MSC. THESIS REPORT

Uncertainties in the derivation of the Dutch flood safety standards

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Date: 4-12-2019

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Preface

By the time of writing, approximately 9 months have passed since I started with the preparations for this study. Over this period, I have learned a lot about the Dutch flood safety standards, its underlying reasoning, the technical calculation process and the human aspects of the new standards. This study gave me many interesting insights about flood risk and spatial characteristics influencing flood risks in the Netherlands.

Firstly, I would like to give many thanks to my supervisors at Royal HaskoningDHV: Marcel Van den Berg and Ric Huting. Their enthusiasm for the subject, the feedback they provided and the discussions we had every now and then have been very helpful and gave me additional inspiration during my research. Also, I would like to thank all the other colleagues at the Rivers & Coasts department of Royal HaskoningDHV in Amersfoort. They provided a good working environment and a nice atmosphere.

Furthermore, I would like to express my gratitude to the various experts and professionals in the field of flood risk & safety standards for the interesting conversations we had, carried out as part of this research. They increased my understanding of the new safety standards and especially the reasoning behind the standards, which cannot be learned from literature alone.

Lastly, I would like to thank my supervisors at the University of Twente: Martijn Booij and Jord Warmink. Over the course of this study they helped me to focus the research and scope, which was a challenge sometimes given the size of the subject and many potential study directions. They also provided useful feedback during the past months, came up with good ideas and assisted to academically write my thesis report.

Sam Westerhof, November 2019

The riverside village of Ophemert during the high discharges of the Waal river in 1995. Source: https://beeldbank.rws.nl, Rijkswaterstaat/Bart van Eyck

Summary

In January 2017, new flood safety standards for the Dutch primary flood defences came into effect. These new safety standards are for most flood defences based on two criteria: a maximum allowed casualty risk and a balance between flood damage and costs for reducing flood probabilities. Two accompanying flood safety standards were derived for these criteria: respectively the so-called local individual risk (LIR) standard and the social cost-benefit (SCBA) standard. The process to derive these new flood safety standards consists of a series of models, assumptions, data and simplifications. It is currently largely unknown how accurate these safety standards are, and which spatial characteristics affect the uncertainty. As the current flood defence improvement tasks and dike designs are guided by these safety standards, there is a desire to derive optimal safety standards fitting the flood risks. Therefore, this study aimed to quantify the uncertainty of the new flood safety standards and has determined the influence of uncertainty sources within the safety standard calculation process.

This study focussed primarily on a specific case study area: Dike ring 43. This dike ring is situated within the Dutch upper river delta between the rivers Waal, Nederrijn/Lek and the Pannerden Canal and is one of the larger dike rings in the Netherlands. The safety standards for the 6 distinguished primary flood defence segments in this dike ring originate from both the LIR and SCBA criterion and are relatively strict, with maximum allowed annual flood probabilities between 1/2250 and 1/13000 (Slootjes & Wagenaar, 2016).

The first step in this study was to derive a set of verification safety standards for dike ring 43, by application of the safety standard calculation process that was also followed to derive the current safety standards in the Dutch Water Act. The safety standard calculation process is extensive, and its documentation is sometimes incomplete. The verification standards derived in this study were therefore a more solid base for the uncertainty analysis performed in this study than the standards defined for the Dutch Water Act. It became clear that the SCBA standards are accurately reproducible, while the LIR standards cannot and deviate for some areas.

Due to the complexity and the large number of potential uncertainty sources in the calculation process of the safety standards, this study continued with the generation of a ranking of the most important uncertainty sources. This ranking was used to determine which sources to include in the uncertainty analysis. This was done by consulting six experts in the field of the Dutch flood safety standards. It became clear that both sources in the LIR standard derivation and in the SCBA standard derivation strongly affect the safety standards and that the most prominent sources are primarily related to the quantification of flood consequences. The found five most important uncertainty sources are: breach development, mortality functions, evacuation of people, damage functions and the investment costs for flood defence improvement.

