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BREACH-METHOD: a new framework to generate event sets for financial flood risk assessment of the Dutch Delta

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Abstract

In the Netherlands, a flood risk assessment method is employed to establish safety standards for levees. This method utilizes a risk-based approach that combines the consequences of flooding with the probabilities of failure of the flood protection system. However, the currently used flood risk assessment method (referred to as the DPV) method has several limitations: 1) it neglects system behavior—treating all levee sections as independent, with no consideration for breaches occurring elsewhere in the system; 2) it does not account for emergency measures; and 3) its definition of failure fails to encompass the entire failure process. When applying the DPV method, particularly concerning spatial adaptation and the financial sector, the probability of flooding in the Netherlands, as well as the overall flood risk, is overestimated. The overestimation of exposure persists despite historic events (the last major flood occurred in 1953) and numerous levee reinforcements. It stems from foundational choices made in the risk assessment method and can lead to undesired consequences, such as excessive insurance costs, a reduced willingness to invest in the Netherlands, lower housing prices, and increased costs for spatial adaptation.

In response, we propose a new flood risk assessment framework for spatial adaptation and the financial sector: the BREACH-METHOD. This method builds upon existing flood risk information and integrates statistical methods with expert judgment for delta areas that have protective infrastructure and hydraulic interdependencies. The proposed model offers a more realistic representation of failure probabilities in the Netherlands compared to historic events. Consequently, it provides new local flood risk profiles that describe the exceedance frequency of water depths at any location in the Netherlands. The proposed model facilitates informed decision-making across various domains, including spatial planning, risk insurance, and investment allocation.

Keywords

Flood risk, spatial adaptation, financial decision-making, insurance.

1 Introduction

Climate change is expected to alter flood risk dynamics, with most countries anticipating an increase in risk unless proactive measures are taken. Globally, many deltas are already densely populated and highly vulnerable to flooding (Santos & Dekker, 2020). Urban areas continue to expand along historical patterns (Tellman et al., 2021; Rentschler et al., 2023), increasing potential consequences as more assets and people become exposed. Climate change is projected to raise sea levels, intensify rainfall, and increase river discharges (IPCC, 2023). Without reinforcement, the probability of levee failure will rise. Even if levees are reinforced to maintain a constant failure probability, the consequences of flooding will still increase due to higher water levels in seas and rivers.

As a result, financial institutions increasingly integrate flood risk into reporting and regulatory frameworks. Key policy developments include the European Central Bank's (ECB) guidelines on climate-related and environmental risk (ECB, 2020), climate stress-testing protocols (ECB, 2022), and EU regulations such as the Corporate Sustainability Reporting Directive (CSRD) and Environmental, Social, and Governance (ESG) ratings. The European Insurance and Occupational Pensions Authority (EIOPA, 2024) uses the 200-year return period loss or the total insured value as a solvency benchmark. Furthermore, both the International Monetary Fund (Lepore & Mok, 2024) and the Central Bank of the Netherlands (Caiola et al., 2023) have analyzed flood risk in the Netherlands under extreme scenarios exceeding Solvency II requirements. Flood risk information also informs local property pricing.

Quantifying flood risk in delta regions with protective infrastructure requires a clear understanding of flooding mechanisms. Risk is typically defined as the product of the probability of an event and its consequences, expressed per year. This definition is widely used in flood risk literature (Kok et al., 2017; Vrijling, 2009; Ten Brinke et al., 2008). Alternatively, risk can be described in terms of hazard, exposure, and vulnerability (Kron, 2002; Gendreau et al., 1998). The term *hazard* refers to the threatening natural event and its probability. *Exposure* includes the people, assets, and infrastructure present in the affected area. *Vulnerability* refers to the susceptibility to damage or loss (Cutter, 1996). Both definitions converge, as they account for the probability of occurrence and the associated consequences.

Flood risk management aims to reduce risk and enhance societal resilience. A widely used approach is to implement measures across multiple layers or lines of defense. In the Netherlands, this is formalized as the multiple-layer safety (MLS) concept, consisting of three primary layers (VenW, 2009). The first layer 'prevention' seeks to reduce the probability of flooding through levee reinforcements or spatial measures such as Room for the River, prevention is sometimes also defined as (European Parliament, 2007). The second layer focuses on spatial planning to limit consequences, including strategic land use and building codes. The third layer improves emergency response capacity. Following the 2021 Limburg floods, recovery and public awareness have been added as supplementary layers (Beleidstafel, 2022). From a cost-benefit perspective, especially in high-value areas, investments in preventive measures are often the most cost-effective form of risk reduction, provided that emergency response systems are in place (Kind, 2014; Kok et al., 2017). In lower-value areas, however, investments in land use planning and crisis management (Layers 2 and 3) may offer relatively greater returns compared to prevention (Kolen & Kok, 2011).

In this study, we focus on the primary flood defenses in the Dutch Delta. Approximately thirteen centuries ago, inhabitants of the region that is now the Netherlands began constructing levees to protect against flooding. Today, the Netherlands is considered one of the safest deltas in the world. The last major flood caused by the failure of primary flood defenses occurred in 1953, when multiple levee breaches resulted in approximately 5% of the country being inundated. Following the 1953 disaster, flood protection standards were introduced for primary flood defenses. In addition, storm surge barriers collectively known as the Delta Works were constructed, and numerous levees and dunes were reinforced. After the extreme river discharges in 1993 and 1995, further levee reinforcements were implemented. Since 2017, new and more stringent safety standards for primary flood defenses have been in effect. A more detailed description of the history of flood risk management and the safety standards in the Netherlands is available in Appendix 6.1.

The safety standards that have been in effect since 2017 are based on a minimization framework that balances the costs of levee reinforcement against expected flood risk (Kind, 2014). The underlying flood risk assessment approach is known as the DPV method, named after the Dutch *Delta Programma Veiligheid* (Slootjes & Van der Most, 2016). This method builds upon earlier national flood risk assessments, including Vrijling (2001) and the FloRiS project (*Flood Risk and Safety in the Netherlands*) by Jongejan & Maaskant (2015).

The latest twelve-yearly assessment of all primary flood defenses, published by ILT (2023), shows that many levees currently do not meet the new standards and therefore require reinforcement. By 2050, all levees—covering approximately 3,500 km divided into 234 sections—must comply with the updated safety standards (Kok et al., 2017).

Beyond safety evaluations, the DPV method is also used as a framework to support urban planning in the Netherlands (IenW, 2024), including mapping the local probability of exposure to various flood depths. However, current mandatory levee assessments do not yet yield fully realistic failure probabilities for all levees, as several failure mechanisms remain insufficiently understood or quantified (ENW, 2024).

The central question in this study is whether the available flood risk data and existing risk assessment methods can be applied within the financial sector. The objective is to evaluate the currently available flood risk data for the Netherlands, clarify the underlying assumptions, and assess the implications of applying the DPV method in a financial context. To this end, we introduce a new method 'BREACH' which generates a large flood event set that explicitly incorporates the assumptions embedded in the underlying flood risk data. This method enables a more realistic and transparent risk assessment tailored to the needs of the financial sector, as it also captures the tail of the distribution.

2 Review of current risk information and underlying data

2.1 Available information about flood probabilities and scenarios

The main source of flood risk data in this study is the *Landelijk Informatiesysteem Water en Overstromingen* (LIWO), accessible via https://basisinformatie-overstromingen.nl. is a national portal and database maintained and annually updated by Rijkswaterstaat and the regional Water Authorities. It serves as the authoritative source for flood risk analyses in the Netherlands and is the result of decades of research and development. So the data and maps based on the DPV method are available on LIWO. The LIWO database (version 2024.0.2) contains:

1. Failure probabilities and safety standards for all 234 levee sections and their subsections under current conditions. In many cases, the current failure probabilities exceed the statutory safety standards, indicating the need for reinforcement.
2. Flood scenarios, including 4,851 modelled events, of which 1,873 relate to primary flood defenses. Each scenario provides detailed information on flood consequences following a levee breach, including flood extent, water depth, economic damage, casualties, and evacuation effectiveness. Representative breach locations have been defined per levee subsection, following a systematic approach based on national flood risk assessments (Jongejan & Maaskant, 2015), accounting for differences in flood impact and levee characteristics. These scenarios are based on hydraulic boundary conditions under the current climate and include variations in water levels with different return periods (e.g., normative, 1/10, and 1/100 frequency levels). All consequences are modelled assuming a breach at a single location, with no simultaneous failures elsewhere in the water system.

Levee failure is driven by hydraulic loading (hydrographs) and geotechnical mechanisms such as seepage, overtopping, and slope instability. The planning horizon for levee reinforcements typically ranges from 50 to 100 years, requiring projections of future hydraulic loads. To account for climate change, we use the W+ scenario developed by the Royal Netherlands Meteorological Institute (KNMI, 2014), which corresponds to the Representative Concentration Pathway (RCP) 8.5 from the IPCC (2013) and aligns with the high-end sea level rise projections from IPCC (2021) and KNMI (2023). The W+ scenario is implemented using the Hydra-NL software tool, which supports statutory levee assessments and redesign efforts in the Netherlands.

2.2 Application of DPV method in financial flood risk analyses and mapping

The DPV method, along with earlier national flood risk assessments, provides estimates of current and future flood probabilities, exposure, and expected damage under various scenarios of climate change and socio-economic development. From a financial sector perspective, however, a key limitation is that these studies offer only single-point estimates of flood probability, exposure, and damage per dike ring or levee section. They do not provide the full probability density functions (PDFs) of exposure, nor the spatial correlations between different regions. For catastrophe modelling in the financial sector, such as risk pricing, stress testing, and solvency assessment, a more detailed understanding of the distribution of exposure across individual locations and on a national scale is essential. Catastrophic risks are typically characterized by fat-tailed distributions, and estimates must often be derived from limited empirical data. These characteristics make it crucial to explicitly account for uncertainty and distributional assumptions in the risk assessment process (Paudel et al., 2012).

In the DPV method, risk is quantified by multiplying the probability of each flood scenario by its associated consequences per levee section. In case that areas or properties flood because of failure of different levee sections the flood risk per levee section is summed assuming all sections to be independent. Using this methodology, a series of national flood maps has been developed and made publicly available through the LIWO portal and the Climate Effect Atlas. These maps include: Flood-prone areas for selected return periods (also used for EU Floods Directive reporting), Local probability of exposure to specific flood depths, Expected economic damage per location, Local individual risk (mortality risk) which are available on LIWO (2024) and *Klimaat Effect Atlas* (KEA 2024). All maps are constructed using combinations of underlying flood scenario data from LIWO, based on the same probabilistic foundation as the DPV method.

