structure and each failure mechanism (incl. sensitivity analysis). Input and output discussed weekly with water boards.

**Determining scenario probabilities** (approx. 2 weeks)

**Calculating flood risk** (approx. 2 weeks): combining scenario probabilities with consequences of each scenario

**Sensitivity analyses** (approx. 1 month): demonstrating the sensitivity of the outcomes on the basis of the principles and assumptions used. The effect of risk reduction measures can also be identified.

**Reporting** (approx. 1 month)

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**Figure 2.** Summary of activities involved in risk analysis of a levee system.

<table>
<thead>
<tr>
<th>LEVEE SYSTEM TEAM MEETING</th>
<th>Delivery and assessment of screening report</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEVEE SYSTEM TEAM MEETING</td>
<td>Delivery and assessment of databases incl. input and output of failure probability calculations and associated reports</td>
</tr>
<tr>
<td>LEVEE SYSTEM TEAM MEETING</td>
<td>Delivery and assessment of databases incl. input and output of scenario probability calculations and associated reports</td>
</tr>
<tr>
<td>LEVEE SYSTEM TEAM MEETING</td>
<td>Delivery and assessment of databases incl. input and output of risk calculations and associated reports</td>
</tr>
<tr>
<td>LEVEE SYSTEM TEAM MEETING</td>
<td>Delivery and assessment of databases incl. input and output of sensitivity analyses and associated reports</td>
</tr>
<tr>
<td>LEVEE SYSTEM TEAM MEETING</td>
<td>Delivery and assessment of main report; various rounds of comments</td>
</tr>
</tbody>
</table>

Main report, background report, and various databases
3
THE METHOD IN BRIEF

Risk is the combination of probability and consequences. To determine flood risk, it is therefore important to know the likelihood of a flood occurring and the impact it will have. In the VNK2 process, flood risk is computed for each individual levee system, or dike ring (as defined by the Water Act). For this purpose, the failure probabilities of the various elements of the flood defence system (various sections of levee and dune, and hydraulic structures) are determined. The consequences (economic damage and fatalities) of failures of the flood defences are also determined. The failure probability and consequences of a levee breach are not the same at each potential failure location within a levee system. Therefore, flood risk can vary sharply within a levee system.

Uncertainty plays a key role in calculating the failure probability of flood defences. We do not, for example, know what the maximum load will be in a given year. The precise strength properties of a flood defence are also seldom known. It is, however, generally possible to assign probabilities to the possible loads and strengths, on the basis of statistics and expert judgment. The failure probability of a flood defence is the overall probability of all combinations of loads and strengths at which the flood defence will fail. This approach is particularly suitable in situations where the actual values for load and strength properties are uncertain, as this makes it difficult to choose a single set of input values. The probabilistic approach allows us to explicitly address the uncertainties surrounding the actual values for loads and strength properties when considering the level of safety afforded by the flood defences.
CONSEQUENCES OF FLOODING
Determine the consequences (damage and fatalities) that will occur if the flood defences fail.

PROBABILITY OF FLOODING
Determine the probability of failure in each part of the levee system.

RISK CALCULATION
For each part of the levee system, combine the failure probability and the associated consequences if that part of the system fails. Repeating this for all parts of the levee system creates a picture of the overall flood risk in the levee system.
4 INDIVIDUAL ELEMENTS OF THE METHOD

VNK2 considers both the probability and the consequences of flooding. The probability and consequences are then combined to give a flood risk. Sensitivity analyses are carried out to reveal the influence of the principles applied and the effectiveness of safety measures.

Determining the consequences involves the following steps:

Step A1. Defining consequence segments
In reality, a breach can occur anywhere. However, it is not practicable or necessary to identify the consequences of flooding for every possible breach location for a sufficiently accurate risk analysis. A levee system can be divided into segments where the pattern of and damage caused by flooding will be virtually the same, irrespective of the precise location of the breach within that segment. Every levee system is divided into a maximum of 13 segments (to limit the number of flood scenarios), and a breach is modelled for each of these (step A2).

Step A2. Producing flood propagation models
To obtain a picture of the flood pattern, water depths, water velocity and rise rates in the event of a breach, flood propagation models are produced for each consequence segment. VNK2 takes account not only of the impact of the location of the breach on the progress of the flooding (see step A1), but also of the load conditions (water level, duration of high water level) under which the flooding occurs. If a levee fails at a time of high outer water levels, more water will flow into the levee system than if it fails at a time of low water levels. Flood propagation models are therefore run for different water levels: the design water level minus one decimation height (TP-1D), the design water level (TP), TP+1D and TP+2D. The normative level (TP+2/3D) is sometimes also considered along the coast.

Step A3. Defining scenarios
Every flood scenario describes a particular series of events starting with breaches in one or more consequence segments. Only if the outer water level falls sharply after a breach so that no further breaches are to be expected in other segments, will the number of scenarios be equal to the number of segments.

Step A4. Selecting consequence estimates for each scenario
Flood propagation models for each consequence segment are used to compute the flood characteristics (size of area affected, water depth, velocity and rise rate) required to estimate consequences for the different flood scenarios. After selection of the flood propagation models, economic damage and number of fatalities are calculated using a consequence model called HIS-SSM.
CONSEQUENCE ANALYSIS

STEP A1
Divide the levee system (cf. Water Act) into segments in which the consequences are (virtually) the same, irrespective of the location of the breach.

STEP A2
Calculate the flood pattern, water depth, velocity and rise rate in the event of a breach on the basis of flood propagation models.

STEP A3
Define scenarios: a scenario consists of a unique combination of failing and non-failing consequence segments. The set of scenarios encompasses all possible sequences of events in a flood.

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>CONSEQUENCE SECTION 1</th>
<th>CONSEQUENCE SECTION 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>fails</td>
<td>does not fail</td>
</tr>
<tr>
<td>2</td>
<td>does not fail</td>
<td>fails</td>
</tr>
<tr>
<td>3</td>
<td>fails</td>
<td>fails</td>
</tr>
</tbody>
</table>

STEP A4
Calculate the economic damage and the number of fatalities for each scenario, using the flood propagation models for each segment (see step A2). The consequences will be different for each scenario.

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>DAMAGE</th>
<th>FATALITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$E_1$</td>
<td>$N_1$</td>
</tr>
<tr>
<td>2</td>
<td>$E_2$</td>
<td>$N_2$</td>
</tr>
<tr>
<td>3</td>
<td>$E_3$</td>
<td>$N_3$</td>
</tr>
</tbody>
</table>
Determining probability involves the following steps:

**Step B1. Decomposing the levee system into elements, or sections**
A levee system can consist of various types of flood defences, including levees, hydraulic structures and dunes. The strength properties of flood defences can differ significantly from one type to another due to e.g. varying geometry and subsurface properties. The levee system is therefore divided into different elements (levee sections, dune sections and hydraulic structures) that can be assumed to have homogeneous strength properties and loads. Failure probabilities can then be calculated for each element. Levee sections are generally around 750 metres long, though they can range from 150 metres to over two kilometres depending on circumstances.

**Step B2. Schematisation of sections and failure probability calculation**
A failure probability is calculated for each element (levee section, dune section or hydraulic structure). In VNK2, failure is defined as the occurrence of a breach. For this purpose, each element and failure mechanism is schematised. Each schematisation describes the properties relevant to the failure probability of that particular element. For example, the geometry of the levee, the quality of the grass cover on the inner slope and the effective fetch for each wind direction are relevant to probability of levee failure due to overtopping.

The failure probabilities calculated for each section and failure mechanism can be combined to give a failure probability for all sections and failure mechanisms in the levee system. This reflects the likelihood that some section of the levee system will fail, which is also the probability that inundation will occur in the area protected by the levee system. As a result of dependencies (due to spatial correlations), the flooding probability (combined failure probability at levee system level) is smaller than the sum of the failure probabilities per section. It is at least as great as the greatest failure probability of the different sections.

For some failure mechanisms, such as overtopping, the spatial correlations are generally strong so that the failure probability at levee system level is virtually the same as the greatest failure probability at section level. On the other hand, for failure mechanisms where uncertain and spatially fluctuating properties of the subsurface play a major role, the correlations between (and within) the sections are often weak. In those cases, the failure probability will be larger for longer stretches of levee (all other things being equal); this is also referred to as the length effect.

The schematisations and failure probabilities for each section and failure mechanism are checked against historical events (such as the formation of sand boils) and the local knowledge and experience of the water board. Schematisation teams also consider the findings of statutory assessments. The statutory assessments and the VNK2 analyses are based on different approaches. Therefore, their results cannot simply be compared. Yet they do both concern the same flood defences. Comparing the schematisations produced during the statutory assessment and the VNK2-risk analysis provides useful insights.
**CONSEQUENCES**

**STEP B1**
Divide the levee system (cf. Water Act) into sections in which strength properties and loads are homogeneous. The boundary of a consequence segment will be the same as the boundary of a section.