Next, the uncertainty of these five sources was quantified. This was done by a combination of literature and available data for the local situation in dike ring 43. For each uncertainty source a 50% confidence interval was defined. The 50% confidence interval was in principle defined around the scenario used in the verification safety standard calculations. In case insights from the considered literature or data provided grounds to question the validity of this verification scenario for the characteristics of the case study area, this scenario was adapted and a new scenario was derived serving as reference scenario. It was shown in this study that especially the verification scenarios for breach development and evacuation do not provide a proper representation of what should be expected in a flood event.
The uncertainty analysis in this study followed a scenario analysis approach. From the defined 50% confidence intervals, the lower 25th percentile, reference and upper 75th percentile scenarios were used in the uncertainty analysis.

The uncertainty analysis in this study consisted of two parts: an analysis into individual uncertainty source influence and an analysis considering uncertainty sources simultaneously. The individual uncertainty analysis investigated the influence of the five sources separately and was aimed at defining spatial characteristics which determine the influence of these sources. The established 25th percentile, reference and 75th percentile scenarios for each uncertainty source were fully propagated through the safety standard calculation process.

Propagation of the obtained reference scenarios for breach development, mortality and evacuation provided significantly less strict LIR standards than the verification LIR standards, while the damage function reference scenario resulted in stricter SCBA standards. The influence of uncertainty for the individual uncertainty sources is strongly dependent on spatial characteristics. Flood arrival times, presence of lines of increased surface elevation and dike composition were all identified as influential spatial characteristics in this study.

The analysis in which uncertainty sources were considered simultaneously, provided an overall estimate of the safety standard uncertainty and showed that especially evacuation uncertainty and damage function uncertainty affect respectively the LIR and SCBA safety standards.

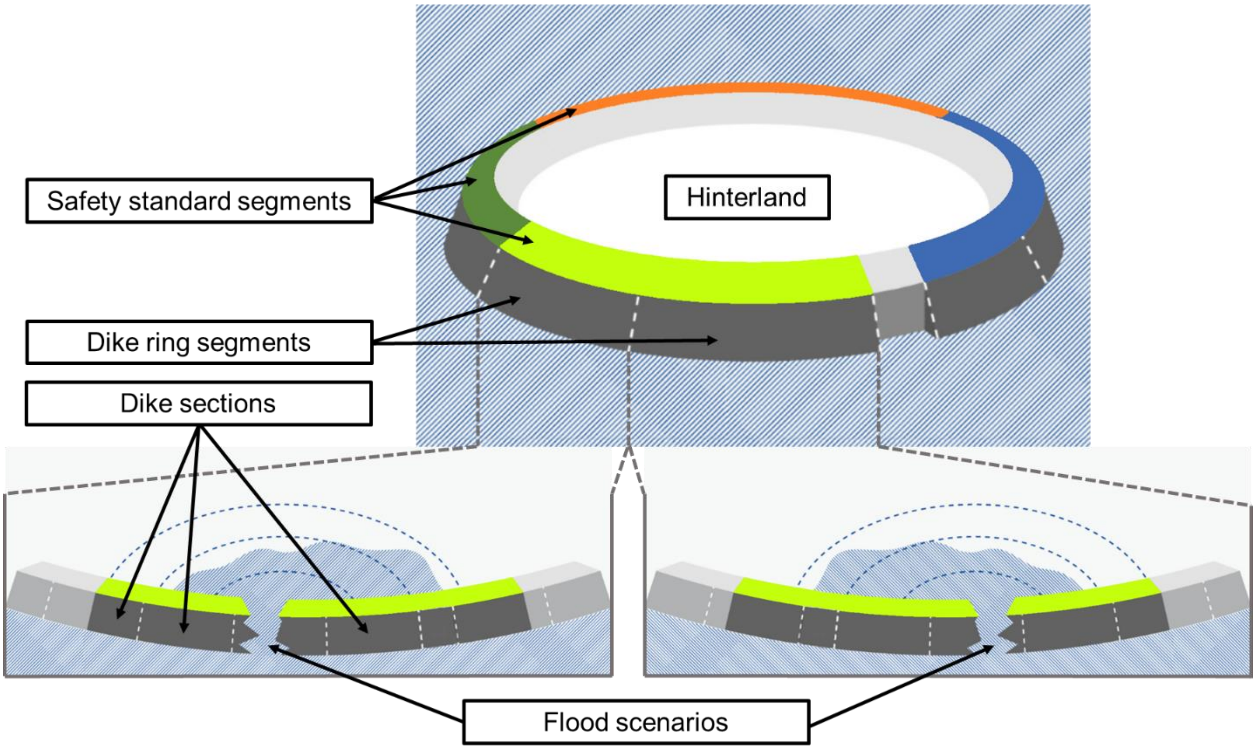
The main conclusion of this study was given by the overall uncertainty quantification of the LIR and SCBA standards. The strictest LIR standards found for the case study are approximately 1.7 times stricter than the least strict standards, while for the SCBA standards approximately a factor 2 was found between strictest and least strict standards. Also, it was concluded that the LIR standard uncertainty varies stronger over different areas than the uncertainty of the SCBA standards. SCBA standards are derived based on characteristics for the entire flood zone, while LIR standards are derived from characteristics of one (normative) neighbourhood within the flood zone. Local variation of uncertainty influence, due to distinct spatial characteristics, therefore does affect the LIR standards but hardly affects the SCBA standards. This conclusion also explains why the LIR standards are more sensitive to the assumptions in the reference scenario and deviate stronger from the verification standards than the SCBA standards. The representative LIR standards found in this study are approximately one order of magnitude less strict than the LIR standards currently set in the Dutch Water Act.