As with any risk assessment method, including the DPV approach, a set of modelling assumptions underpins the estimation of flood risk. While the DPV method was originally developed to support the design and evaluation of safety standards, its application is now extending to financial flood risk assessments. However, when directly applying the DPV method to the financial sector, both the probability of flooding and the overall risk in the Netherlands, under current and future climate conditions (e.g., 2050 projections), tend to be overestimated. This overestimation persists despite the rarity of historical flood events (the last major flood occurred in 1953) and the extensive reinforcements made to the levee system after 1953 over recent decades. It stems from fundamental modelling choices embedded in the risk assessment framework (a more detailed explanation of these assumptions and their implications is provided in Appendix 6.2):

1. Neglect of system behavior in failure probability estimation. In the DPV method, system behavior (also referred to as hydraulic interdependencies) is not considered in the estimation of flood probabilities. System behavior refers to dynamic interactions within the water system, whereby a levee breach can lead to reduced water levels, subsequently lowering the probability of failure at other levee sections (Van Mierlo et al., 2007; De Bruijn et al., 2014). This phenomenon includes mechanisms such as short-cutting (where water seeks an easier path following a breach) and cascade effects (where the failure of one component affects the likelihood of failure in others). In the current implementation of the DPV method, failures of all 234 levee sections are assumed to be independent. This simplification ignores the potential mitigating effect of a breach on downstream hydraulic loads. While this assumption has a limited effect on the derivation of safety standards (Dupuits, 2019), it may lead to overestimated flood probabilities when applied in financial risk assessments. Previous studies (Van Mierlo et al., 2007; De Bruijn et al., 2014) demonstrate that system behavior can be incorporated through the use of hydraulic models in combination with (perfect) fragility curves, which define the failure probability as a function of the hydraulic load. Integrating such dependencies would improve the realism of probability estimates, particularly in aggregated risk analyses relevant for insurers and financial institutions.
2. Incomplete representation of the levee failure process. In current failure probabilities as well as the reinforced levees are based on models in which the levee failure is defined as the initiation of the failure process under a given hydraulic load. In addition, conservative assumptions are intentionally made when modelling levee failure probabilities to ensure public safety (ENW, 2024). The failure probability is not the actual onset of flooding which has a lower probability. This definition reflects limitations in current modelling capabilities, as several critical processes in the failure mechanism remain poorly understood and are therefore not included in the models (IenW, 2017; Deltares, 2018; Pol et al., 2024). As a result, both the estimated failure probabilities and the design of reinforced levees are based on partial representations of the physical failure process. Key aspects such as the progression from initial instability to full breach and inundation are not captured. Curran et al. (2020) highlights the potentially large impact of incorporating time-dependent behavior into fragility curves, particularly when system behavior is considered. However, due to existing knowledge gaps, the inclusion of time as a factor in fragility modelling is not yet feasible.

3. Exclusion of emergency measures in failure probability estimation. Emergency measures such as temporary reinforcements, mobile pumps, and sandbagging are not taken into account when estimating levee failure probabilities. This omission persists despite the fact that such measures are integral components of the operational flood emergency plans maintained by all regional water authorities. Research by Lendering et al. (2016) shows that emergency interventions can reduce the probability of failure by a factor of 1.5 to 4. The current exclusion of these effects leads to conservative, and likely overstated, estimates of failure probabilities in the DPV framework.

4. Neglect of system behavior in the modelling of flood consequence. System behavior is also excluded from the modelling of flood consequences. All flood scenarios in LIWO are based on the assumption that a single breach occurs, with no simultaneous flooding in other areas of the water system. This implies that interdependencies such as how upstream or downstream breaches may influence water levels and flood extent are not considered. While this assumption simplifies scenario development, it limits the realism of compound and cascading failure analyses, which are particularly relevant for financial stress testing and correlated loss estimation. The impact of this assumption is expected to be limited, Riedstra (2018) shows that the average damage of all LIWO scenario based on a frequence of the load related to the safety standards increase by a factor of 0.35 if the frequency of the load increases by a factor of 10.

When the DPV method is applied for financial flood risk analysis in the Netherlands, the results are summarized in Table 1. For this purpose, the Netherlands was divided into spatial areas that can reasonably be assumed to be independent, based on the cause of flooding (Ten Brinke et al. 2010). Within each area, we calculated the flood probability under two contrasting assumptions. First, we assumed fully independent levee sections which is a strict application of the DPV method, where each levee section is assumed to fail independently. Second, we assumed fully correlated levee sections of the coastal areas and the upper river areas which is an upper-bound estimate. Perfect correlation is assumed between levee failures for all coastal areas and for all river areas. In this case, by definition system behavior cannot reduce flood probability.

Assuming the areas themselves are independent, we derived national flood probabilities. Under current climate conditions, this approach yields a flood probability of approximately 1/3 per year, and 1/5 per year for 2050. These values are clearly inconsistent with empirical evidence: the last major flood caused by primary levee failure occurred in 1953, and since then the country has implemented extensive reinforcements including the Delta Works and Room for the River and significantly tightened its safety standards. Notably, extreme river discharges such as the 1995 event on the Rhine (Chbab, 1995) and the 2021 Meuse peak did not result in levee breaches. Assuming full correlation within coastal areas, and full correlation within the upper river systems, the resulting national flood probabilities are estimated at 1/20 per year for the current system and 1/30 per year for 2050. These figures remain implausibly high in light of historical flood performance and ongoing investments in flood protection. Moreover, the results illustrate the limitations of directly applying the DPV method to financial risk assessments and highlights the urgent need to refine modelling approaches for this purpose.

Table 1: Flood probabilities for the Netherlands and per independent area for the current situation and in 2050 applying the DPV method.

Probability of flooding per year	Current state of levees (year 2023)		Safety standards (year 2050)	
Area (number of sub levee sections)	Fully independent	Fully correlated	Fully independent	Fully correlated
Upper river area (Meuse) (23)	1/40	1/217	1/250	1/1000
Upper river area (Rhine) (97)	1/7	1/100	1/30	1/100
Lake IJssel area (73)	1/12	1/68	1/15	1/100
Coast south (180)	1/18	1/61	1/23	1/100
Coast middle (23)	1/8.200	1/25.381	1/250	1/1000
Coast north (49)	1/77	1/358	1/43	1/300
Lower tidal area (177)	1/8	1/126	1/17	1/300

3 New BREACH-METHOD

3.1 Philosophy behind the method

Due to limited understanding of the relationship between hydraulic loads and levee failure probabilities, developing a fully physical model of the failure process is currently not feasible. To address this gap, we extend existing flood risk estimation approaches by incorporating structured expert judgment. This extension allows us to explicitly consider system behavior, single and multiple breach events, additional components of the levee failure process, and emergency management effects. Expert judgment provides valuable insights and contextual understanding, particularly where empirical data are limited or incomplete. However, its use also introduces subjectivity and potential biases. Balancing expert input with quantitative data and diverse viewpoints is essential to ensure robustness in the risk assessment process (Rongen et al., 2022). Notably, subjectivity is also present in existing levee assessments and underlying datasets, where expert judgment plays a vital role (see e.g., RWS, 2020).

In this paper, we introduce a novel approach—termed BREACH-METHOD—for assessing financial flood risk in delta regions with protective infrastructure. BREACH-METHOD combines available flood risk data, statistical analysis, and structured expert judgment to quantify risk in complex hydraulic systems. It builds upon all available flood scenarios, including low-probability extreme events, and incorporates current knowledge of failure probabilities.

The method is grounded in the exceedance frequency of extreme water levels in adjacent seas, rivers, and lakes. By linking these loads to current failure probabilities and statutory safety standards, the method identifies levee sections with elevated risk. Expert input is then used to incorporate interdependencies between levee sections, uncertainties in the failure process, and emergency response capabilities. BREACH-METHOD leverages existing flood scenarios and does not require new hydraulic simulations. As a result, the effect of system behavior on flood extent is not included. While incorporating system behavior in consequence modelling may improve future risk estimates, we expect that uncertainties in failure probabilities will remain the dominant driver of risk outcomes.

We apply BREACH-METHOD to the Netherlands and compare the results with those from the existing DPV-based risk assessment. We also reflect on the methodological assumptions and implications of our approach.

3.2 Methodology

The BREACH-METHOD results in an event set which can describe the exposure distribution to flood risk in the Netherlands. The event sent can be used to define the damage distribution as well. The results can be analyzed on a national scale (e.g., what is the exposure of the Netherlands), a regional scale (an area) or a local scale to describe the exposure of a property. As a result, the method allows for the quantification of correlations in exposure between properties, which is an important input for financial risk modelling.

The BREACH-METHOD produces an *event set* that describes the distribution of exposure to flood risk across the Netherlands including the tail of the distribution. This event set can also be used to derive the corresponding damage distribution. The results can be analyzed at various spatial scales: nationally (e.g. total exposure across the Netherlands), regionally (e.g. flood risk in a specific area), or locally (e.g. the flood exposure of an individual property).

The probability of flooding is calculated by combining the failure probabilities of all levee sections with the consequences of individual flood scenarios. Local exposure distributions are derived by aggregating exceedance frequencies of flood depth, based on all flood scenarios and their associated probabilities that affect a given location. In this study, we assume that by 2050, all levees will meet exactly their respective safety standards. This assumption is conservative and results in a failure probability which is too high as levee reinforcements typically follow a life cycle of 50 to 100 years. Some levees already perform substantially better than the required standard due to historic over-dimensioning. In practice, it is expected that by 2050 several levees will have failure probabilities well below the statutory threshold.

Climate change is explicitly considered in the analysis. Due to more extreme river discharges and accelerated sea level rise, the probability of flood events is expected to increase. Levee reinforcements are anticipated to maintain risk within acceptable bounds, as defined by maximum allowable failure probabilities.

The BREACH-METHOD adjusts for three key conservative assumptions in the standard DPV-based risk approach: incorporating system behavior in the estimation of failure probability, a broader definition of failure accounting for uncertainty in the failure process, emergency measures which reduce the failure probability. In addition, the method allows for multiple simultaneous breaches across levee sections. The model generates a large event set for primary flood defenses, using failure probabilities of (sub)levee sections and flood scenarios which describe the water depth from the LIWO database.

The BREACH-METHOD consists of a structured sequence of analytical steps as listed below (a detailed description is provided in Appendix 6.3, a flow chart to illustrate the steps with an example for one class is given in Figure 1).

1. Selection of available information. We use the basic information as described in section 2.1. For the year 2050 we assume that all levees will exactly meet the safety standards, which is a conservative assumption, as reinforcements are done on different moments in time, using a life cycle of 50 to 100 years and taking climate change into account.

2. Zoning of (in)dependent areas. Based on the nature of the threat, eight areas are distinguished for primary flood defenses, following a similar approach to that used in the preparation of worst credible flood scenarios (Ten Brinke et al., 2010; Kolen & Wouters, 2007). Limburg is not taken into account. Flood events in different areas are considered independent.