**STEP B2**
For each section: calculate failure probabilities for the various failure mechanisms. Combining the failure probabilities per failure mechanism and section yields the probability that inundation will occur somewhere in the levee system. Dependencies are taken into account when combining the failure probabilities per section and/or failure mechanism.

<table>
<thead>
<tr>
<th>SECTION</th>
<th>FAILURE PROBABILITY PER FAILURE MECHANISM</th>
<th>FAILURE PROBABILITY PER SECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overflow</td>
<td>Piping</td>
</tr>
<tr>
<td>1</td>
<td>Probability(_{\text{over,1}})</td>
<td>Probability(_{\text{pip,1}})</td>
</tr>
<tr>
<td>2</td>
<td>Probability(_{\text{over,2}})</td>
<td>Probability(_{\text{pip,2}})</td>
</tr>
<tr>
<td>3</td>
<td>Probability(_{\text{over,3}})</td>
<td>Probability(_{\text{pip,3}})</td>
</tr>
<tr>
<td>4</td>
<td>Probability(_{\text{over,4}})</td>
<td>Probability(_{\text{pip,4}})</td>
</tr>
<tr>
<td>5</td>
<td>Probability(_{\text{over,5}})</td>
<td>Probability(_{\text{pip,5}})</td>
</tr>
<tr>
<td>Combined</td>
<td>Probability(_{\text{over}})</td>
<td>Probability(_{\text{pip}})</td>
</tr>
</tbody>
</table>

**STEP B3**
Determine the probabilities that the scenarios will occur (see step A3) using the probabilities for each section to calculate the probability that, for example, consequence segments 1 and 2 will experience simultaneous breaches. The scenario probabilities are needed to link probabilities and consequences.

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>SCENARIO PROBABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Scenario probability(_{1})</td>
</tr>
<tr>
<td>2</td>
<td>Scenario probability(_{2})</td>
</tr>
<tr>
<td>3</td>
<td>Scenario probability(_{3})</td>
</tr>
<tr>
<td>4</td>
<td>Flooding probability</td>
</tr>
</tbody>
</table>

Since the set of scenarios encompasses all possible flood sequences, the sum of the scenario probabilities equals the probability that a flood will occur somewhere in the levee system.
**Step B3. Calculate scenario probabilities**

A levee system can flood in many different ways, and the consequences of each potential flood scenario can be significantly different. To calculate risk, the probability of each flood scenario must be computed. These probabilities are referred to as scenario probabilities.

Each scenario probability is calculated on the basis of the failure probabilities calculated for the levee system’s sections. The consequence segments (which consist of one or more sections) play an important role in this calculation. If, for example, a certain scenario occurs as a result of a breach in consequence segment 1, the probability of this scenario is equal to the probability that consequence segment 1 will fail somewhere (in one of its sections), while all other consequence segments do not. In other words: this scenario probability is equal to the probability that at least one of the sections in consequence segment 1 fails, while all other sections do not.

Though VNK2 does take multiple breaches into consideration (breaches may occur in several consequence segments during a single high water event), for practical reasons only one breach is modelled for each consequence segment. The number of combinations of breach locations rises sharply with every extra potential breach location (see also section 5.3) which radically increases computing time. But while additional breaches within the same consequence segment could significantly increase the rate-of-rise of flood water in the levee system, the overall impact on the total risk is typically minimal. In practical terms, the modelling of two potential breach locations in a consequence segment would mean splitting that segment into two new ones (with one breach location in each). In VNK2, a levee system is normally divided into a maximum of 13 consequence segments (13 possible breach locations). This is because the computation of scenario probabilities could otherwise become prohibitively time consuming (the maximum number of scenario’s equals $2^n-1$, where $n$ is the number of consequence segments). Thirteen consequence segments is typically sufficient for an accurate risk analysis for a Dutch levee system. If not, a tailor-made solution is sought.

Since all the scenarios in combination characterise all possible floods, the sum of all the scenario probabilities equals the probability that a flood will occur somewhere in the levee system (see also step B2).

**Calculate flood risk**

The flood risk is calculated on the basis of the probabilities and consequences of each scenario. Every scenario contributes to the flood risk. The sum of these contributions gives the total flood risk, given the fact that all the scenarios together represent all possible floods in the levee system.
### RISK CALCULATION

Calculate the expected value of economic damage and the expected value of the number of fatalities on the basis of the product of the probability and consequences per scenario. The expected value is the probability-weighted sum of all possible outcomes. The scenario probabilities and consequences of each scenario can be used to describe the societal risk (FN curve), the economic damage curve (FS curve), the local individual risk (LIR) and the local individual risk without evacuation.

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>SCENARIO PROBABILITY X DAMAGE</th>
<th>SCENARIO PROBABILITY X FATALITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Scenario probability₁ × E₁</td>
<td>Scenario probability₁ × N₁</td>
</tr>
<tr>
<td>2</td>
<td>Scenario probability₂ × E₂</td>
<td>Scenario probability₂ × N₂</td>
</tr>
<tr>
<td>3</td>
<td>Scenario probability₃ × E₃</td>
<td>Scenario probability₃ × N₃</td>
</tr>
<tr>
<td>Sum total</td>
<td>Expected value for damage</td>
<td>Expected value for fatalities</td>
</tr>
</tbody>
</table>
5
INDIVIDUAL ELEMENTS
OF THE METHOD IN DETAIL

5.1 Step A1. Defining consequence segments
VNK2 takes account of the impact of the location(s) of breaches on the sequence of events during a flood. For this purpose, the levee system is divided into consequence segments: areas in which the pattern of flooding and economic damage will be virtually the same, no matter where the breach is located within that segment. Consequence segments are at any rate defined in the case of: contiguous high-lying linear features such as elevated roads or (regional or secondary) levees and embankments; a shift in the load threat (e.g. from a river to the sea) branching or convergence of rivers.

In practice, the definition of consequence segments on the basis of the above principles yields approx. 5-13 sections per levee system. An example of a levee system divided into consequence segments is shown in Figure 3.

5.2 Step A2. Producing flood propagation models
The consequences of a flood are determined by the flood’s characteristics (water depth, velocity and rise rate) and the vulnerability of the people or objects affected. In VNK2, the characteristics of floods are estimated by means of flood propagation models produced by the provincial authorities and made available to the VNK2 Project Office.

Figure 3. Example of a levee system divided into consequence segments: division of levee system 36, Land van Heusden/De Maaskant, into 12 sections.
Besides the impact of breach locations on floods (see step A1), VNK2 also takes account of the loading conditions that cause them. If a levee fails at a time of high outer water levels, more water will flow into the levee system than if it fails when water levels are low. To generate the necessary flood characteristics for each scenario, flood propagation models are run for each consequence segment using different loads: the design water level minus one decimation height (TP-1D), the design water level (TP), TP+1D and TP+2D. A simulation for the normative level (TP+2/3D) is also available for the coastal area. Sensitivity analyses are performed by varying certain assumptions in the flood propagation models, such as the width of the breach, the stability of secondary flood defences and the duration of the high water level.

Flood propagation models are typically developed using the following assumptions:
- Regional flood defences are assumed to be stable, unless the provincial authority is of the opinion that this would give a distorted picture. High-lying linear features like roads and railway lines are regarded as stable in so far as they are able to withstand flood water. Openings such as tunnels are included in the flood propagation models. The effect of the assumed stability on the estimates of the economic damage and the number of fatalities depends on its effect on the size of the area affected as well as water depths, flow velocities and rise rates. Stable regional flood defences can lead to higher rise rates and greater water depths in the compartment affected, which can greatly increase the economic damage and number of fatalities there. Outside the affected area, however, there will be no fatalities or damage.
- VNK2 assumes that breaches occur during the top of high water waves. The width of the breach is determined for most levee systems on the basis of a breach growth formula included in the flood propagation model. In determining the width of the breach, the erosion resistance of the levee is taken into account. This depends strongly on the material of which it is built (sand or clay). Breaches are typically wider in the upstream riverine areas and smaller along the coast. - The maximum depth of a breach is assumed to be equal to the height of the foreland if the width of the foreland/foreshore measured perpendicular to the flood defences is greater than 50 metres. In other cases, the assumed breach depth is no lower than the ground level behind the defences.

5.3 Step A3. Defining scenarios
Consequence segments can fail simultaneously during the same high water event, leading to a multiple breach scenario. For a riverine event, the failure of one consequence segment could lead to a reduction in the hydraulic loads on other consequence segments. This is referred to as ‘relief’. Such relationships between the failure behaviour of different consequence segments have a major bearing on flood risk, because multiple breaches can lead to different flood patterns and different consequences than single breaches. VNK2 distinguishes three basic possibilities:
1. No relief in the event of a breach.
2. Relief in the event of a breach, with the weakest segment failing first.
3. Relief in the event of a breach, with the segment first subjected to the load failing first.