Similar dike rings along the Dutch rivers are prone to the same uncertainty sources included in this research for dike ring 43. Further research should therefore especially focus on analysis and quantification of uncertainty in different types of dike rings. To derive more accurate flood safety standards, it is recommended to focus further study on evacuation and reduction of evacuation uncertainty. Furthermore, this research showed that especially for LIR standards, a more location specific approach in the safety standard calculation results in safety standards which better represent the local flood risks. A more location specific approach in safety standard calculation is therefore recommended as well.

Glossary

Spatial categorisation of dikes:

Concept:	**Explanation**:
Primary flood defence system	The totality of flood defence structures such as dikes and hydraulic structures together make up the flood defence system of a dike ring against outer water(s) such as the Rhine river branches.
Dike ring	Series of flood defence structures (and high grounds) which together form a closed system to protect a certain area of land. Dutch term: “Dijkring”
Safety standard segment	A certain part of a dike ring for which separate flood safety standards are defined and established by law in the Dutch Water Act. Dutch term: “Dijktraject”
Dike ring segment	Safety standard segments often consist of multiple dike ring segments. Dike ring segments are the spatial level for which flood scenarios are defined and used in the calculation process of the safety standards. The flood consequences from one defined flood scenario are assumed representative for the entire dike ring segment. Dutch term: “Ringdeel”
Dike section	Part of a flood defence structure with statistically homogeneous strength properties and loads. Dutch term: “Dijkvak”
Hinterland	The area inland from the primary flood defence system, which is protected by this primary flood defence system
Secondary dikes	Dikes which separate a dike ring into multiple smaller sub-systems or compartments.
Increased surface elevation lines	Long and narrow areas of higher surface elevation than the surrounding areas. Examples are (secondary) dikes, elevated roads and railways.



Flood safety standards and related concepts:

Concept	Explanation:
Flood safety standard	A requirement appointed to a safety standard segment, which defines the maximum allowed annual flood probability to meet the flood risk criteria.
Local individual risk (LIR)	The local individual risk is defined as the annual risk to become a casualty in a flood event at a certain location, with incorporation of the possibility to evacuate (Slootjes & Van der Most, 2016a)
Economic risk	The economic risk expresses the monetary losses directly or indirectly caused by disruption of economic processes and monetised damage to human beings (e.g. casualties, injuries etc.)
Societal risk	Societal risk is a measure of risk that expresses the likelihood that there will be large numbers of casualties in a flood event (ENW, 2017)
LIR criterion	The LIR criterion expresses that the local individual risk may not surpass a certain value ($1*10^{-5}$ / year for the derivation of the lower limit standard and $5*10^{-6}$ /year for the derivation of the alert standards)
SCBA criterion (Economic risk criterion)	The SCBA criterion (social cost-benefit analysis criterion) expresses a monetary cost balance between monetised flood consequences and monetised costs required to reduce flood probabilities.
Lower limit standard	Expresses the annual flood probability of a safety standard segment for which it marginally meets the dominant flood risk criterion
Alert standard	Expresses the moment in time when flood defence managers should start planning interventions to prevent that the lower limit standard will later be exceeded
Safety standard classes	The safety standard classes are a translation of the directly calculated safety standards into coarser legislative classes used by dike designers and for dike assessments. The safety standard class is derived by aggregation of the initially calculated standards into predefined classes (such as a safety standard class 1/30000 for calculated standards between 1/17000 and 1/55000)
Verification standard	The verification standards are standards derived in this study by application of the safety standard calculation process as described in the documentation of the process.
Reference standard	The reference standards are defined in this study as the safety standards originating from the most likely scenario for the underlying uncertainty source(s).
Decimal height (of the flood defence crest level)	The decimal height is defined as the increase in flood defence crest level at a certain location, for which the annual flood probability decreases with a factor 10 (Slootjes & van der Most, 2016b). In relation to the flood safety standard derivations, for the Dutch upper river delta this corresponds to a crest level increase for which the annual flood probability decreases from 1/1250 per year to 1/12500 per year
Test level hydraulic conditions (TL)	The hydraulic conditions which the primary flood defence system should be able to withstand without breaching according to the old safety standards. For the Dutch upper river delta, the hydraulic conditions with a 1/1250 annual occurrence probability. Dutch term: “Toetspeil”
Test level + 1 decimal height hydraulic conditions (TL +1D)	The hydraulic conditions with a 10 times lower reoccurrence probability. For the Dutch upper river delta, hydraulic conditions with a 1/1250 annual occurrence probability. Dutch term: “Toetspeil + 1 decimeringshoogte”

Flood processes and flood consequences

Concept	Explanation
Mortality	The mortality expresses for an individual present at a certain location within the dike ring the probability to pass away in a flood event.
Weighted mortality	The weighted mortality values represent the probability to become a flood casualty at a certain location, not knowing on beforehand which flood scenario will occur (mortality weighted from multiple flood scenarios).
Flood casualties	People who die in a flood event
Flood victims	People whose house is inundated in a flood event
Personal flood damage	All flood casualties and flood victims are combined referred to as personal flood damage
Monetary flood damage	Combination of all material flood damage (damage to property, economic short and long term damage caused by production losses inside and outside the flooded area)
Preventive evacuation	The organisation and horizontal movement of people from a potentially exposed area to a safe location outside this area, before the onset of the disaster (Kolen, 2013)
Acute evacuation	The organisation and movement of people from a potentially exposed area to a safe location outside this area, initiated after the onset of a disaster and before exposure (Kolen, 2013)
System effect	The system effect in the context of flood safety expresses the interdependency of flood probabilities and flood characteristics between multiple areas.
Positive system effect	The positive system effect expresses the decrease in flood probability at certain locations as a result of flooding elsewhere. Along rivers, the positive system effect can decrease downstream flood probabilities due to upstream flooding.
Negative system effect (also called cascade-effect)	The negative system effect expresses the increase in flood probability for certain areas due to flooding elsewhere. In the context of rivers, an example of the negative system effect is the flooding of dike ring 16 caused by flooding in dike ring 43.