3. Classification of flood scenarios by probability. For each defined area (as determined in Step 2), flood scenarios are grouped into nine probability classes, each representing a characteristic annual exceedance probability: 1/100, 1/200, 1/500, 1/1,000, 1/2,000, 1/5,000, 1/10,000, 1/100,000, and 1/1,000,000 per year. Each flood scenario is assigned to one of these classes. The first criterion is the failure probability of the relevant levee section, which defines the maximum probability of a flood event originating at that location. The second criterion is the hydraulic load used in the scenario (e.g., water level or discharge), noting that multiple scenarios with varying severities may exist for a single breach location. This classification enables a structured aggregation of flood scenarios across a consistent probabilistic scale, allowing for scalable risk analysis at local, regional, and national levels.

4. Estimation of conditional probabilities for zero to multiple breaches per class. For each area defined in Step 3 and for each hydraulic load class (as defined in Step 2), we estimate the conditional probability of observing zero to nine simultaneous levee breaches. This step addresses uncertainties and knowledge gaps in the basic data (Section 2.2) by incorporating structured expert judgment. A standard Delphi approach is used to elicit expert opinions to convergence toward consensus probability estimates. For each class of hydraulic load, experts assess the likelihood of observing different numbers of breaches (from 0 to 9) within a given area, conditioned on the occurrence of the specified load level. In appendix 6.3.4 the selection of experts, the questions and the steps in the Delphi process are presented.

5. Generating single and multiple breach events for the event set. In this step, the full event set is constructed by defining all flood events based on the number of simultaneous breaches for all classes. Flood events of multiple breaches are generated by combining the maximum flood extents and water depths of the relevant flood scenarios associated with each breach location. To manage computational complexity and avoid an unmanageable number of combinations, a simplification is introduced: for cases involving four or more simultaneous breaches, a composite "maximum impact" scenario is defined. This scenario represents the upper bound of the flood extent and water depths, based on expert judgment and the spatial combination of the most impactful available flood scenarios.

6. Assignment of individual flood event probabilities. In this step, the (conditional) probability of each flood event is determined. The procedure for deriving these probabilities per area, class and the number of breaches uses a uniform distribution. The probability of a flood event is the weighting probability of a class, multiplied by the conditional probability of the number of breaches in the class, and divided by the number of flood events with the same number of breaches. To avoid overestimating the likelihood of extreme multiple breach events, the

"maximum scenario" for four or more breaches receives only half of the total probability assigned to that breach category. The remaining half is redistributed to the set of three-breach events, ensuring a more realistic allocation of probability mass. This redistribution prevents the maximum scenario from dominating the probability space, in line with its low plausibility.

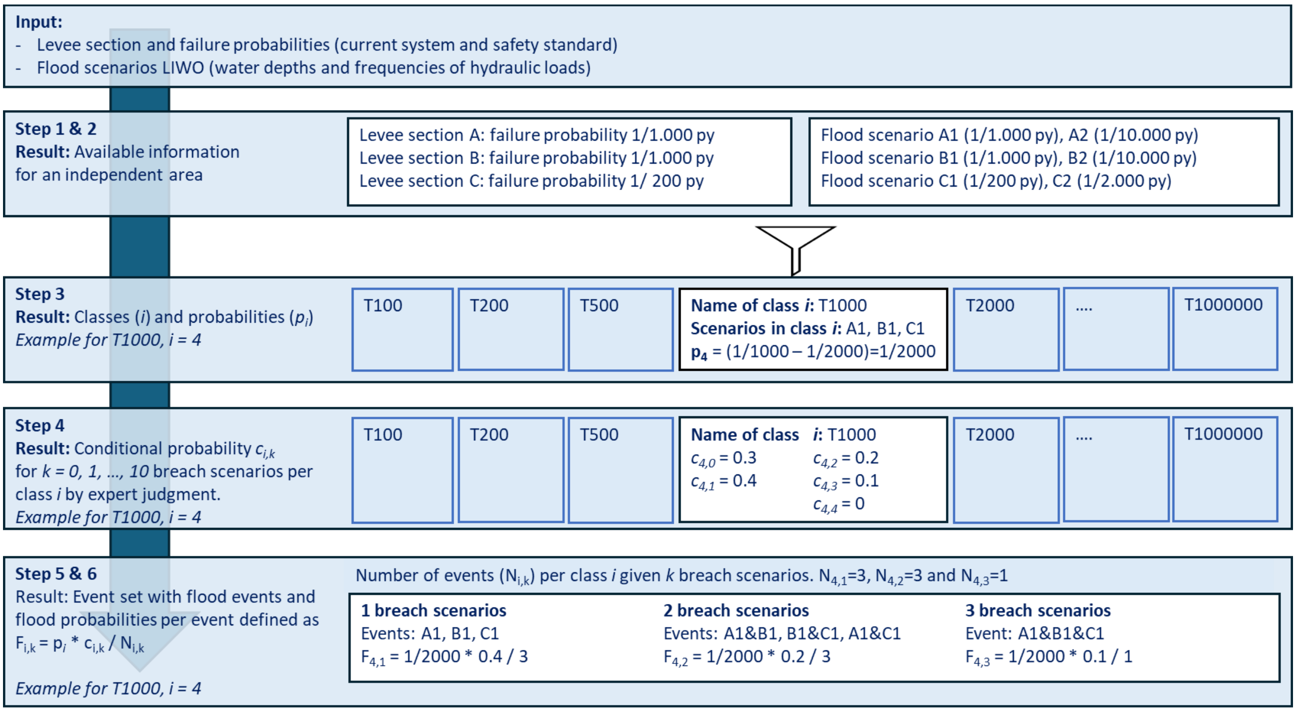

Figure 1: Flow chart of the BREACH-METHOD illustrated by an example for one class (T1000) and one independent area.

3.3 New flood event set

Table 2 presents the number of unique flood events (~5 million) based on the BREACH-METHOD per area. The LIWO database consists of nearly 1,900 scenarios.

Table 2: Number of LIWO scenarios and number of events per area.

Arean	Number of breach locations in LIWO	Number flood scenarios in LIWO	Number of flood scenarios in BREACH-METHOD
Upper river area (Meuse)	(23)	64	8859
Upper river area (Rhine)	(97)	258	623047
Lake IJssel area	(73)	213	148883
Coast south	(180)	575	1344582
Coast middle	(23)	71	2099
Coast North	(49)	174	35427
Lower tidal area	(177)	518	2921516

4 Results

4.1 Probability of flooding for different areas and the Netherlands

The BREACH-METHOD has been applied to reassess the probability of flooding occurring in the Netherlands, as well as the probability of flooding within each independent area (see Table 3). Notably, the BREACH-METHOD yields lower flood probabilities compared to approaches that consider only system behavior (as in Table 1). This is because the method also incorporates failure definitions, emergency measures, and the possibility of multiple breaches across different levee sections. The results clearly demonstrate that each of these assumptions significantly influences the overall risk estimates.

The probability of flooding within a single independent area is substantially lower than the national flood probability. The BREACH-METHOD results in a consistent reduction of flood probability across all areas, both under current conditions and for the 2050 scenario. The only exception is the flood probability for the Coast Middle area under current conditions. In this case, the newly estimated failure probabilities are higher than previous estimates, primarily due to the treatment of coastal flood defenses such as dunes. In LIWO, these structures are assigned extremely low failure probabilities, often lower than both the applicable safety standards and expert judgment. For the Rhine River, Lake IJssel, and the tidal region, the flood probability under current conditions is reduced by a factor of more than 40. This reduction is partly attributable to the considerable number of levee sections in these areas, which—in the DPV method—accumulate to a high aggregate failure probability per water system. Along the coast, the relative impact of the BREACH-METHOD on flood probability is generally smaller than in inland areas.

Table 3: Flood probabilities for the Netherlands and per independent areas for the current situation and in 2050 with the DPV method and BREACH-METHOD.

Area	Probability of flooding DPV method	Probability of flood BREACH-METHOD	Reduction factor	Probability of flooding DPV method	Probability of flooding BREACH-METHOD	Reduction factor
	Current climate			2050		
Upper river area (Meuse)	1/40	1/300	8	1/250	1/400	2
Upper river area (Rhine)	1/7	1/300	44	1/30	1/300	10
Lake IJssel area	1/12	1/800	67	1/15	1/800	55
Coast south	1/18	1/300	16	1/23	1/300	13
Coast middle	1/8.200	1/4.000	0.5	1/250	1/4.000	15
Coast north	1/77	1/300	4	1/43	1/300	7
Lower tidal area	1/8	1/400	50	1/17	1/400	24
Netherlands (upper - lower limit)	1/3 – 1/20	1/57-1/91	21-4.5	1/5 – 1/30	1/58 – 1/89	12-3

The national flood probability for the Netherlands can also be estimated using the BREACH-METHOD, under the assumption that the defined areas are independent. Under current conditions, the national flood probability is reduced to 1/57 per year, compared to 1/3 per year when using the DPV method, a reduction by a factor of 21. For 2050, the probability is 1/58 per year, down from 1/5 per year, representing a 12-fold reduction.

When assuming full correlation within coastal areas and full correlation within the upper river systems, the reduction is smaller, as expected. Under this assumption, the flood probability for the Netherlands is reduced to 1/91 per year under current conditions, compared to 1/20 per year with the DPV method—approximately a 4-fold reduction. For 2050, the national flood probability becomes 1/89 per year, which is roughly three times lower than the DPV-based estimate of 1/30 per year.

4.2 Failure probability at breach locations

The failure probability of an area is the result of the weakest link of all levee sections. The impact on the flood probability of an area is not influenced by system behavior because the flood probability of the system is determined by the failure probability of the weakest link. The failure probability of the second weakest link however is influenced by system behavior. Also the other elements (failure definition and emergency measures) influences the failure probability, including the failure probability of the weakest link. Figure 2 shows the assessed impact of the BREACH-METHOD for each individual breach location, note that each area holds multiple breach locations:

- Part A presents the differences between DPV and the BREACH-METHOD for 2050. We present the impact on the failure probability per breach location by a multiplicative factor.
- Part B presents the difference between the current climate and 2050 using the BREACH-METHOD. The figures show the impact of climate change in 2050 (which can increase flood risk) but also for the foreseen levee reinforcements which must be implemented before 2050.

Panel A of Figure 2 clearly shows that the impact on the failure probability per levee (sub)section can vary far more than the impact to the flood probability of an area or the Netherlands. Panel B shows that due to reinforcements, the failure probability of several breach locations will be reduced by 2050. Panel B also shows that for some sections the failure probability does increase. The increase occurs because it is assumed that the failure probability of each levee section in 2050 is exactly equal to the safety standards. In contrast, in the current situation, the failure probability is based on the actual strength of the levees, which may be significantly lower or higher than the safety standards. For example, in the Coast South area, the current failure probabilities are much lower than the safety standards for many sections (see Waterveiligheidsportaal, 2024). Only some weak spots will require reinforcements and although climate change will increase the failure probability of the other levee sections still have a failure probability less than the safety standards.