In reality, for a riverine scenario especially, a breach in one segment will lower the load in others. So, the ‘no relief’ scenario overestimates actual risk and the 2 relief scenarios underestimate the actual risk.
Figure 4. Relationship between number of consequence segments and number of scenarios in the event of relief, and of no relief.
If there is no relief (multiple breaches possible) the number of scenarios for n consequence segments equals 2^n-1. The number of scenarios therefore rises sharply with the number of consequence segments (Figure 4). For instance, the maximum number of scenarios in case of 13 consequence segments is 8,191. If there are 25 consequence segments (in other words, 25 potential breach locations), the number of scenarios is 33,554,431. If relief does occur (only single breaches), the number of scenarios equals the number of consequence segments.

To limit computation time, VNK2 normally assumes a maximum of 13 consequence segments. The maximum number of scenarios is therefore 8,191. In order not to exceed this maximum, several consequence segments sometimes have to be combined. This essentially means sacrificing some of the detail in the definition of consequence segments. It should be noted that a set comprising several hundred to several thousand scenarios is already vastly more detailed than a single (worst case) scenario.

5.4 Step A4. Identifying consequences in each scenario

Calculating damage and casualty numbers

The economic damage resulting from a flood depends on the water depth, the total area inundated, and the use of land or the infrastructure present. The number of fatalities depends on the rise rate and flow velocity of the flood water, as well as the potential for evacuation. The damage and casualty numbers are calculated for each scenario with the aid of the HIS Damage and Fatalities Module (HIS-SSM) version 2.5. The key statistics for value at risk and the number of inhabitants in the levee system are based on 2001 figures (due to the availability of data), indexed to 2006 (the year VNK2 started). A schematic representation of the operation of HIS-SSM is shown in Figure 5.
The method in brief

Figure 5. Schematic representation of damage and fatalities module.

SCHEMATIC REPRESENTATION OF OPERATION OF SSM
The economic damage caused by flooding consists of damage to capital goods such as homes and infrastructure, and damage due to disruption of commercial operations. The economic damage calculated in VNK2 concerns the net damage to the Netherlands as a whole. The calculation of economic damage includes the effect of substitution within the country: disruption of commercial operations in the area hit by flooding will lead to increased activity outside the area. As such, the total economic damage to the country is smaller than the economic damage in the area that is directly affected. The scale of the difference between the economic damage in the affected area and the economic damage to the entire country is uncertain, and depends on the factors of production that have been hit. No monetary value is assigned to fatalities in calculating the economic damage (this can however be done quite simply by hand, by multiplying the number of fatalities by a nominal sum per casualty).

**Preventive evacuation**

Unlike economic damage, the number of fatalities can be strongly influenced by preventive evacuation (prior to the levee breach). VNK2 therefore considers the effect of preventive evacuation. The effect of evacuation during a flood (fleeing) is not modelled separately, since it is already implicitly included in the casualty functions. The casualty functions relate flood characteristics to the probability of dying. Preventive evacuation is included in the risk analyses by dividing each flood scenario into four partial scenarios. The following two factors play a key role in defining these partial scenarios:

1. The time remaining between the moment a flood is predicted and the actual occurrence of the flood.
2. The degree to which the evacuation proceeds in an organised manner.

Each of the four combinations of these factors has its own conditional probability\(^1\) and outcome (see also Figure 6). As part of the WV21 project (flood protection for the 21st century), a study was conducted to determine conditional probabilities and evacuation fractions.\(^2\) An evacuation fraction is the percentage of the population expected to have left the levee system by the time the flood occurs. The approach and numerical values (conditional probabilities and percentage of evacuees) used in the VNK2 project are based on the results of this study. The expected values for the evacuation fractions in each levee system are the same in WV21 and VNK2.

\(^1\) The probabilities are conditional, i.e. they are conditional on the occurrence of a flood.
A failed preventive evacuation can increase the number of fatalities. For example, a preventive evacuation may cause more fatalities as a result of traffic congestion in low-lying areas. In VNK2, it is assumed that evacuation can lead only to a reduction in the number of fatalities. This means that the most adverse scenario occurs when no evacuation takes place.
Combining flood propagation models in the event of multiple breaches

Ideally, a separate flood propagation model would be produced for every flood scenario, including those scenarios associated with simultaneous breaches in two or more consequence segments. In practice, however, most computational results refer to single breaches. To estimate the consequences of multiples breaches, VNK2 combines the outcomes of flood propagation models for single breaches, applying the following principles:

- Water depths are added together, which gives a conservative estimate of the economic damage and casualty numbers. The sum of water depths may nowhere exceed the worst case scenario.
- The local for flow velocity and rise rate maxima in the event of single breaches are used. They are not added together because this could easily yield unrealistic values.

The VNK2 procedure gives accurate results if the inundation patterns of different breach locations do not overlap. However, if there is overlap, the VNK2 procedure could potentially underestimate or overestimate consequences, and therefore risk, depending on the characteristics of the scenario.

Incorporating load conditions in the event of failure

Higher water levels at the time of levee failure will typically lead to higher rise rates, flow velocities and rise rates, and, therefore, to higher consequences (see also section 5.2). The most likely loading conditions to trigger a scenario are observed when calculating the consequences of that scenario.

5.5 Step B1. Defining sections

Section boundaries are assumed under the following circumstances:

- A change in load and/or strength characteristics such that they can no longer be regarded as statistically homogeneous.
- A change in the category the flood defence belongs to.
- A change in the type of flood defence.
- The boundary of the water board district.
- The boundary of a consequence segment.
- The presence of structural elements.

The section boundaries defined in the statutory safety assessment are sometimes adopted. This makes it easier to interpret the results of the statutory assessment in relation to the results of VNK2 (and vice versa). An example of section definitions is shown in Figure 7.
Hydraulic structures are treated as sections. Just like a levee or dune section, a hydraulic structure can be regarded as a separate element. For the purposes of risk calculation, there is, in principle, no difference between hydraulic structures and levee or dune sections.

5.6 Step B2. Schematisation of sections and failure probability calculation

The failure mechanisms considered
The failure mechanisms considered in VNK2 are shown in Table 1. The table briefly describes how the failure mechanisms are modelled, and roughly indicates how this differs from the modelling applied in the statutory assessment. It should be noted that the statutory assessment framework is semi-probabilistic, while VNK2 employs fully probabilistic techniques.
Table 1. Failure mechanisms considered and description of model.

<table>
<thead>
<tr>
<th>TYPE OF FLOOD DEFENCE</th>
<th>FAILURE MECHANISM</th>
<th>BRIEF DESCRIPTION OF MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levee</td>
<td>Overflow/wave overtopping</td>
<td>The CIRIA model is used to determine an overtopping discharge at which the grass cover will fail. The discharge can be as high as 25 l/s/m, depending on the quality of the grass cover and the angle of the inner slope. The calculation does not therefore use a fixed critical overtopping discharge, such as that used in the assessment (0.1 l/s/m, 1 l/s/m or 10 l/s/m). Nor is any account taken of residual strength (the time needed for the erosion of the covering clay layer), in order to prevent excessive optimism. Some caution is required because liquefaction of the inner slope (and thus its contribution to failure probability) is not included in VNK2, due to the limited reliability of the available models for this failure mechanism.</td>
</tr>
<tr>
<td></td>
<td>Inward macro instability</td>
<td>In case of inward macro instability, the inner slope of the levee slides. The failure probability is calculated using MProSTab. The safety factors used in the detailed statutory safety assessment are based on calculations with this probabilistic model. In VNK2 a rough residual strength calculation is carried out, to establish the probability of failure after a slide. This is not included in the statutory assessment. Another important difference between VNK2 and the statutory safety assessment is that VNK2 considers only slides that affect the flood defence capacity, not, for example slides at the toe of the levee that might make it less accessible, which is considered in the statutory assessment.</td>
</tr>
</tbody>
</table>
### The method in brief

The failure probability is calculated according to Sellmeijer’s formula. The seepage length must be greater than the required seepage length, otherwise an incipient erosion process will start. The Sellmeijer formula is also used in the regulatory safety assessment, albeit in a semi-probabilistic framework, i.e. it is fed with design values rather than probability density functions. The regulatory assessment also allows the use of the Bligh rule, which sometimes allows shorter seepage lengths than Sellmeijer’s formula. VNK2 does not use the Bligh rule. ENW has in fact recommended that the Bligh rule no longer should be used in statutory assessments.

VNK2 uses various models for grass, stone and asphalt covers (with/without filter layers etc.). Unlike in the statutory assessment, the probability of a breach after initial damage is considered (using a rather simple model). The probabilistic models for damage to cover layers differ to some extent from the models used in the statutory safety assessment.