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1 Introduction

1.1 The new Dutch flood safety standards

Ever since the Dutch lands were inhabited by people, flood protection has been a major concern in the low-lying Dutch river delta. The primary flood defence system in the Netherlands protects flood prone areas from flooding by the Rhine-Meuse river system, the North Sea and lake IJssel. After hundreds of years of setting-up, reconstructing and developing the primary flood defence system, today it consists of a system of dikes, dunes and hydraulic structures which protect the Netherlands from frequent flooding. Along with the continuous development of the flood defence system, policies and regulations for these flood defence structures have been developed as well. In the aftermath of the catastrophic floods in the Dutch southwestern river delta in 1953, national programs were established for the first time to generate a uniform policy on flood safety standards for the primary flood defences.

These first flood safety standards were based on probability of occurrence of certain design peak water levels, which the local flood defence system should be able to withstand safely (ENW, 2017). These occurrence-based standards were enforced up to 2016 (Figure 1-1). Since 2017, these have been replaced by new flood safety standards which are no longer defined as exceedance frequencies of water levels, but as an annual probability of flooding. The current standards followed from flood risk analyses for all flood-prone areas in the Netherlands, in which three distinct criteria were considered. The first criterion is a maximum allowed local individual risk (LIR), which expresses the annual probability to become a casualty in a flood event (with incorporation of evacuation possibilities) and is reflected in the LIR standard (Slootjes & Van der Most, 2016a). The second criterion aims for an optimal balance between reduced economic flood risk and required investments for flood defence improvement. This criterion is considered via a societal cost-benefit analysis (SCBA) and results in an SCBA standard. A third criterion considers minimisation of the risk for large groups of casualties due to a single flood event, which is reflected in the so-called group risk (GR) (Slootjes & Van der Most, 2016a). The normative standards established by law for the primary flood defence system in the Dutch Water Act are given by the strictest of the flood safety standards derived from these three risk criteria.

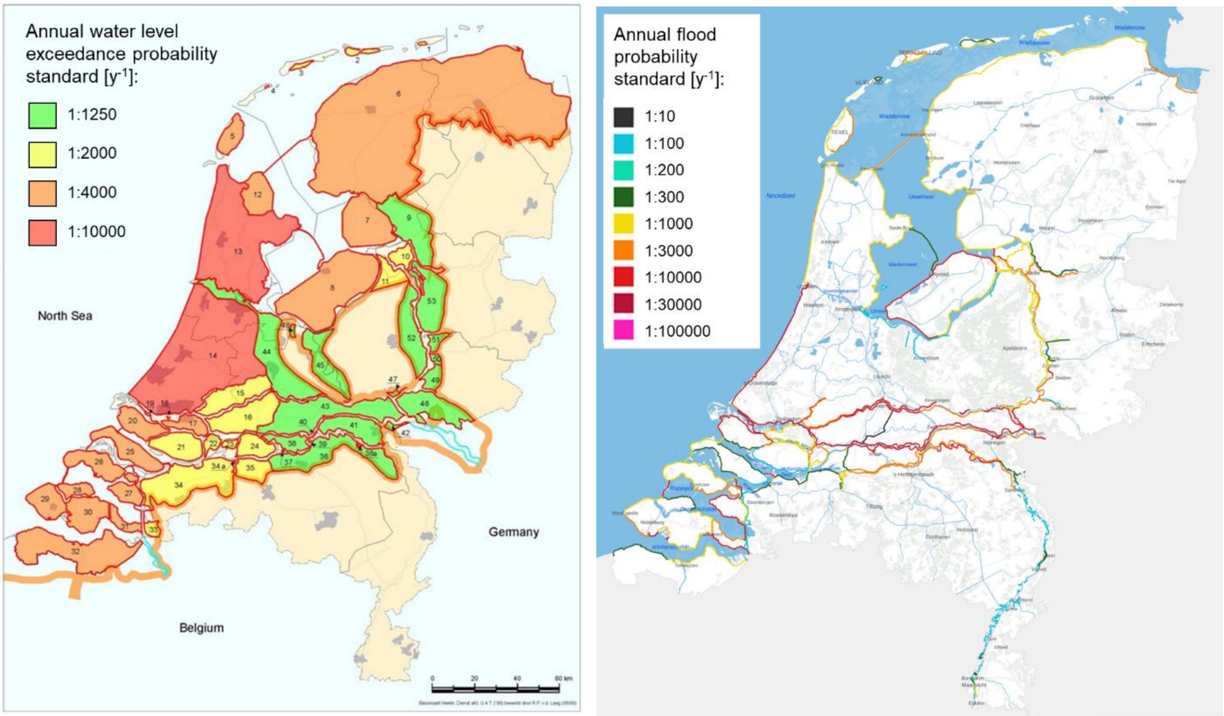

Figure 1-1: Old (left) and new (right) flood safety standards in the Netherlands.