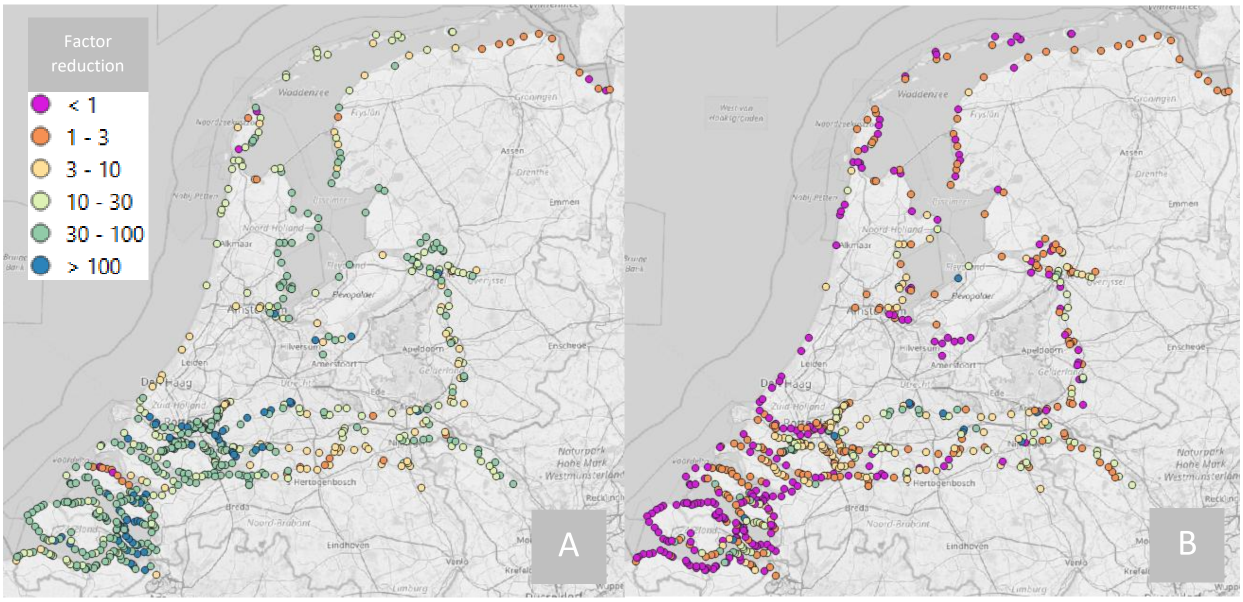

Figure 2: Factor reduction in failure probability per breach location. A: The BREACH-METHOD compared with the DPV method model for 2050. B: The 2050 situation compared with the current situation for the BREACH-METHOD. A factor <1 means that the flood probability increases. Please note that in 2050 the failure probabilities of levees are assumed equal to the safety standards, while in the current situation the probability can be much lower or higher.

4.3 Impact on local exposure by risk profiles

A flood risk profile quantifies the exceedance frequency of flood depths at a specific location. Such a profile is constructed by evaluating all potential flood events relevant to that location, each characterized by a specific flood depth and associated probability. By combining these values, the exceedance frequency of various flood depths can be derived. Figure 3 presents flood risk profiles for six locations in the Netherlands, both under current conditions (reflecting the present state of the levees) and under projected conditions for 2050, which account for climate change and assume that all levees comply exactly with the applicable safety standards. The selected locations represent different flood-prone regions: Sexbierum (coastal north), Wissenkerke (coastal south), Empel (upper Meuse), Bleskensgraaf (lower tidal area), Lelystad (Lake IJssel) and Rijnenburg (upper Rhine).

Each location is subject to a distinct set of flood scenarios, each with a unique combination of flood depth and exceedance probability. The flood risk profiles reveal spatial differences in both the frequency and severity of potential flooding. In many cases, the choice of method (DPV vs. BREACH-METHOD) has a greater impact on the exceedance frequencies than the difference between the current and the 2050 scenario, even when the latter includes both climate change and levee reinforcements. The 2050 profiles represent maximum future exceedance frequencies, as the safety standards require that levees be reinforced to address climate-induced increases in hydraulic loading.

Flood risk profiles also offer insight into correlations between properties that may be exposed to the same flood event. Since the BREACH-METHOD includes both single and multiple breach events, each property can be linked to a set of scenarios with known flood depths and probabilities. The BREACH-METHOD enables the creation of portfolio-level flood risk profiles, where cumulative exposure can be assessed while accounting for spatial correlations. Such profiles are valuable for estimating maximum potential damage, supporting investment strategies, and allocating risk. Additionally, by applying damage curves and fatality curves, the flood risk profiles can be extended to quantify expected economic losses and loss of life. The information about probabilities and consequences supports decision makers to select and prioritize flood risk mitigation and adaptation measures.

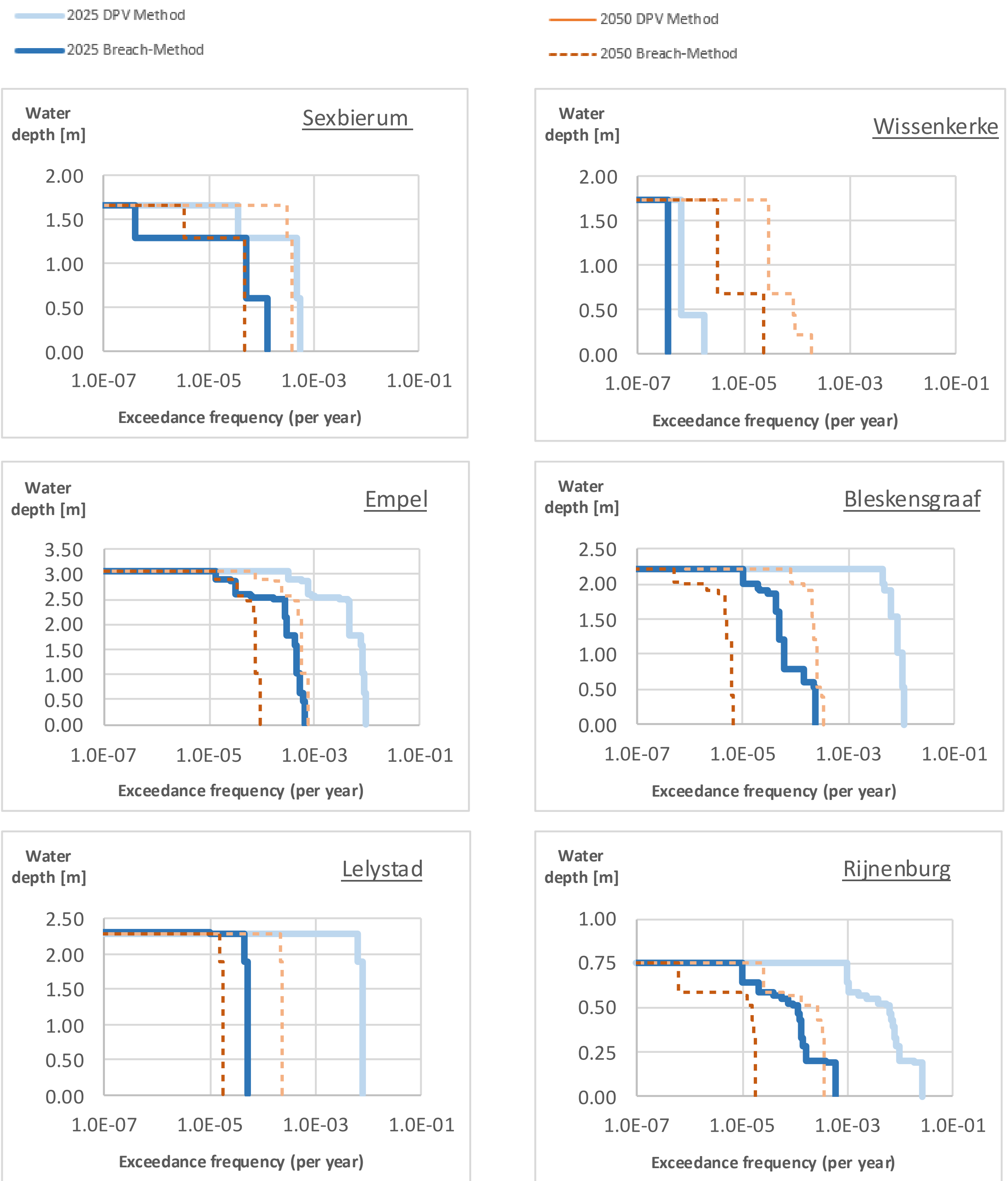

Figure 3: Flood risk profiles following the DPV method (light blue line) and the BREACH-METHOD (orange line) for the current climate.

4.4 Sensitivity analyses

In the BREACH-METHOD, expert judgment is used to adjust risk analyses for several assumptions embedded in the DPV method, which was originally developed to establish new safety standards. Because the individual contributions of these assumptions cannot be isolated directly, a sensitivity analysis is conducted to identify the most influential modelling choices (see Table 4).

The first key modelling choice concerns the definition of areas and probability classes. This definition ensures that the overall flood probability in an area does not exceed the failure probability of its weakest levee section. The areas are delineated based on exposure to storm surges or extreme river discharges. The upper and lower bounds presented in this study demonstrate the effect of assuming either full statistical independence or complete correlation between coastal and river systems. For the Netherlands, this results in a national flood probability ranging from 1/57 to 1/91 per year under current conditions, and from 1/58 to 1/89 per year in 2050, under the assumption that all levees meet their safety standards.

The second key modelling choice involves the conditional probabilities derived from expert judgment to correct for modelling limitations. For example, if experts estimate a 50% chance of a single breach and 50% chance of no breach, the contribution to risk is effectively halved. If the estimated conditional probability is only 10% for one breach and 90% for no breach, the contribution to risk is reduced by a factor of ten. This demonstrates how expert-based assumptions significantly influence overall risk estimates.

Despite potential local variations, the difference in national flood probability between the current situation and 2050 is relatively small. The small difference is because it is assumed that by 2050 all levees exactly comply with the safety standards. Each independent area contains levee sections with different safety levels (e.g., 1/100 or 1/300 per year), but these are generally small areas associated with limited potential damage. Additionally, the actual failure probability of many levee sections is expected to be lower than the standard, since system behavior, emergency measures, and key elements of the failure process are not fully captured in the current assessment methods.