The load model implemented in PC-Ring is based on the probabilistic models used in the statutory safety assessment. The strength model (DUROS-PLUS) also ties in with the model used in the statutory assessment. A dune fails (according to the definition in the statutory assessment and VNK2) when the calculated position of the erosion point is further inland than the critical erosion point. The critical erosion point is determined on the basis of the limit volume of sand that would still be needed to prevent a breach. As described in the Dune Erosion

<table>
<thead>
<tr>
<th>Levee</th>
<th>Piping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage to cover and erosion of levee core</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dune</th>
<th>Dune erosion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Technical Guideline, it is assumed that a dune will breach if the erosion point lies further inland than the critical erosion point; the limit profile describes a limit condition, and does not include a safe margin.

Both the statutory assessment and VNK2 use the overtopping and overflow formulae from the Hydraulic Structures Guideline. The statutory assessment looks first at the overtopping discharge and the crest freeboard relative to the design water level. If they do not meet certain requirements, the stability of the object in the event of overflow/overtopping has to be considered. In VNK2, the critical overflow/overtopping discharge is based on the levee system’s storage capacity and strength (stability) of the structure’s bed protection.

The failure probability is based on the probability that a flood gate fails to close during a high water, and the conditional probability that the structure loses its stability when this happens.

Both the statutory assessment and VNK2 project use Bligh and Lane’s rules for hydraulic structures. While the statutory assessment allows the use of specific groundwater flow models as a basis for an advanced assessment, such models are not available in VNK2.
### Hydraulic structure

### Structural failure

This failure mechanism concerns the loss of a structure’s flood defence function due to extreme loading conditions. In some cases (failure of gates and collisions) residual strength is taken into account, in the sense that the failure probability of bed protection is considered. Analysts first looks at the design principles followed and the extent to which the load and safety factors used in the design correspond to the current situation. Residual strength is not considered.
Potential failure mechanisms including liquefaction, foreland failure, failure of the outer slope, micro instability, liquefaction and heave are included in the statutory assessment, but not in VNK2. Nor does VNK2 consider damage to cover layers caused by currents. This is because, with the exception of micro instability (see notes on overflow/wave overtopping in Table 1), these failure mechanisms do not lead directly to the formation of a breach and/or are not driven by high water levels (so the probability that these failure mechanisms will occur during high water is very small). It is assumed that excluding these failure mechanisms will have no relevant bearing on the picture of flood risk that emerges. The VNK2 reports do however include a qualitative discussion of the failure mechanisms for which no failure probability could be determined.

Component transitions cannot be analysed with the instruments used in VNK2. Experiences in other countries have shown that transitions between soft and hard structures are often weak points. It is not clear to what extent the Dutch guidelines for the design of component transitions are sufficiently safe. Given the lack of suitable models, VNK2 does not consider the failure of component transitions. To what extent this leads to flood risks being underestimated is unknown. These structures also represent a blind spot in the statutory safety assessment.

It must be emphasised that the objective of VNK2 (to quantify flood risks) should not be confused with that of the statutory assessment (evaluate whether flood defences comply with safety standards). The level of detail in the analyses carried out under VNK2, and therefore also the selection of failure mechanisms, reflects the primary objective of the project: to produce a picture of flood risk. The VNK2 approach relies primarily on the current models available to support estimation of failure probabilities and resulting consequences. Where there are knowledge gaps, assumptions are made on the basis of engineering judgment. Analysing the impact of these assumptions provides insight into the importance of these issues.
The hydraulic loading conditions
The hydraulic load on a flood defence generally consists of two components: the water level and the wave action. VNK2 uses the so-called TMR2006, the outcomes of a load model, that is based on our latest understanding. The TMR2006 deviate in some respects from the HR2006 which were used in the most recent statutory safety assessment. The parameters for Lake IJssel and the levees and dunes along the coast are virtually the same, but there are some differences in the area around the major rivers. Generally speaking, however, the differences are small, at no greater than 0.20 m, with the exception of the Vecht delta, where the differences are an average of 0.30-0.50 m. Unlike the statutory safety assessment, VNK2 works with water level distributions, not only design water levels (a water level with an exceedance probability of e.g. 1/1250 a year). A flood defence can also fail at water levels higher or lower than the design level, which has to be taken into consideration in failure probability calculations. This concept is illustrated in Figure 8, which shows an increase in the conditional probability of failure with an increase in water level. There is no single water level at which the probability suddenly jumps from zero to one. By combining the conditional failure probability at each water level with the probability that that particular water level will occur, it is possible to determine the (unconditional) failure probability of the flood defence.

Figure 8. Schematic representation of a failure probability calculation based on a water level distribution and a ‘fragility curve’.

NB
The failure probability is the product of multiplying the probabilities of certain water levels by the conditional failure probabilities at those water levels. The probability of a certain water level is smaller than the probability that that water level will be exceeded.
Every river discharge has its own exceedance probability. The relationship between the discharge (or, alternatively, the water level) and the exceedance probability is represented by an average exceedance frequency curve. The uncertainties associated with this curve are not taken into account either in VNK2 or in the statutory safety assessment.

Water level data for various locations in the river centerline can be obtained from load models. These are translated to water level data for riverbank locations perpendicular to the river center line. VNK2 uses the water levels at the riverbank locations to calculate failure probabilities. These locations are no more than 100 m apart. Wave loads are always determined separately, taking into account effective fetch and water depths.

Emergency measures not considered

VNK2 does not take account of emergency measures (flood fighting) when calculating failure probabilities. For example, the effectiveness of using sandbags is not considered in the calculation of a failure probability for overtopping, and the positioning of sandbags around sand boils is not considered in the failure probability calculation for piping. Emergency measures are not taken into account for the following reasons:

1. Practical considerations: It is highly uncertain whether emergency measures will actually be successful in the very rare and extreme conditions that the flood defences should be able to withstand. Sandbags are regularly placed around boils in some piping-prone areas, but this is done under relatively calm conditions, in which boils are easy to spot (not too numerous), the site is still accessible and there is still enough time to intervene. It is, however, not certain that this will be the case at much higher water levels that are a factor 10-100 less probable. Including the effectiveness of emergency measures in failure probability calculations is unlikely to have significant effect when a breach is likely to occur in circumstances that occur less than once per century.

2. Matter of principle: If emergency measures are not regarded as an integral part of the flood defence system, they may not be taken into account when assessing flood defences. This is also the philosophy underlying the statutory assessment rules and design guidelines, which also ignore flood fighting measures.

The basis of the failure probability calculation

The failure probability for each failure mechanism is calculated on the basis of ultimate limit state functions, or Z-functions. An ultimate limit state function describes the difference between load and strength:

\[ Z = R - S \]

where \( R \) = strength (Resistance) and \( S \) = load (Solicitation).

As long as an ultimate limit state function is greater than zero (\( Z > 0 \)), the strength will be greater than the load and the element will not be in a state of failure. If \( Z \leq 0 \), the load is at least as great as the strength and the element will fail.

If the strength properties and loads are uncertain, all values of the strength variables and the loading conditions have some probability of occurrence. Some combinations will cause failure, others will not. The failure probability of an element equals the sum of the probabilities associated with all combinations where \( Z \leq 0 \). Every failure mechanism has a different ultimate limit state function.
Various techniques can be used to calculate failure probabilities. They include FORM (First Order Reliability Method), SORM (Second Order Reliability Method), Directional Sampling and Monte Carlo. VNK2 uses FORM, in view of the calculation time required. In FORM, all probability distributions are transformed into a standard normal distribution and the Z-function is linearized at the point where Z=0 is most likely (known as the design point, see also chapter 7). In practice, FORM yields accurate results for a large number of cases. In case of inaccuracies, VNK2 switches to more time-consuming techniques such as Directional Sampling, whereby a large number of draws are made from the probability density functions of the various stochastic variables (uncertain quantities).

Each failure probability is determined first per cross-section for a short time period. The failure probability is then scaled up to a failure probability for the entire section and an entire year (see also chapter 6 for discussion of the length effect). Correlations in the time and space domains are taken into account in this scaling up process. Strength properties generally change little from year to year. It would therefore be incorrect to assume several independent realisations of these properties per year when computing an annual failure probability. However, there can be several high water events during a year.

**Combining the failure probabilities per failure mechanism and section**

Correlations in the space domain are taken into account when combining the failure probabilities per failure mechanism for each section to an overall failure probability for the entire system. The failure probabilities per failure mechanism and section are not simply added together in VNK2.

A levee system can be regarded as a serial system. A serial system fails if one of its elements fails (as with simple Christmas tree lighting). The lower limit of the failure probability (lowest possible failure probability) in a serial system equals the maximum failure probability of the elements (each with failure probability \(P_i\)). The upper limit of the failure probability (highest possible failure probability) in a serial system equals the sum of the failure probabilities of the elements:

\[
\text{Lower limit: } P_{\text{combi}} = \text{Max}(P_i) \\
\text{Upper limit: } P_{\text{combi}} = \text{Sum}(P_i)
\]

In practice, the failure probability of a serial system will fall somewhere between these two extremes, depending on the overlap between the combinations of strength properties and loads at which the various elements fail.