Furthermore, with the introduction of the new flood safety standards for the primary flood defence system, the spatial entity for which these standards are defined has been revised as well. Previously, separate standards were defined for each dike ring in the Netherlands, which differ greatly in size. The new standards are defined for so-called safety standard segments instead of entire dike rings. These segments are smaller entities and are more consistent in length than dike rings (see Figure 1-1). This approach allowed for more variation of the flood safety standards, depending on differences in origin of the flood hazard and differences in flood consequences among different safety standard segments (Slootjes & Van der Most, 2016a). This has resulted in a better relation between the protection level and the foreseen local consequences. The revised approach and spatial scale of the new standards has especially along the Dutch rivers resulted in stricter flood safety standards compared to the old situation (Jorissen et al. 2016).

1.2 Research motivation

The methodology to derive the new flood safety standards for each safety standard segment is a technical calculation process, consisting of a series of steps in which several models are used and in which many assumptions, simplifications and decisions are made. As a result, the new calculation process for the standards involves various sources of uncertainty which might influence the resulting outcomes, as was earlier shown by Gauderis et al. (2011). This uncertainty already gave motivation to aggregate the current standards in certain safety standard classes and incorporate these classes in the Dutch Water Act as legally binding value (Slootjes & Van der Most, 2016a).

Due to uncertainty, flood probabilities and consequences might currently not be properly estimated. This uncertainty is embedded in the calculation process of the safety standards. As the flood defence system is designed and tested based on the derived safety standards, the uncertainty affects the flood defence improvement policies and spending of public funds on these systems. Enhanced insight into how different sources of uncertainty influence the standards might provide possibilities to enhance the calculation process for the safety standards and therefore optimise the spending of public funds on flood defence systems. Furthermore, this could help to identify important uncertainty sources and help prioritising research pathways aimed at reduction of uncertainty influence on flood risk calculations. Therefore, studying the influence of uncertainties on the safety standards is useful from both societal and scientific perspectives.

1.3 Current knowledge & research gap

Since the development of the new methodology to calculate safety standards for the Dutch primary flood defences, little research has been conducted into the influence of uncertainties on the flood safety standards themselves. Although the risk-based flood safety standards were implemented in 2017, the concept of risk-based flood safety standards emerged in the Netherlands a few years earlier. In light of this new concept, Gauderis et al. (2011) performed a nationwide uncertainty and sensitivity analysis for the methodology to derive the flood safety standards for the cost-benefit criterion (the SCBA standard). They quantified the effects of 14 different uncertainty sources on the calculated SCBA standards through a Monte-Carlo analysis. Due to the long run and processing times, their Monte-Carlo analysis did not consider the models used in the calculation process of the standards. They used an analytical equation to approximate the standards, parameterised the uncertainty sources and implemented them in the analytical equation via probability distributions. Based on their analysis, they showed that there is a considerable uncertainty bandwidth around the calculated SCBA standards for almost all safety standard segments in the Netherlands. The 90th percentile standard in their uncertainty bandwidth is on average for the Netherlands 5 times stricter than the 10th percentile standard (Gauderis et al. 2011). Furthermore, they showed that the main sources of uncertainty responsible for the SCBA standard uncertainty are the extent of the flooded area, the mortality, costs for dike improvement and evacuation of people.