The impact of system behavior on flood consequences is relatively limited. Riedstra (2018) demonstrated that, on average, flood damage increases by a factor of only 0.35 when comparing scenarios with a hydraulic load equal to the safety standard to those with a ten times more extreme load. Given the demonstrated sensitivity of the BREACH-METHOD to flood probabilities and the underlying modelling assumptions, these factors are more influential in determining overall flood risk than the uncertainties in flood consequences resulting from system behavior. The limited impact on flood consequences highlights the importance of improving failure probability estimation.

Table 4: Flood probabilities for the Netherlands and per independent areas for the current situation and in 2050 with the current method and BREACH-METHOD.

Area	Probability of flooding upper limit	Probability of flooding lower limit	Probability of flooding upper limit	Probability of flooding lower limit
	Current climate		2050	
River area	1/146	1/287	1/164	1/287
Coastal area	1/140	1/269	1/136	1/255
Netherlands (upper lower limit)	1/57	1/91	1/58	1/89

5 Discussion

Validation. The difference in flood risk estimates between the BREACH-METHOD and the DPV method can exceed the projected impact of climate change, and in some cases even surpass the effect of planned levee reinforcements. As with any model, it is essential to critically evaluate the underlying assumptions and identify opportunities for improvement. Due to the lack of empirical flood data, the current flood probability for the Netherlands is not precisely known. As a result, the BREACH-METHOD—like all other flood risk models—cannot be fully validated against observed flood events. Nevertheless, the overall flood probabilities produced by the BREACH-METHOD are considered plausible in the light of historical experience and the extensive implementation of flood protection measures. The estimated failure probabilities for the Netherlands and the independent areas, as generated by the BREACH-METHOD, cannot be rejected, instead of applying the DPV method, based on historical flood records and system reinforcements. The most recent major flood event due to primary levee failure occurred in 1953, after which the Delta Works were constructed to significantly improve coastal and estuarine flood protection. In 1995, the discharge on the Rhine River was estimated to correspond to a 100-year return period (Chbab, 1995). In 2021 the river Meuse recorded the highest discharge at Borgharen (Jonkman et al. 2023). Despite widespread evacuations, no primary levees failed. Since the 1995 event, multiple large-scale flood risk reduction programs have been implemented, including the Room for the River program, the national levee reinforcement program, targeted reinforcement of weak spots along the coast, and various other levee improvement projects. Collectively, these measures have substantially reduced failure probabilities throughout the country. At the same time, however, climate change is already affecting hydrological conditions, particularly through increased precipitation extremes (STOWA, 2019), and soil subsidence continues to pose long-term challenges to flood safety. This will result in new levee reinforcement if needed to meet the safety requirements.

Expert judgment. The BREACH-METHOD integrates statistical and physical data while explicitly incorporating expert judgment. Although expert choices also underpin the data used in the DPV method, these consequences are generally less transparent to the end user. By contrast, the BREACH-METHOD makes expert contributions explicit, compensating for conservative assumptions resulting from gaps in knowledge about physical processes. Expert input is particularly important in areas such as hydraulic interdependencies between levee sections, levee failure mechanisms, and the effectiveness of emergency measures. While system behavior can be modeled (e.g., Van Mierlo et al., 2007; De Bruijn et al., 2014; Curran et al., 2020), failure probabilities derived from fragility curves and current levee assessment procedures remain imperfect. The results of the models which apply system behavior for the Netherlands do not result in a correct overview of the risk in the current situation or the expected situation in 2050, these models only result in a theoretical assuming the failure probability to be known. For financial flood risk assessments, expert judgment is indispensable—especially given that the standard methods used for statutory levee assessments (ENW, 2024) do not yet yield realistic failure probabilities for all levees and emergency measures are not taken into account. As a result, current failure probabilities for existing systems tend to be overestimated, while newly designed levees often achieve lower actual failure probabilities than officially assumed.

In the BREACH-METHOD we structured the group decision-making process through the Delphi method (Linstone & Turoff, 1975; Rowe & Wright, 1999), offering a systematic and effective way to address complex, uncertain problems. The method can be further strengthened by involving a broader set of experts, which may also improve acceptance among stakeholders. Alternative approaches, such as Cooke's method, can be considered, as it applies non-uniform expert weighting to account for varying levels of expertise (see Rongen et al., 2022). In addition, expert assessments should be periodically updated as new knowledge about physical processes becomes available. The methodology could also benefit from more extensive use of physical data to inform and support expert input. Currently, all combinations of breaches within an area are considered, even when they occur in close proximity. In practice, however, a breach can reduce water levels locally, thereby lowering the likelihood of nearby breaches. Incorporating local hydrographs into the modelling framework would enhance the accuracy of flood risk profiles, particularly at the local level, without substantially changing national or regional flood probability estimates.

Failure probability in 2050. The assumption that all levee sections will exactly meet their safety standards in 2050 is a conservative one. In reality, some levees already have extremely low failure probabilities, and even under projected climate change scenarios, many will continue to perform well below their prescribed thresholds. Also, the moment of the reinforcement is relevant. Under Dutch law levee assessments are required every 12 years. If a levee does not meet the standard a reinforcement is made, the reinforcements must account for climate projections over a 50–100 year horizon (ENW, 2017). As a result, the average failure probability of a levee is typically lower than the safety standard for most of its design life, approaching the standard only toward the end of its service period. To ensure more accurate risk estimates, future assessments should be updated using the latest levee performance data, and any 2050 risk evaluation should be based on actual levee conditions rather than assuming universal compliance with regulatory standards.

Application of BREACH-METHOD for spatial planning. A key question is whether the BREACH-METHOD should also be applied to determine acceptable levee failure probabilities and to inform spatial planning decisions. Acceptable failure probabilities are typically derived from risk assessments that balance the costs and benefits of flood protection measures. Applying the BREACH-METHOD would result in lower estimated failure probabilities at the levee-section level, leading to less stringent safety standards compared to those derived using the DPV method. This would, in turn, reduce the expected benefits from further risk reduction and slightly lower estimates of local individual risk. Nevertheless, flood defenses remain the most cost-effective layer in the Dutch multi-layer safety framework. Climate change is expected to increase hydraulic loads on levees, which may justify a more conservative approach in spatial planning. In response, the Dutch government has recently introduced a framework for flood risk evaluation in urban development (IenW, 2024), which classifies areas based on the required level of protection. However, the continued use of the DPV method, despite its tendency to overestimate flood risk, could lead to unintended consequences. These include unnecessarily reduced property values, and inflated insurance premiums and mortgage costs, without corresponding societal benefits. On the other hand, current debates about the rising costs of levee reinforcement programs (H2O, 2025) underscore the potential for cost savings if the BREACH-METHOD were adopted in determining protection standards.

Climate change and flood scenarios. With respect to flood consequences, climate change is primarily reflected in the increased frequency of flood events. Existing flood scenarios are based on hydraulic loads from rivers and the sea, and climate change increases the probability of these loads occurring. However, such events are not expected to exceed the safety standards, and the overall scenario set may even contract under climate change, especially for the most extreme events. Adding new, climate-adapted flood scenarios would primarily affect low-probability events and slightly expand flood extents. While developing a new dataset with approximately 1,900 climate-adjusted scenarios would be ideal, it is unlikely to significantly change the overall flood risk compared to the uncertainty in flood probability. The reason is that only a limited number of new extreme events would be added, and the increase in flood extent would be modest compared to the areas already affected in current scenarios. Moreover, the reduction in failure probabilities achieved through levee reinforcements often outweighs the potential increase in consequences due to more frequent extreme hydraulic loads. Riedstra (2018) showed that, based on the current LIWO dataset, the effect of increased hydraulic loads on flood extent and depth is relatively minor. On average, flood damage increases by 35% if the exceedance frequency of the hydraulic load increases by a factor of 10. As a result, the current dataset of flood scenarios remains appropriate for future climate assessments—particularly because the anticipated risk reduction from levee reinforcements through 2050 is expected to far exceed any increase in flood consequences due to climate change.

6 Conclusion and recommendations

This study demonstrates that applying the DPV method for financial flood risk analyses results in overestimated flood probabilities. This overestimation of risk might influence housing markets, insurance and economic stability negatively. In contrast, the BREACH-METHOD produces flood exposure estimates that are more consistent with historical flood events and the extensive flood protection measures implemented in the Netherlands. The resulting flood event set provides a more refined and realistic quantification of national flood risk. Additionally, the BREACH-METHOD enables detailed analysis of the tail of the exposure distribution—at the level of individual properties, across property portfolios, and in the context of solvency and stress-testing frameworks for financial institutions.

Available flood risk data have been adjusted to correct for conservative assumptions related to levee failure probabilities and the exclusion of system behavior and emergency measures, factors that previously led to overestimated risk assessments. The application of the BREACH-METHOD provides a more realistic evaluation of flood risk across the Netherlands. The impact of the BREACH-METHOD varies by region and individual properties. In particular, areas such as the River Rhine, Lake IJssel, and the lower tidal region show reductions in flood probability by a factor of more than 40 compared to estimates based on the DPV method. For individual properties, the difference in flood risk can be even more pronounced, as each breach affects only a portion of the area, and the number of relevant breach scenarios per location is limited.

We strongly advocate for an evaluation of the BREACH-METHOD for application in other policy domains, such as land use planning, to ensure that decisions are grounded in realistic and credible risk estimates. As climate change progresses and adaptation efforts require long-term investments, accurate and transparent risk assessments are crucial for effective communication, fostering public trust, and stakeholder engagement. Moreover, persistent overestimation of flood risks may erode confidence in both the data and the decision-making processes that rely on these assessments.

Future research should explore the integration of new physical knowledge with alternative structured expert judgment methods, such as Cooke's method, which applies non-uniform weighting to expert input. This approach could also be used to quantify the local contribution of individual modelling assumptions to overall risk reduction, thereby enhancing the transparency and traceability of expert-based adjustments. The BREACH-METHOD could be extended to include other types of flooding, such as those from regional flood defenses, unembanked areas, or pluvial (rainfall-induced) flooding, which may also affect property values and financial risk assessments. While these events may exhibit some correlation with primary flood defense failures, their frequencies are typically higher, and their flood extents and depths are generally smaller. Although highly relevant for land use planning and property-level financial decisions, these types of flooding are less critical for national-level stress-testing of countries or financial institutions. We also recommend examining the potential impact of long-term transitions in flood risk management strategies prompted by climate change, including rising sea levels, more extreme river discharges, and intensified precipitation. These transitions raise fundamental questions about the long-term habitability of delta regions. The Dutch Sea Level Rise Knowledge Programme has outlined several alternative strategies that may, over time, replace the current flood protection approach (Van Alphen et al., 2025). Such transitions could also have far-reaching implications for financial risk assessments and investment strategies, necessitating a deeper understanding of their effects.

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Data access statement

The data acquired in the study and used/analyzed/reported in this paper can be found on the LIWO website (LIWO, 2024).

Declaration of interests

The author reports no conflict of interest.