A flood probability is equal to the probability that one or more elements (levee section, dune section, hydraulic structure) fails. This probability can be computed by combining the failure probabilities of all the elements. In VNK2, this is a step-by-step process. Two combined elements constitute a new (larger) element, which can then be combined with another original element, and so on. This ‘combinatory process’, as it is known, is represented schematically in Figure 9.
5.7 Step B3. Calculate scenario probabilities

Every flood scenario has its own probability of occurrence. Each scenario is a unique sequence of events (the flood sequence) that is triggered by a breach in one or more consequence segments. The consequence segments therefore play a key role in the calculation of scenario probabilities. The sections in each segment are first combined, as shown in Figure 9. Then the probability that one segment will fail while all others remain intact etc. is calculated, taking account of system effects within the levee system: relief, relief with sequence effect, or no relief (see section 5.3 for more information on the relief concept). Together, the scenarios characterise all possible flood events. The sum of the scenario probabilities is therefore equal to the flood probability. The sum of the scenario probabilities and the system’s failure probability calculated in step B2 (the probability that at least one of the sections will fail in a given year) are not exactly the same due to approximation errors in the computational routines.

The reason for the small discrepancies between the system’s failure probability and the sum of the scenario probabilities lies in the fact that they are calculated differently. In calculating the system probability, sections that are most strongly correlated are combined first (experience has shown this to be the most accurate approach). In calculating the scenario probabilities, the sections belonging to the same segment are combined first. These need not be the sections that are most strongly correlated. The number of times that the combinatory process is applied in the calculation of all scenario probabilities is often considerably higher than in the calculation of the system probability. As a result, the system probability is not usually equal to the sum of the scenario probabilities. In practice, however, the difference is very small (only a few percentage points).
The data used to calculate scenario probabilities are the reliability indices and influence coefficients of the different sections, the correlations between the sections and the stated relationships between the failure behaviour of the segments (relief, relief incl. sequence effect, no relief). A combinatory routine based on the Hohenbichler-Rackwitz method, the first-order concept mentioned in section 5.6, is used in calculating the scenario probabilities. A design point is determined for each scenario, describing the most likely conditions in the event of failure (Z=0). The design point values of the stochastic load variables are used in the selection of flood simulations (section 5.4).

5.8 Calculating flood risk
Every scenario has a probability of occurrence and certain consequences (damage and fatalities). Each scenario thus contributes to the overall level of flood risk. Since the scenarios together represent all possible flood sequences, the sum of all scenarios’ contribution to the risk is equal to the total flood risk. Flood risk is expressed and represented in various ways in VNK2 (Table 2). No assessment criteria are associated with the outcomes of VNK2. All measures of risk are calculated for the entire levee system, though this is not a necessity (for example, the expected value of economic damage can also be calculated for each segment or scenario.)
Table 2. The measures of risk used in VNK2, and their meaning.

<table>
<thead>
<tr>
<th>TYPE OF RISK</th>
<th>MEASURE OF RISK</th>
<th>DESCRIPTION</th>
<th>POSSIBLE APPLICATION (INDICATION)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic risk</td>
<td>Annual expected value of economic damage</td>
<td>Weighted average of all possible damages, using the probabilities of these damages as weighting factors.</td>
<td>The value of economic risk in cost-benefit studies (actuarially fair insurance premium).</td>
</tr>
<tr>
<td></td>
<td>Annual expected value of economic damage per hectare.</td>
<td>Annual expected value of economic damage calculated by hectare and represented on a map of the levee system.</td>
<td>In cost-benefit studies for certain parts of the levee system.</td>
</tr>
<tr>
<td></td>
<td>Damage curve (‘FS-curve’).</td>
<td>Describes the probabilities of floods with S or more damage. The FS-curve in fact represents the cumulative probability distribution of economic damage.</td>
<td>This measure of risk provides insight into the probabilities of extreme damages; relevant for planning the response to major flood disasters/compensation for victims (e.g. government loans or insurance).</td>
</tr>
<tr>
<td></td>
<td>Annual expected value of number of fatalities.</td>
<td>Weighted average of all possible numbers of fatalities, using the probabilities of those numbers of fatalities as weighting factors.</td>
<td>In cost-benefit studies, whereby a monetary value is assigned to each fatality.</td>
</tr>
</tbody>
</table>
### The method in brief

<table>
<thead>
<tr>
<th>TYPE OF RISK</th>
<th>MEASURE OF RISK</th>
<th>DESCRIPTION</th>
<th>POSSIBLE APPLICATION (INDICATION)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Societal risk (‘FN-curve’)</td>
<td>Describes the probabilities of flooding with N or more fatalities. The FN-curve in fact represents the cumulative probability distribution of the number of fatalities.</td>
<td>This measure of risk provides insight into the probabilities of large numbers of fatalities occurring; it is therefore a measure for the risk of social disruption.</td>
<td></td>
</tr>
<tr>
<td>Local individual risk without evacuation (PR)</td>
<td>Annual probability that a permanently present individual will die in a particular location, excluding the effect of preventive evacuation.</td>
<td>This measure of risk gives an insight into the basic level of safety provided and can be used in decisions on preventive measures and spatial planning.</td>
<td></td>
</tr>
<tr>
<td>Local individual risk (LIR)</td>
<td>Annual probability that an individual will die in a particular location, including the effect of preventive evacuation.</td>
<td>This measure of risk gives an insight into the basic level of safety provided, taking account of the potential for evacuation, and can be used in decisions on preventive measures, spatial planning and disaster response.</td>
<td></td>
</tr>
</tbody>
</table>

All measures of risk can be calculated on the basis of the scenario probabilities and their consequences. This is illustrated below in the calculation of the expected value for the number of fatalities and of societal risk, for a levee system in which all possible floods can be characterised in three flood scenarios with probabilities of 1/100, 1/500 and 1/1,000 per year, leading to 10, 20 and 100 fatalities respectively.
The method in brief

**EXPECTED VALUE**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability x fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01 x 10 = 0.1</td>
</tr>
<tr>
<td>2</td>
<td>0.002 x 20 = 0.04</td>
</tr>
<tr>
<td>3</td>
<td>0.001 x 100 = 0.1</td>
</tr>
</tbody>
</table>

Annual expected value of the number of fatalities = 0.1 + 0.04 + 0.1 = 0.24/year

---

When there are thousands of scenarios, it is highly laborious to compile flood propagation models, calculate the consequences (damage and fatalities) and link them with scenario probabilities for every scenario. To simplify the calculations, we could assume that the maximum consequences will materialize for all scenarios, but that would often introduce a significant overestimation error. By assuming consequences that actually occur rather than the maximum consequences for more and more scenarios, it is possible to gradually refine the risk estimate. Further refinement will have less and less impact on the overall picture of flood risk. This is because, firstly, many scenarios have a very low probability of actually occurring (like a tenfold breach whereby breaches occur in 10 consequence segments during a single high water event). Secondly, scenarios with a very low probability generally occur only under very extreme circumstances. This means that the consequences of those scenarios often differ little from the maximum consequences.

**VNK2** takes the following practical approach to reduce the computational load while avoiding unacceptable errors:

1. All scenario probabilities are calculated and sorted by size.
2. The 50 scenarios with the highest probability are selected.

---

**SOCIETAL RISK**

Exceedance probability

- 0.01 + 0.002 + 0.001 = 0.013
- 0.002 + 0.001 = 0.003
- 0.001

Exceedance probability

- 0.01 + 0.002 + 0.001 = 0.013

1 10 20 100

No. of fatalities

NB The FN-curve is on a double logarithmic scale

---

Figure 10. Calculation of the expected value for the number of fatalities and the FN-curve.
The sum of the probabilities of the selected scenarios is calculated and compared with the sum of all scenario probabilities. This result is reported.

3. The selected scenarios are linked to their consequence estimates. The consequences calculated for these scenarios are thus used, rather than the maximum consequences.

4. Extra scenarios are included in the risk calculation if the resulting expected value would otherwise be too conservative (great). This depends on:
   - the proportion of the scenario probabilities whose consequences have been subjected to further consideration;
   - the difference between the maximum consequence and the greatest consequence of the more closely examined scenarios. If this difference is large, it will be detectable in the FN-curve or FS-curve, which will then have a very long, square tail, as shown in the centre of Figure 11.

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**Figure 11. Illustration of the more accurate definition of the FN-curve as a result of increasing the number of scenarios for which detailed consequences are included, rather than assuming the maximum consequences.**
6
THE LENGTH EFFECT

6.1 An intuitive approach
The longer a flood defence structure, the more likely it is that there will be a weaker spot somewhere. The phenomenon whereby the failure probability increases with the length of the flood defence is known as the length effect. An inspector that walks over a geometrically uniform levee has a chance of encountering a dangerous situation every step of the way. The greater the distance he walks, the greater the likelihood that he will encounter a problem somewhere.

The length effect is not the same for all failure mechanisms, even if the water level is the driving force behind them all. An inspector checking a levee for overflow during a high water will probably not need to go far to make a fair assessment of the likelihood that the levee will overflow somewhere at some point. After all, if the levee starts to overflow at one point, this is also likely to happen further along, and vice versa. This is because the height of a flood defence has a relatively low spatial variance. By contrast, the spatial variance of the levee’s resistance to piping is fairly high: the properties of the subsurface might change every 100 metres. The greater the distance the inspector goes, the greater the chance he will encounter a sand boil somewhere. So the probability of piping along the entire levee system is greater than the probability that this failure mechanism will occur in some random one-kilometre stretch.

Example from chemical or external safety practice
The length effect has long been taken into account in other policy domains. Risk analyses for high-pressure gas pipelines apply a failure probability per kilometre of pipeline. Besides the spatially distributed loading conditions (e.g. from local excavation activity), the spatial distribution of the strength properties also plays a key role here. Corrosion or welding errors can cause local weaknesses in the wall of a pipeline. Since it is not known in advance where this will be the case, a failure probability per unit length is used. Hence: the longer the pipeline, the greater the probability of a failure somewhere along the pipeline. To deal with this length-effect, the Dutch risk criteria for the transport of hazardous materials are defined on a per kilometer basis. The stringency of these criteria is such that the probability of a disaster somewhere in the Netherlands is deemed acceptable.

A flood defence is similar in many respects to the wall of a pipeline: both guide the movement of a dangerous substance (gas or water) and their failures cause a loss of containment. Furthermore, in both cases it is not clear where the weakest spot of the containment is, and how weak it is, giving rise to a length effect.

6.2 Basic principles
Though the strength of a flood defence is, in principle, deterministic, it is unknown until it has actually been measured. It would be impractical and prohibitively costly to probe and bore into a levee metre by metre. Although this would theoretically allow the uncertainty about the properties of the subsurface to be eliminated entirely, in practice, such uncertainties will always exist to some extent or other. So although it is not clear how weak the weakest spot is, a statistical description of the spatially distributed strength of a levee allows us to estimate the probability that the levee is weaker than a given value.

Flood defences will always fail first where they are actually weakest. However, as a result of limited knowledge/data we do not generally know how weak the weakest spot is, or where it
is located. Here lie the origins of the length effect, which results from the fact that an even weaker spot could potentially be located in an extra unit of length. Sometimes this probability is low (small length effect) and sometimes it is high (large length effect). In the event of a large length effect, the estimated probability of a breach *somewhere in a stretch of levee* will increase sharply with the length of the stretch. This is illustrated by Figure 12, which shows the spatial distribution of the resistance to piping, for a fictitious levee. The actual resistance is deterministic, but is not known for all locations (as a result of limited data). The resistance is only known with certainty at the measurement locations (measurement errors apart). The resistance between measurement locations is unknown. If the failure probability calculations were based on the lowest resistance measured, the failure probability would be underestimated. After all, the lowest resistance might be lower than the lowest measured value. The correct approach is to statistically describe the spatial distribution, and use this as a basis for calculating the failure probability.

![Figure 12. Though the resistance to piping is deterministic, it is known only at the locations where it is measured. The figure shows the actual development in resistance to piping (extrapolated curve) and the locations where measurements have been taken and the resistance is known (points). At greater distances from a measurement location, the more the resistance can deviate from the value measured.](image-url)
Figure 13 shows one of the many possible realisations associated with a statistical description of resistance to piping (a realisation is a possible outcome with a certain probability of corresponding to the actual situation). The probability that the flood defence’s resistance to piping falls short somewhere in the stretch of levee can be calculated for all possible realisations of failure probabilities, and these results can be weighted by their probabilities of occurrence.

Since the statistical properties are the same all along the entire stretch of this statistically homogeneous levee, its failure probability can be expressed per unit length – 100 metres, for example. Although the failure probabilities are the same for each 100-metre stretch, the actual (but unknown) resistance to piping might be different in each 100-metre stretch.

The failure probability of the entire stretch is greater than the failure probability calculated for a 100-metre section. After all, the greater the length considered, the greater the chance that the weakest spot turns out to be even weaker. If the calculated failure probability per 100 metres were 1/10,000 per year, the failure probability per kilometre could be around 1/1,000 per year. The fact that the failure probabilities roughly add up in this example (strong length effect) is explained by the fact that the resistance to piping may be entirely different after 100 metres (see the scale of fluctuation in Figure 14).

If we were to take measurements everywhere and calculate the failure probability on the basis of the lowest observed resistance to piping (and the statistical description of the spatial fluctuations were correct), a failure probability of about 1/1,000 years would be obtained here too (provided the stretch is long enough). The main difference compared to the situation before the measurements would be that the failure probability would now be different for each 100-metre section. The failure probability would after all fluctuate with the resistance measured. Since the weakness of the weakest spot would be known if measurements were taken everywhere, the failure probability for the weakest spot would be equal to the probability of piping for the entire levee. There would no longer be a length effect. This demonstrates that the length effect is inextricably linked to spatial uncertainty.

It will be clear from the above that the length effect is strong in the following circumstances:

1. Large variance in strength properties and/or loads
2. Rapid spatial fluctuations (small scale of fluctuation)
3. Uncertainty regarding the actual values of the strength properties and/or loads at various locations

If the resistance to piping were to fluctuate very slowly (strong spatial correlations), the actual lowest resistance could only differ noticeably from the lowest resistance measured at large distances away from the measurement location. In that case, the failure probability calculated for a 100-metre stretch of levee would be virtually equal to that calculated for a one-kilometre stretch. The length effect is therefore small when spatial correlations are strong.
The method in brief

Figure 13. One of the many possible realisations associated with the statistical description of resistance to piping (based on average, distribution and spatial correlations).

Figure 14. Possible realisations for various sizes of standard distribution and spatial correlation.
6.3 Mathematical explanation of the length effect

Section 6.2 explains why large and rapid spatial fluctuations, combined with uncertainty, give rise to a length effect. When the length effect is strong, the failure probability at levee system level will be greater than the greatest failure probability at section or cross-section level. Although there is also a length effect within sections, for the sake of simplicity the explanation below refers only to discrete sections.

**Extreme value theory**

Let us divide the stretch of levee in Figure 12 into n sections each with the same statistical properties, and lengths such that the resistance to piping in each section can be regarded as independent. This last fact means that, for each realisation (possible spatial development in resistance, see above), there is no connection (correlation) between the lowest resistance in one section and the lowest resistance in the adjacent one. In the top left of Figure 14 this means that the length of the section is greater than the distance between two points that are spatially correlated.

The minimum resistance\(^3\) in each section can be described using a probability density function. The probability that a section will fail is equal to the probability that the minimum resistance is smaller than the load:

\[
P_{f,i} = P(Z_i \leq 0) = P(R_i \leq S)
\]

The probability that at least one section will fail in a stretch of levee consisting of n sections is equal to the probability that the load is greater than the minimum resistance present in any of these sections:

\[
P_f = P(\text{Min}(R_i) \leq S)
\]

To determine the failure probability, one therefore needs to determine the probability distribution of the minimum resistance in the stretch of levee. The probability that the resistance in a section is smaller than \(\bar{R}\) (notation: \(F_{R_i}(\bar{R})\)) can be expressed as:

\[
P(R_i \leq \bar{R}) = F_{R_i}(\bar{R})
\]

The probability that the resistance in a section is greater than \(\bar{R}\) is thus:

\[
P(R_i > \bar{R}) = 1 - F_{R_i}(\bar{R})
\]

The probability that the resistance throughout n sections is greater than \(\bar{R}\) can be expressed as:

\[
P(R_1 > \bar{R} \text{ en } R_2 > \bar{R} \text{ en } ... \text{ en } R_n > \bar{R}) = (1 - F_{R_i}(\bar{R}))^n
\]

The probability that the resistance somewhere in one of the sections is smaller than \(\bar{R}\) is thus:

\[
P(\text{Min}(R_i) < \bar{R}) = 1 - (1 - F_{R_i}(\bar{R}))^n
\]

By differentiating, we can then determine the probability that the weakest spot has a resistance equal to \(\bar{R}\):

\[
P(\text{Min}(R_i) = \bar{R}) = n \cdot f_{R_i}(\bar{R}) \cdot (1 - F_{R_i}(\bar{R}))^{n-1}
\]

\(^3\) Where a lowest value is referred to, this means a local average on a temporal and spatial scale which could cause the flood defence to fail if exceeded. A single outlier on an atomic scale, for example, would not lead to the failure of a flood defence.
This equation shows that the failure probability of a serial system increases, the greater the variance of its resistance to failure and the greater the number of independent elements (in other words: more rapid spatial fluctuations). This phenomenon was also described under 'Basic principles'. It is illustrated numerically below by an example.
Example of length effect based on the theory of extreme values
Let us assume that a serial system consists of n elements. The strength of each element is not precisely known. We do however know that the probability that an element has a certain strength can be described on the basis of a normal distribution with average $\mu_{R_i}$ and standard deviation $\sigma_{R_i}$. Each element is subjected to the same load ($S$). The probability distribution of the greatest load in a year follows a normal distribution with average $\mu_S$ and standard deviation $\sigma_S$.