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Appendices

6.1 History of flood risk management in the Dutch Delta

Approximately thirteen centuries ago, the inhabitants of what is now the Netherlands began constructing levees to protect against flooding. Today, the country is one of the most well-protected deltas in the world. The last significant flood event occurred in 1953, marked by multiple levee breaches and about 5% of the Netherlands was flooded. The catastrophic North Sea flood was triggered by a severe storm surge and the failure of primary flood defenses, resulting in an estimated 1,835 casualties in the Netherlands. In the aftermath of the 1953 disaster, substantial investments were made in the Dutch levee system and river management, significantly reducing the likelihood of future flooding. Furthermore, the government incorporated the Delta Commission's safety standards into the Dutch Water Act, which were based on the flood risk analysis conducted by Van Dantzig (1956).

In 1995, water levels in the Rhine and Meuse rivers reached levels corresponding to a 100-year return period (Chbab, 1995). Although unembanked and unprotected areas were flooded, the primary flood defenses remained intact, with no breaches occurring. In response to this event, the government swiftly launched the Room for the Rivers program (van Vuren et al., 2015) and undertook levee improvements to reduce the likelihood of failure (Deltawet Grote Rivieren, 1995).

In 2017, new safety standards (see were established based on a flood risk approach (referred to as DPV method) and the anticipated consequences of a flood in 2050 (Kok et al., 2017). The levees, divided into 234 sections which have an average length of 15km, must meet these new safety standards from now until 2050. Consequently, the primary flood defenses are assessed every twelve years by the water boards and reported to the Dutch Parliament. If reinforcements are necessary, they are incorporated into the national levee reinforcement program. Reinforced levees are designed for a lifespan of 50 to 100 years, taking climate change into account. Figure 5 shows the failure probabilities of the Dutch levees for the current situation and the safety standards. Figure 4 shows the flood extent based on a combination of more and less extreme events for all sections of the Dutch primary flood defenses. However, this map significantly overestimates the flood extent of a single event, as it includes flooding in coastal, lake, and river areas, each driven by different factors. Thus, not all flood-prone areas will flood during a single event. The worst credible flood (with a likelihood of 1/1,000,000 per year) affects only about 10% of the Netherlands (Ten Brinke et al., 2010; Kolen & Wouters, 2007), in this study also areas have been defined which are assumed to be independent, these are highlighted in Figure 4.

Figure 4 : Flood extent as a result of failures of primary flood defenses, based on the LIWO (2024) web portal, including independent areas (the dotted line describes the borders of these areas) described in section 3.2.2 and the six locations discussed in section 4.3. The red lines show the primary flood defenses.

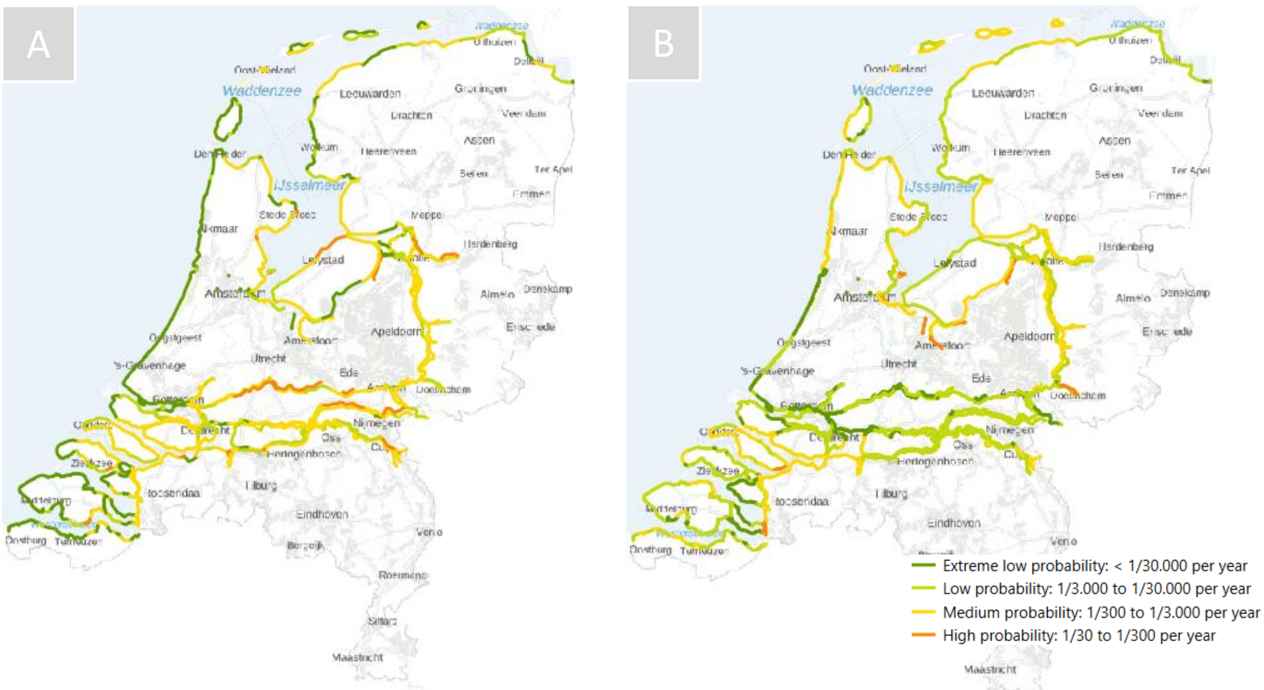

Figure 5: Failure Probabilities and Safety Standards of Primary Defenses in the Netherlands. A: Current failure probabilities. B: Minimum failure probabilities based on safety standards. Each levee must meet this requirement by 2050. In the case of future climate change, levees will need to be reinforced to comply with these standards. Therefore, this failure probability can be considered the maximum allowable probability of failure.

6.2 Assumptions in DPV method

6.2.1 System behavior that influences the failure probability levees

System behavior, also referred to as hydraulic interdependencies, describes the phenomenon where breaches in flood defenses lead to reduced water levels, thereby lowering the probability of subsequent failures in other levee sections (Van Mierlo et al., 2007; De Bruijn et al., 2014; Curran et al., 2020). Related concepts include short-cutting, where water follows an easier path after an initial breach, and cascade effects, where the impact of one failure influences the likelihood or consequences of others. In the DPV method, system behavior is not accounted for; all 234 levee sections are treated as statistically independent. This means that a breach in one section does not affect the failure probability of others, even though, in practice, a drop in water level due to an initial breach would reduce hydraulic pressure and lower the likelihood of further failures. While it has been shown that this assumption has a limited effect on safety standards (Dupuits, 2019), it introduces conservatism in flood risk estimates.

In terms of cost-benefit analysis, the DPV method accounts for multiple breach events only within individual levee sections, not across multiple sections. This is done by applying a "maximum scenario," in which all possible breaches or the worst-case flood scenario within a section are modeled using a hydraulic load with a frequency ten times lower than the normative design scenario. Additionally, the local individual risk component of the DPV method aggregates flood probabilities from multiple potential breach locations, again assuming independence among them. However, both historical evidence—such as the 1953 North Sea flood—and previous research (De Bruijn et al., 2014; Ten Brinke et al., 2010) confirm that multiple simultaneous breaches across different levee sections can and do occur.

The effect of neglecting system behavior in failure probability estimation is particularly important when modeling the distribution of exposure. Consider the simple system shown in Figure 6, in which a single levee section protects a polder area from river flooding. If this levee is designed to a safety standard of 1 in 1,000 per year, then the flood probability of the protected area is also 1 in 1,000 per year. Now consider a more complex system consisting of two polders (North and South) located along the same river, protected by six levee sections, each with the same 1 in 1,000 per year safety standard. These standards are defined independently per section, meaning that the failure of one section does not influence the assigned standard of another. A naïve summation of individual failure probabilities would suggest a total system flood probability of 1 in 167 per year (i.e., 6 × 1/1,000). However, this does not reflect the true behavior of the system.

All levee sections are designed to withstand a water level associated with a 1 in 1,000 year event. Thus, the overall system—in terms of maximum hydraulic load—cannot have a higher probability of failure than this threshold. In other words, system behavior does not affect the initial failure probability of the entire system, because the probability that the first levee fails is governed by the hydraulic load and independent failure assumptions. However, the flood probability of individual polders in the North or South or the flood probability of a specific location is affected by system behavior. If, for example, the most upstream levee section fails during a 1-in-1,000-year river discharge, the resulting breach would cause downstream water levels to drop, thereby reducing the hydraulic load—and hence the failure probability—for the remaining levee sections. Since all levees are designed under the assumption of statistical independence, this interdependency is not captured in standard assessments. As a result, risk estimates, particularly those related to the tail of the exposure and damage distribution, are systematically overestimated when system behavior is ignored.

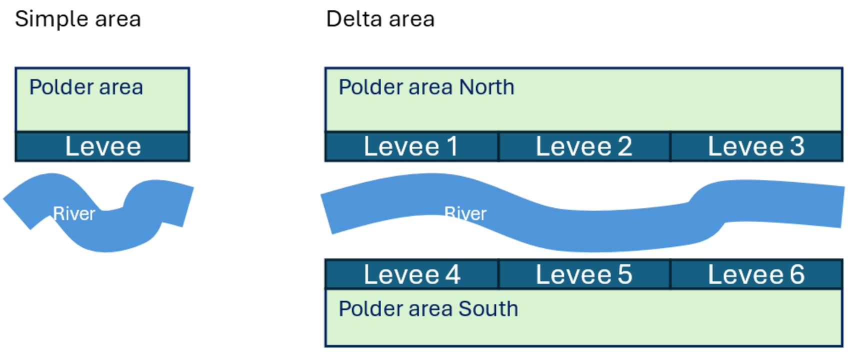

Figure 6: Example of a Simple and Complex System. Each levee section has a failure probability of 1 in 1,000 per year, assuming that these levees are independent.

6.2.2 System behavior is neglected in the flood consequences

System behavior also influences flood extent and flood depth within a given area. In the DPV method, all flood scenarios—available through LIWO—are developed under the assumption that no other levee failures occur simultaneously. However, in the event of a breach, especially in riverine areas, but also in lake systems and lower tidal zones, the water level in the system will drop as water flows into the breached polder. As a result, part of the river discharge or stored water volume is diverted into the flooded polder and is therefore no longer available to inundate a second polder downstream. This effect is particularly relevant in delta areas where multiple polder regions are hydraulically connected. Additionally, a lower water level in the river following an initial breach may also reduce the breach width and thus limit the volume of water that can enter the polder area. Despite this, Riedstra (2018) showed that, for the current set of flood scenarios in LIWO, the impact of higher hydraulic loads on flood extent and depth is relatively small. On average, flood damage increases by only 35% when the exceedance frequency of the hydraulic load increases by a factor of 10. Consequently, the current flood scenario dataset has also been deemed suitable for future climate assessments, as the risk reduction achieved through levee reinforcements by 2050 is expected to significantly outweigh the potential increase in flood consequences due to higher hydraulic loads.