Let us assume that $f(R_i) = \text{Norm}(12;1)$ and $f(S) = \text{Norm}(10;1)$. The left-hand side of Figure 15 shows the probability distributions of the load and the minimum strength for a system consisting of a single element. The right-hand side shows the probability distributions for a serial system consisting of five elements. The probability that the weakest spot is weaker still is greater in the system consisting of five elements. The failure probability of each element is 0.08 per year. The failure probability for the serial system consisting of five elements is 0.24 per year. The increase in the failure probability of the serial system as the number of elements increases depends not only on the failure probability of each element, but also on the standard deviation of their strength (see also Basic principles).

Figure 15. Probability distributions of the load and minimum strength of a serial system consisting of one element (left) and a serial system consisting of five elements (right).
Let us assume that the probability distribution of the strength of an element is not Norm (12; 1) but Norm \((10;1 + \sqrt{10}, 2)\). The failure probability of each element will still be equal to that in the above example, but the standard deviation will be greater. Figure 16 shows the probability distributions of the load and minimum strength when the standard deviation of the strength of an element is not 1 but 2 (and the average is not 12 but \(10 + \sqrt{10}\)). The figure shows that the probability that the strength is smaller than the load is now greater in the serial system with five elements. The failure probability of each element is still 0.08 per year. But the failure probability for a serial system consisting of five elements is now 0.30 per year.

On the basis of the examples above, we can (again) conclude that the length effect is greater:

1. the greater the number of independent elements (or, when the levee is modelled continuously rather than discretely: the smaller the scales of fluctuation of the stochastic variables);
2. the greater the spatial variance of strength properties.

Figure 16. Probability distributions of the load and minimum strength in a serial system consisting of one element (left) and a serial system consisting of five elements (right) when the spatial variance of strength is greater.
Combining failure probabilities for each element using the Hohenbichler-Rackwitz method

The Hohenbichler-Rackwitz method is used to combine the failure probabilities of different elements (levee sections or structures). It is a first-order method in which the linearised reliability functions of different are combined in a step-by-step manner. The probability density functions of all stochastic variables are transformed into standard normal distributions (average 0 and standard deviation 1).

Let us assume that the reliability functions of the two elements can be represented as follows:

\[ Z_1 = \beta_1 - u \]
\[ Z_2 = \beta_2 - v \]

Where:
- \( Z_i \) = reliability function of element \( i \)
- \( \beta_i \) = reliability index of element \( Z_i \)
- \( u, v \) = standard normally distributed stochastic variables

If the \( Z \)-functions are uncorrelated, the two elements will be independent. In that case, the failure probability of a serial system consisting of these two elements equals:

\[ P_f = P(Z_1 \leq 0 \cup Z_2 \leq 0) = P(Z_1) + P(Z_2) - P(Z_1) \cdot P(Z_2) \]

(Z-functions uncorrelated)

The failure probability of the serial system with independent elements is almost equal to the sum of the failure probabilities of the elements when these probabilities are small. In practice, there might be significant correlations between the \( Z \)-functions of different sections. Let us assume that the correlation coefficient for the \( Z \)-functions of the two elements in the example is equal to \( \rho \). The \( Z \)-function of the second element can then be expressed as:

\[ Z_2 = \beta_2 - \rho \cdot u - \sqrt{1 - \rho^2} \cdot v \]

The value of stochastic variable \( u \) therefore entirely determines the value of \( Z_1 \) and partially determines the value of \( Z_2 \). The degree to which \( Z_2 \) is determined by the value of stochastic variable \( u \) depends on the correlation coefficient \( \rho \). If the \( Z \)-functions are fully correlated (\( \rho = 1 \)), then both \( Z_1 \) and \( Z_2 \) are wholly determined by the value of \( u \). Since a serial system fails if one of its element fails, the element with the smallest reliability index (highest failure probability) then determines the failure probability of the system. In the event of perfect correlation, the failure probability of the serial system is equal to the greatest failure probability of the two elements:

\[ P_f = P(Z_1 \leq 0 \cup Z_2 \leq 0) = \text{Max}(P(Z_1 \leq 0), P(Z_2 \leq 0)) \]

(Z-functions fully correlated)

The weaker the correlation between the two elements, the greater the failure probability of the serial system. In other words: the weaker the correlation, the stronger the length effect. It turns out that the length effect declines sharply only in the event of strong correlations. This phenomenon, also referred to as the ‘hockey stick effect’, is represented in Figure 17, which shows the relationship between the reliability indices of two identical elements and the probability that at least one of those elements will fail. This probability can be interpreted as the failure probability of a serial system consisting of two identical elements. When the correlations are weak, the system failure probability will be (virtually) equal to the sum of the
Relationship between the failure probability of an element and the failure probability of the serial system consisting of two elements.

Figure 17. The relationship between the correlation between the Z-functions of two elements with equal failure probabilities (or reliability indices) and the failure probability (reliability index) of a serial system consisting of these two elements; the relationship is shown for various values of the reliability indices.

failure probabilities of the two elements. In the event of perfect correlation, the system failure probability will be equal to the failure probability of a single element. As Figure 17 shows, the length effect only starts to decline sharply once correlations exceed a value of about 0.9. This means that correlations have to be high for the length effect to be small.
A flood defence fails if its strength is exceeded by a load. If both the load and strength are uncertain, it is uncertain which combination of load and strength will actually cause a failure. Each of the combinations that could cause a failure of a flood defence has its own probability of occurrence. The combination with the greatest probability density is called the design point.

If a levee could fail only as a result of overflow and the levee’s height were known precisely, the value of the water level in the design point would be equal to the levee’s crest height. This would be the water level with the greatest probability density that would cause the levee to fail (Figure 18). The flood defence could also fail at higher water levels. But these water levels would have lower probability densities.

Figure 18. If the water level is the only stochastic variable, the value of the water level in the design point is equal to the minimum crest height.
If the strength properties of a flood defence are not precisely known, it is not certain which water level will cause it to fail. The value of the water level in the design point can then no longer be interpreted as a critical value above which the flood defence will fail, since it might fail at a higher or lower water level.

Design points play an important role in FORM failure probability calculations. If the strength ($R$) and the load ($S$) are uncertain, the linearized reliability function (after transformation of the probability functions into standard normal distributions) has the following form:

$$Z = \beta - \alpha_R \cdot u_R - \alpha_s \cdot u_s$$

Where:
- $\beta$ = reliability index
- $\alpha_R$ = influence coefficient of strength
- $u_R$ = strength
- $\alpha_s$ = influence coefficient of load
- $u_s$ = load

Since $u_R$ and $u_s$ are normally distributed, $Z$ is too. The expected values $u_R$ and $u_s$ are equal to zero, so the expected value of $Z$ ($\mu_Z$) is equal to $\beta$. The standard deviation of $Z$ is equal to 1 because $\sqrt{\alpha_R^2 + \alpha_s^2} = 1$. As such, the following applies to the failure probability of the system:

$$P_f = P (Z \leq 0) = \Phi (-\beta)$$

Where:
- $\Phi$ = cumulative standard normal distribution.
Figure 19. The probability that $Z \leq 0$ and the calculation of the design point.
The design points are inspected in the VNK2 project to get a better feel for the outcomes of failure probability calculations. If the local water level in the design point is unrealistic or differs markedly from the design point for a similar section, the failure probability calculations are checked (input, possible convergence problems).
The statutory safety assessment and VNK2 differ in terms of their nature, substance and status (Table 3). The tools used in VNK2 are not the same as the ones used in the statutory assessment. The statutory assessment establishes whether primary flood defences comply with the standards laid down in the Water Act. These standards are defined as exceedance probabilities for water levels against which protection must be provided, taking account of all factors affecting the flood defence capacity of the system. If a flood defence system does not comply with the standard, it must be reinforced.

VNK2 quantifies flood risks, considering not only the flood defences but also the consequences of flooding. VNK2 is a research project designed to enhance our understanding of factors that have a bearing on flood protection. It is not, however, a statutory assessment. No statutory requirements are associated with flood probabilities or risk. The flood probabilities calculated in VNK2 cannot directly be compared with the exceedance probabilities (safety standards) laid down by the Water Act. Firstly, flood probabilities refer to the actual occurrence of flooding, the exceedance probabilities do not. Secondly, a flood probability (as computed by VNK2) refers to the probability of a breach somewhere in the levee system, while the statutory assessment asks whether individual sections or cross-sections of a levee can provide protection against a certain exceedance probability without regard to the flood defence system as a whole. As described in the previous section, the length effect means that the failure probability of an entire levee system is greater than the failure probability of a single section or cross-section.