6.2.3 Failure is defined as the beginning of the failure process

A levee failure is generally defined as an event in which a breach forms and expands, resulting in uncontrollable water flow through the levee. The publicly available LIWO portal provides the best available estimates of failure probabilities for the current situation at the levee section level. These estimates are based on the national flood risk analysis (Jongejan & Maaskant, 2015) and account for the effects of the Room for the River program and recent levee reinforcements.

In theory, failure probabilities represent the probability of flooding. However, the failure probabilities reported—particularly for newly designed or reinforced levees—only reflect the initial stages of the failure process. This limitation arises from incomplete understanding of the physical processes, and the use of conservative modelling assumptions to ensure safety (ENW, 2024). As a result, the actual failure probability is lower than the calculated values.

Several key aspects of the levee failure process are not included in the current models due to the absence of robust quantitative formulations. Figure 7 illustrates which components of piping and erosion processes are not yet captured. Consequently, the current failure definition is conservative, and the calculated failure probability overestimates the actual flood probability (or safety standard), as levees typically possess additional structural resilience not accounted for in formal assessments.

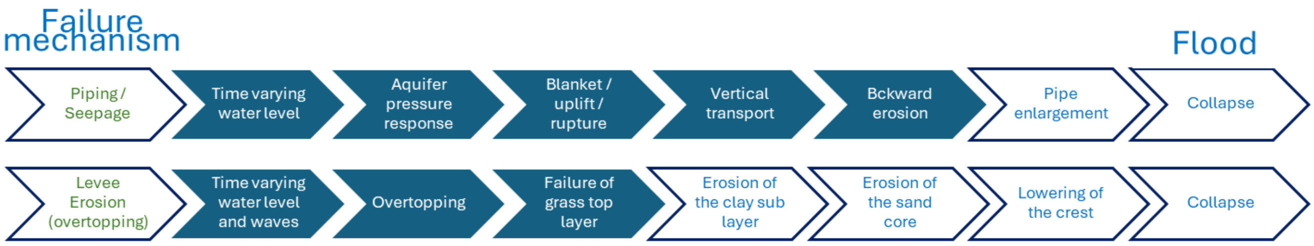

Figure 7: Description of failure mechanisms piping (based on Pol et al. (2024)) and erosion due to overtopping (based on Deltares (2018)). The filled boxes represent aspects that are considered in the assessment of levee failure probability and in the design of new levees. In contrast, the white boxes indicate elements that are not considered in the assessment of failure probability according to the Dutch standard approach (IenM, 2017).

6.2.4 Emergency measures are neglected

Emergency measures are currently not considered when determining the failure probabilities of flood defenses. However, emergency measures are an integral part of flood risk emergency plans for all water boards. During the 2021 flood in Limburg, emergency measures successfully prevented immediate flooding (Jonkman et al., 2023; Endendijk et al., 2023; Endendijk et al., 2024). Examples of such measures include ringing boils with sandbags to create counterpressure, heightening levees by placing sandbags and deploying temporary barriers that provide immediate protection. Although the time required to implement emergency measures is crucial, they can reduce flood probability by a factor of 1.5 to 4 (Lendering et al., 2016). The reduction in the failure probability of a levee section can be described by three components:

1. Detection – Requires forecasting and early warning to activate the crisis organization or mobilize citizens.
2. Implementation – Installing the measures, which depends on coordination and availability of (trained) personnel.
3. Operation – The effectiveness of measures (e.g., sandbags being washed away or overtopped).

6.2.5 Impact of flood risk method for financial sector

This section discusses the impact of applying the DPV method to estimate the probability of exposure to flooding under current conditions and in 2050, if all levees meet their design safety standards (i.e., their failure probability equals the safety standard). Flood probabilities are determined for the Netherlands as a whole and the independent areas as considered in this research.

The results presented here are based on a DPV approach and do not yet incorporate system behavior, emergency measures, and interdependence in the failure probability of a levee section and the scenario probability of an event. Two contrasting approaches to applying the DPV method are compared:

- Fully independent levee sections (within an area): The probability of flooding in a given area is calculated as the sum of the failure probabilities of all levee sections in that area—this represents the standard DPV approach.
- Fully correlated levee sections (within an area): The flood probability of an area is taken as the maximum failure probability among its levee sections. This approach illustrates the potential effect of system behavior on failure probability, though it applies only to the frequency of flooding and not the distribution of exposure within the area.

At the national level, the assumption of full independence between areas may not be realistic for extreme events, where physical processes introduce correlations between regions. To account for this, national flood probabilities are presented as a range:

- Lower bound: Assumes full statistical independence between areas.
- Upper bound: Assumes full correlation for the coastal areas (South, Middle, and North) and full correlation for the upper river areas (Meuse and Rhine).

Table 5 shows that flood probabilities are higher under the independence assumption than under the correlated assumption. For the Netherlands as a whole, the flood probability ranges from 1 in 3 to 1 in 20 per year under current conditions, and from 1 in 5 to 1 in 30 per year if all levees meet their safety standards by 2050. For the lower bound, correlation within the Upper Rhine River and South Coast areas plays a significant role. If the flood probability in these regions is as low as 1 in 300 to 1 in 1,000 per year, then the national flood probability could be as low as 1 in 40 to 1 in 50 per year.

Table 5: Flood probabilities for the Netherlands and per independent area for the current situation and in 2050 applying the DPV method.

Probability of flooding per year	Current state of levees (year 2023)		Safety standards (year 2050)	
Area (number of sub levee sections)	Fully independent	Fully correlated	Fully independent	Fully correlated
Upper river area (Meuse) (23)	1/40	1/217	1/250	1/1000
Upper river area (Rhine) (97)	1/7	1/100	1/30	1/100
Lake IJssel area (73)	1/12	1/68	1/15	1/100
Coast south (180)	1/18	1/61	1/23	1/100
Coast middle (23)	1/8.200	1/25.381	1/250	1/1000
Coast north (49)	1/77	1/358	1/43	1/300
Lower tidal area (177)	1/8	1/126	1/17	1/300

When we assume these areas to be independent also the flood probability for the Netherlands can be defined: 1/3 per year for the current climate and 1/5 per year for 2050.

6.3 BREACH-METHOD

6.3.1 Step 1: Available information about flood probabilities and scenarios

The BREACH-METHOD is based on the LIWO data for flood probabilities (current climate and 2050) en flood consequences (spatially defined maximum flood depths) per breach location given the hydraulic load.

For 2050 we assume that all levees will exactly meet the safety standard, which is a conservative assumption, as each reinforcement is based on a life cycle of 50 to 100 years. Also, some levees have a failure probability far less than the safety standard because of historic choices. This means that in 2050 several levee sections are expected to have failure probabilities far lower than the safety standards. Climate change is considered: due to more extreme river discharges and accelerated sea level rise, the likelihood of flood events is expected to increase by 2050 (note that if needed also levees are reinforced given the maximum allowed flood probability). For 2050, we assume an increase in hydraulic load frequency because of climate change. This increases the frequency of a flood scenario so these might be added to a different class (see step 3). Therefore, the W+ scenario is used as earlier described.

The failure probability of a breach location is equal to the failure probability per levee subsection. If a levee section contains multiple breach locations (levee subsections), the failure probability of each breach location is adjusted based on the length of the section according to the FLORIS project (Jongejan & Maaskant (2015). For example, a levee section with a safety standard of 1/1,000 per year and a length of 10 km contains two breach locations representing the first and second 5 km. In this case, both breach locations have a failure probability of 1/2,000 per year.

6.3.2 Step 2: Zoning of independent areas

The nature of the threat (e.g., river discharge, storm surge, lake levels) and the relationship between these factors determine which areas are simultaneously threatened by floods and which are not. Flood levels on the Wadden Sea and the Meuse are considered independent, as storm surges on the Wadden Sea are unrelated to river discharge in the Meuse. Based on the nature of the threat, eight areas can be distinguished for primary flood defenses, following a similar approach to that used in the preparation of worst credible flood scenarios (Ten Brinke et al., 2010; Kolen & Wouters, 2007). In total, we identify eight distinct areas based on the worst credible events (Limburg is excluded, as most levees have a low safety standard, and overtopping is already considered in the downstream hydraulic loads):

- Upper River Area (Meuse) – High discharge levels on the Meuse.
- Upper River Area (Rhine) – High discharge levels on the Rhine.
- Lake IJssel Area – Storm surge in Lake IJssel.
- Coast South – Storm surge in the North Sea / Western Scheldt at the Southwestern Delta.
- Coast Middle – Storm surge in the North Sea along the Holland coast.
- Coast North – Storm surge in the North Sea and Wadden Sea.
- Lower Tidal Area – Combination of high discharge and storm surge in the North Sea.

6.3.3 Step 3: Classification of flood scenarios by probability.

The failure probabilities per levee section are point estimates that describe the expected annual failure probability. The probability combines multiple extreme and less extreme events in which a levee fails. Additionally, these levee sections are combined with flood scenarios, using the frequency of hydraulic loads from these flood scenarios as a boundary condition.

For all areas, we define different probability classes to group flood scenarios based on failure probability of a levee. We have established nine probability classes (see Table 6). The lower and upper limits of these classes are defined using a logarithmic scale. E.g., class T200 has representative value $r_2 = 1/200$ and ranges from 1/141 to 1/316. The probability of class i is defined as $p_i = 1/r_i - 1/r_{i+1}$, where r_i is the representative value of class $i = 1, \ldots ,9$ and $\mathrm{r}_{10} = 0$.

Per breach location, only one scenario is assigned to a probability class. Per class, the most representative flood scenario is allocated: the flood scenario with a hydraulic load of 1/1,000 per year is used for the T1000 class and the flood scenario with a hydraulic load of 1/10,000 per year is used for the T10,000 class. The failure probability for the levee section is used as highest class, so if the failure probability of a levee section is 1/1,000 per year no flood scenarios of classes with a higher frequency are taken into account. If the frequency of the hydraulic load of a scenario does not match with the probability classes, the flood scenario with the closest exceedance probability is assigned to this class.

To account for events with four or more breaches, we developed separate "maximum" flooding scenarios for each probability class and area. Each maximum scenario represents an event where all single-breach scenarios within a given area occur for a specific probability class. The use of the maximum scenario limits the size of the event set, this choice impacts the tail of the distribution but because of the low frequency these are not relevant for pricing and solvency (e.g., EIOPA focuses on 1/200 per year events).

Table 6: Definition of the probability classes.

Name	Representative value (r_i)	Upper bound	Lower bound	Probability of class (p_i)
T100	1/100	1	1/141	1/200
T200	1/200	1/141	1/316	3/1000
T500	1/500	1/316	1/707	1/1000
T1000	1/1000	1/707	1/1414	1/2000
T2000	1/2000	1/1414	1/3162	1/3333
T5000	1/5000	1/3162	1/7071	1/10000
T10000	1/10000	1/7071	1/31623	9/100000
T100000	1/100000	1/31623	1/316228	9/1000000
T1000000	1/1000000	1/316228	0	1/1000000

6.3.4 Step 4: Estimation of conditional probabilities for zero to multiple breaches per class

The conditional probability of one or more levee breaches occurring during a flood event, given a specific return period for each area, was determined using a structured Delphi approach. The BREACH-METHOD applies this structured group decision-making process to address complex estimation problems, following well-established methods (Linstone & Turoff, 1975; Rowe & Wright, 1999).

The Delphi process followed these six steps:

1. Definition of the research question. The purpose was to estimate the probability distribution of the number of levee breaches under specified hydraulic conditions for each area (as defined in Step 2) and return period class (Step 3). For example, they estimated the probability of observing 0, 1, 2, 3, or more breaches given a discharge wave, storm surge, or combination of both with exceedance probabilities of 1/100, 1/1,000, ..., up to 1/1,000,000 per year. This resulted in a matrix of conditional probabilities, indicating the expected number of breaches in each area and class. These estimates are used in the BREACH-METHOD to correct for conservative assumptions in the underlying failure probability data. Example: Consider a once-in-a-thousand-year event in the lower tidal area, involving simultaneous high-water levels on rivers such as the Lek, Nieuwe Maas, Hollandse IJssel, and Haringvliet. Experts were asked the following:
    a. What is the probability that no primary flood defenses will fail under these conditions?
    b. What is the probability that exactly one flood defense fails?
    c. What is the probability that two flood defenses will fail?
    d. What is the probability of three or more breaches?

    These questions were asked for all areas and for a range of return periods.

2. Selection of experts. Five Experts were selected based on their qualifications and experience in the national flood risk assessment (Jongejan & Maaskant, 2016), risk modelling for the new safety standards, estimation of worst credible flood scenarios, policy and emergency response, flood insurance and financial risk. The process was chaired by a risk modeler with expertise in optimization and decision frameworks. All experts were affiliated with research organizations.
3. First round: Individual assessment in which each expert independently submitted their estimates for the research questions.
4. Group discussion in which all experts reviewed each other's estimates and shared their arguments and reasoning behind their values.
5. Second round: Revision of estimates by all experts, they had the opportunity to revise their assessments based on the group discussion.
6. Final round to discuss consensus. A final discussion was held to consolidate the estimates and establish the final conditional probabilities per area and class.

An example matrix for Lake IJssel is presented in Table 7 The conditional probability of zero breaches in class T2000 is 0.6. The probability of a flood, given a T2000 load, is 0.4, resulting in an annual flood probability of 1/2,000 × 0.4 = 1/5,000. The conditional probability of one breach is 0.3, implying a frequency of 1/6,667 per year for all single-breach scenarios in this class. The conditional probability of two breaches is 0.1, corresponding to a frequency of 1/20,000 per year for all two-breach events. Note that each class may include multiple breach scenarios for both the one- and two-breach cases.

The complete set of conditional probabilities resulting from the structured expert judgment process for all areas is presented in Appendix 6.4.

Table 7: Example of the conditional probability of 0, 1, 2, … breaches in an area for all probability classes.

No. of breaches	T100	T200	T500	T1000	T2000	T5000	T10000	T100000	T1000000
0	1.0	1.0	0.8	0.7	0.6	0.3	0.1	0.0	0.0
1	0.0	0.0	0.1	0.2	0.3	0.3	0.3	0.3	0.1
2	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.1
3	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.1
4	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

6.3.5 Step 5: Generating single and multiple breach events for the event set

In step 5 all flood scenarios per area are compiled for each probability class. The set of scenarios includes single-breach scenarios (equal to 1,873 LIWO flood scenarios) and multiple breach scenarios. These events were generated by combining the maximum extent and water depth of the selected flood scenarios within the same probability class.

To account for events with four or more breaches, separate "maximum" flooding scenarios were developed for each probability class and area. Each maximum scenario represents an event in which all single-breach scenarios for a given area occur within a specific probability class. For example, Table 12 shows that the conditional probability of four or more breaches in probability class 1/2,000 (T2000) is zero, making a maximum scenario inapplicable. However, a maximum scenario is applicable for T10,000.

6.3.6 Step 6: Assignment of individual flood event probabilities

In this step, the (conditional) probability of a flood event is determined based on the previous steps. The procedure for deriving these probabilities per area, class and the number of breaches using a uniformly distribution. The conditional probability for single breaches for probability class i is given by:

$$P_{i,1} = \frac{c_{i,1}}{\mathrm{N}_{i,1}}$$

where:

- c_{i1} is the conditional probability of one breach in probability class i, following from Step 4 (see e.g., Tabel 7).
- N_{i1} is the number of single-breach events in class i, following from Step 2.

For example, if three single-flood scenarios are included in class T1,000 (i=4) and the conditional probability of single breaches is 1, then the conditional probability of each single breach event in this class is $P_{4,1}$= 1/3,000 per year.

For multiple-breach events in an area, the procedure is similar. The conditional probability is given by:

$$P_{i,k} = \frac{c_{i,k}}{\mathrm{N}_{i,k}}$$

where:

- $c_{i,k}$ is the conditional probability of k > 1 breaches in class i, based on the expert judgment in Step 4.
- $\mathrm{N}_{i,k}$ is the number of scenarios with k > 1 breaches in class i, following from Step 2 and is given by:

$$N_{i,k} = \binom{N_{i,1}}{k}$$

The conditional probability of the maximum scenario is set to half of the conditional probability of four or more breaches ($\sum_{k=4}^{10} c_{ik}$). The probability of three breaches is adjusted by distributing the remaining half of the probability of four or more breaches. The probability space is redistributed to ensure that not all probability space is allocated to the maximum scenario, as it has a much lower probability.

The calculation of conditional probabilities or probability contributions of the events is illustrated in Tabel 8 by an example. The left-hand section of the table contains the conditional probabilities for *i* breaches (from Tabel 7). The right-hand section specifies the number of scenarios for each number of breaches (0, 1, 2, 3) and for the maximum scenario.

Table 8: Example of conditional probabilities of flood events in probability class i.

No. of breaches k	Conditional probability	No. of scenarios with k breaches N_{ik}	Contribution to probability per breach
0	0.6	-	-
1	0.3	7	$P_{i,1}$=0.3/7=3/70
2	0.1	21	$P_{i,2}$=0.1/21=1/210
3	0	35	$P_{i,3}$=0/35=0
4-10 (maximum)	0	1 (by definition)	$P_{i,4}$=0/1=0

The total probability of a flood event is the product of the probability contribution and the weighting probability of the given class, which is given in the last column of Table 6. For each flood event (with *k*=0, 1, 2, 3 or more breaches) the probability contribution in the last column of Table 8 ($c_{i,k}/N_{i,k}$) is multiplied by the probability p_i of the related class.

6.4 Conditional probability breaches for independent areas

Table 9: Conditional probability of 0, 1, 2, … breaches for coast south

No. of breaches	T100	T200	T500	T1000	T2000	T5000	T10000	T100000	T1000000
0	1.0	1.0	0.8	0.5	0.2	0.1	0.0	0.0	0.0
1	0.0	0.0	0.1	0.2	0.2	0.2	0.2	0.1	0.1
2	0.0	0.0	0.1	0.1	0.2	0.2	0.2	0.1	0.1
3	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.2	0.1
4	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.1
5	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
6	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
7	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

Table 10: Conditional probability of 0, 1, 2, … breaches for coast middle.

No. of breaches	T100	T200	T500	T1000	T2000	T5000	T10000	T100000	T1000000
0	1.0	1.0	1.0	0.9	0.8	0.6	0.3	0.0	0.0
1	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.5	0.2
2	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.3
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 11: Conditional probability of 0, 1, 2, … breaches for coast north.

No. of breaches	T100	T200	T500	T1000	T2000	T5000	T10000	T100000	T1000000
0	1.0	1.0	0.8	0.5	0.2	0.1	0.0	0.0	0.0
1	0.0	0.0	0.1	0.2	0.2	0.2	0.2	0.1	0.1
2	0.0	0.0	0.1	0.1	0.2	0.2	0.2	0.1	0.1
3	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.2	0.1
4	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.1
5	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
6	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
7	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

Table 12: Conditional probability of 0, 1, 2, … breaches for lake IJssel.

No. of breaches	T100	T200	T500	T1000	T2000	T5000	T10000	T100000	T1000000
0	1.0	1.0	0.8	0.7	0.6	0.3	0.1	0.0	0.0
1	0.0	0.0	0.1	0.2	0.3	0.3	0.3	0.3	0.1
2	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.1
3	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.1
4	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

Table 13: Conditional probability of 0, 1, 2, … breaches for tidal area.

No. of breaches	T100	T200	T500	T1000	T2000	T5000	T10000	T100000	T1000000
0	0.9	0.9	0.6	0.3	0.2	0.1	0.1	0	0
1	0.1	0.1	0.3	0.4	0.4	0.4	0.4	0.3	0.2
2	0	0	0.1	0.2	0.3	0.3	0.3	0.3	0.4
3	0	0	0	0.1	0.1	0.2	0.2	0.3	0.3
4	0	0	0	0	0	0	0	0.1	0.1
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0

Table 14: Conditional probability of 0, 1, 2, … breaches for upper river Rhine.

No. of breaches	T100	T200	T500	T1000	T2000	T5000	T10000	T100000	T1000000
0	0.9	0.8	0.5	0.1	0.1	0	0	0	0
1	0.1	0.2	0.4	0.4	0.4	0.3	0.3	0.2	0.2
2	0	0	0.1	0.4	0.4	0.4	0.3	0.3	0.2
3	0	0	0	0.1	0.1	0.3	0.3	0.3	0.3
4	0	0	0	0	0	0	0.1	0.2	0.2
5	0	0	0	0	0	0	0	0	0.1
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0

Table 15: Conditional probability of 0, 1, 2, … breaches for upper river Meuse.

No. of breaches	T100	T200	T500	T1000	T2000	T5000	T10000	T100000	T1000000
0	0.9	0.8	0.5	0.1	0.1	0	0	0	0
1	0.1	0.2	0.4	0.4	0.4	0.3	0.3	0.2	0.2
2	0	0	0.1	0.4	0.4	0.4	0.3	0.3	0.2
3	0	0	0	0.1	0.1	0.3	0.3	0.3	0.3
4	0	0	0	0	0	0	0.1	0.2	0.2
5	0	0	0	0	0	0	0	0	0.1
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0