Table 3. Differences between the assessment and VNK2.

<table>
<thead>
<tr>
<th>ASPECT</th>
<th>STATUTORY ASSESSMENT</th>
<th>VNK2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key question</td>
<td>Can the flood defences safely withstand the normative load?</td>
<td>What are the probability and likely consequences of a flood?</td>
</tr>
<tr>
<td>Status</td>
<td>Part of a statutory system.</td>
<td>Research project.</td>
</tr>
<tr>
<td>Method</td>
<td>Assessment of flood defences by failure mechanism and section/cross-section on the basis of a set of instructions (statutory assessment tools).</td>
<td>Risk analysis of levee systems, using probabilistic techniques, flood propagation models, consequence models and links between probabilities and consequences.</td>
</tr>
</tbody>
</table>
### The Method in Brief

#### Statutory Safety Assessment and VNK2

All failure mechanisms

The failure criterion differs from one failure mechanism to another. Even if a criterion is not met, the probability of a breach is not necessarily high. In the case of damages to cover layers, for example, only initial damages are considered (not the subsequent erosion of the levee core).

<table>
<thead>
<tr>
<th>Outcome</th>
<th>All failure mechanisms</th>
<th>The failure criterion differs from one failure mechanism to another. Even if a criterion is not met, the probability of a breach is not necessarily high. In the case of damages to cover layers, for example, only initial damages are considered (not the subsequent erosion of the levee core).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Passes or fails</td>
<td>Only failure mechanisms which are expected to have a major bearing on the failure probability/flood risk.</td>
</tr>
<tr>
<td></td>
<td>Result per section/cross-section.</td>
<td>The failure criterion used in failure probability calculations is a loss of flood defence function in the element such that the water flows into the levee system.</td>
</tr>
<tr>
<td></td>
<td>Focus solely on flood defences.</td>
<td>Flood probability, flood risk (with qualitative consideration of elements/failure mechanisms not fully computed).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Result per section/hydraulic structure and result for the entire levee system and the entire levee system.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Focus on flood defences and on the consequences of flooding (damage, fatalities).</td>
</tr>
</tbody>
</table>
Despite the differences between the statutory safety assessment and VNK2, there are also many similarities (Table 4). Both look at the same physical structures. They are also both aimed at gaining insight into the level of protection afforded by our primary flood defences. The different approach taken in VNK2 can provide valuable additional insights to improve that level of protection.

The insights gained in VNK2 can be used to trace potential gaps in protection and assess investment decisions when budgetary restrictions mean difficult choices have to be made. The return, in terms of risk reduction, on an investment in flood protection can differ sharply from one location to another, depending on the consequences of flooding and the probability of a breach.

Table 4. Similarities between assessment and VNK2.

<table>
<thead>
<tr>
<th>ASPECT</th>
<th>SIMILARITY BETWEEN ASSESSMENT AND VNK2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scope</strong></td>
<td>Both look at the same flood defences, albeit from different perspectives.</td>
</tr>
<tr>
<td><strong>Method</strong></td>
<td>Although the models produced in VNK2 are entirely probabilistic, the descriptions of many failure mechanisms are similar to those in the statutory assessment tools (Table 1). The main differences concern the inclusion of the strength of the grass cover in considering overflow/overtopping rather than the use of a fixed, maximum overflow rate, and the use of rudimentary residual strength models after initial failure.</td>
</tr>
<tr>
<td></td>
<td>In both the statutory assessment and the VNK2 analysis, the local knowledge of the water board plays a crucial role. In both cases, water boards make a vital contribution by comparing the results and underlying schematisations with their background-knowledge and experiences.</td>
</tr>
</tbody>
</table>
Although the statutory safety assessment does not use fully probabilistic techniques, there are intrinsic links between the assessment rules and the models used in VNK2. The semi-probabilistic assessment rule for slope stability was derived using the same fully probabilistic model used in VNK2. However, this is not the case for all failure mechanisms. For example, the simple assessment rule for piping (Bligh rule) was not derived on the basis of a fully probabilistic analysis.

In the statutory safety assessment, failure probabilities are not calculated, but an evaluation is made whether a flood defence is likely to safely withstand a certain load. The word ‘safe’ does imply a verdict as to probability of failure, but the definition of ‘safe’ varies based on the context of the situation. The VNK2 approach provides the additional information necessary to determine the likelihood of failure, and to inform the discussion of whether failure is unlikely enough. VNK2 results show that levees that comply with the current statutory assessment rules (cf. VTV-2006) may sometimes have a greater probability of failure than was previously thought.
Suggestions for further reading are given below. The recommended papers, reports and books examine the background and origins of the methods and techniques used in VNK2 in greater depth. Should your questions nevertheless remain unanswered, the VNK2 Project Office will be more than happy to provide further information.

**Calculating flood probabilities: schematisation and modelling**

**Calculating the consequences of flooding**

**Calculating flood risk**

**General theory: probability, design points**
The length effect
Decimation height
The variation in crest height associated with an increase or reduction in exceedance probability by a factor 10.

Design point
The most probable combination of stochastic values at which the limit state function (strength – load) equals 0.

Dune erosion
Failure mechanism for dunes associated with erosion of the dune in storm conditions.

Exceedance probability
The probability that a certain value will be reached or exceeded. The exceedance probabilities stipulated in the Water Act are probabilities that the design water level will be reached or exceeded.

Expected value
The average value of a stochastic variable; the first moment of the probability density function.

Failure
General: non-compliance with one or more requirements. In VNK2: loss of flood defence function.

Failure mechanism
The manner in which a flood defence fails. Four failure mechanisms are considered for levees and hydraulic structures. Dune erosion is considered in the case of dunes.

Flood probability
The probability that an area will flood because the flood defences around it (the levee system) fail in one or more places.

Flood propagation model
A model that simulates the sequence of flooding following one or more breaches in a levee system.

Flood risk
The combination of probabilities and consequences of flooding. The consequences are expressed in terms of economic damage or fatalities. Economic risk and fatalities risk are expressed in different ways in the VNK2 project.

Flood scenario
A unique series of events following the occurrence of one or more breaches. Flood scenarios are mutually exclusive; if one occurs, another does not.

Foreland
The area immediately outside the flood defences. It is also known as the foreshore. Foreland may lie above or below the water line.

Length effect
The phenomenon whereby the failure probability of a flood defence increases with length. This results from the fact that, the greater the length examined, the greater the probability that there will be a weaker spot.

Levee section
Part of a flood defence with statistically homogeneous strength properties and loads.

Levee system
A system of flood defences and/or high ground that encircles an area, protecting it from flooding.
Limit profile
The minimum profile required to prevent the breach of a dune.

Local individual risk
The probability that a person who is continually present at a certain spot within a levee system will die as a result of flooding. The calculation of local individual risk also incorporates the potential for preventive evacuation.

Local individual risk without evacuation
The probability that a person who is continually present at a certain spot within the levee system will die as a result of flooding. The calculation of local individual risk without evacuation does not incorporate the potential for preventive evacuation.

Macrostability
A failure mechanism whereby a slope slides.

PC-Ring
A probabilistic model that allows failure probabilities to be calculated for various failure mechanisms in levees, dunes and hydraulic structures. PC-Ring can also combine failure probabilities for each section and failure mechanism to give failure probabilities for the entire system. It can also calculate scenario probabilities.

Piping
The phenomenon whereby a channel forms underneath a levee as a result of erosion by groundwater.

Primary flood defences
A flood defence that either belongs to the system of flood defences encircling a levee system – sometimes but not always including high ground – or is situated in front of a levee system.

Probability density function
A function that assigns a probability density to every possible value of a stochastic variable.

Levee system
An area that is protected from flooding by the sea, IJsselmeer lake, Markermeer lake and/or the major rivers by a system of flood defences and/or high ground.

Realisation
A possible outcome.

Residual strength
Residual strength is a collective term for the strength of a levee after an initial failure mechanism has occurred. In the event of the failure mechanism ‘damage to cover and erosion of dike core’ VNK2 uses a number of residual strength models to calculate the probability that a breach will occur once the cover is damaged. In the event of the failure mechanism ‘inward macrostability’, the strength of the dike after the occurrence of a relatively small-scale slide/slip can be incorporated into the calculation of failure probability.

Scenario probability
The likelihood that a certain scenario will actually occur.

Seepage length
The distance seepage water travels in the ground, from the entry point to the exit point.

Societal risk
Refers to the probability of a certain number of fatalities being exceeded.
**Standard deviation**
A measure of the variation/uncertainty round an average.

**Stochastic variable**
An uncertain quantity. The probability of the various values of a stochastic variable is expressed by a probability density function.

**Consequence segment**
Part of the levee system within which the location of the breach has no significant impact on the flood pattern and damage sustained.

**Ultimate limit state**
A state in which the strength of a structure or part of a structure just enables it to withstand the loads to which it is subject.

**Wave overtopping**
Water passing over a flood defence due to wave action.