Besides the study by Gauderis et al. (2011), no other studies directly investigated the uncertainty influence on the flood safety standards. There have however been many studies describing the uncertainty of individual components relevant in the calculation of the safety standards. For instance, the uncertainty in the normative peak river discharges has been described by Diermanse (2004), uncertainty in breach development has been discussed by Domeneghetti et al. (2013) and uncertainty in the monetary valuation of personal flood damage was studied by Bockarjova et al. (2012). Jongman et al. (2012) described uncertainty in damage functions and showed that different plausible damage functions result in a high degree of uncertainty in calculated flood damage. These examples of individual uncertainty sources are all relevant in the calculation process of the flood safety standards and can therefore influence the derived standards. Although many uncertainty sources have been studied before, not each of these uncertainty sources has been studied specifically for the situation in the Netherlands. Furthermore, the uncertainty might spatially differ. For instance, the uncertainty in economic growth was incorporated in the uncertainty analysis by Gauderis et al. (2011) at a national level, while the economic growth and associated uncertainty might vary over different sub-areas.

Flood risk calculation is closely related to the calculation of the flood safety standards, and many of the same uncertainty sources are relevant in flood risk calculations. This makes it useful to consider existing uncertainty analyses in flood risk calculation studies as well, to see how influential certain uncertainty sources are. Multiple flood risk uncertainty analyses have been performed, which all focussed on economic flood risk. A study by De Moel et al. (2012) studied the effects of different uncertainty sources on coastal flood risks in The Netherlands, in which they showed that uncertainty in damage functions, storm duration and dike material are of significant influence on economic flood risk. De Moel et al. (2014) performed a similar study to the influence of 6 uncertainty sources on the economic risk in a dike ring along the Dutch part of the river Meuse. De Moel et al. (2014) concluded that the uncertainty of the damage functions, return period of extreme discharges and the duration of a flood wave are of most influence on the economic risk uncertainty. A study by Saint-Geours et al. (2015) into uncertainty influence on economic flood risk for a case study along a French river showed that uncertainties influencing the economic risk can also vary among land use categories. Merz & Thieken (2009) studied a different case study along the river Rhine at Cologne. They found that uncertainties associated with the flood frequency determination explain most of the uncertainty in economic flood risk output, while application of different plausible damage estimation models and inundation models have less but still significant influence.

For various case study areas and by using several different methods, these uncertainty analysis studies showed that potentially there are multiple sources of uncertainty which could influence the economic flood risk, while their relative importance also differs over different areas. As the economic flood risk is determined by the combination of flood probability and flood consequences, the SCBA standards are likely also influenced by these sources of uncertainty.

It becomes clear that no study has yet tried to systematically approach uncertainties in flood risk or safety standard calculations. Multiple uncertainty analysis studies exist, but each of these has focussed on a few uncertainty sources without first considering the full range of possible uncertainty sources and tackle the likely most important ones.

Furthermore, in both flood risk uncertainty studies and the single study directly into the uncertainty of the flood safety standards, there has been a clear focus on the economic flood risk and the associated SCBA standard. The standards for the Dutch primary flood defence system followed from multiple risk analyses. Next to economic flood risk, many of the new flood safety standards in the Netherlands resulted from the individual risk analysis (the LIR standard) (Slootjes & Wagenaar, 2016). This leaves a knowledge gap for the uncertainty of the LIR standards. It is therefore especially useful to study the influence of uncertainties on the LIR standards as well, as uncertainty influencing the individual risks can result in shifting safety standards as well.

Lastly, until now uncertainty analyses directly for the safety standards were performed in a simplified analytical way rather than by propagating uncertainty through the model chain used in the original safety standard derivations. This prohibits considering all relevant uncertainty sources. Gauderis et al. (2011) did not consider uncertainty sources within the flood propagation model such as uncertainty related to breach development or the hydraulic conditions. They aggregated many uncertainty sources to be able to use an analytical equation for the safety standard derivation. Directly propagating uncertainty through the model chain to derive the safety standards, is an approach which has not been applied before and enables a more detailed study in which uncertainty sources in all components of the model chain can be considered.

1.4 Problem statement & research objective

As LIR standards were previously not considered and uncertainty analyses were performed in an analytical way, it is currently largely unknown how uncertain the Dutch safety standards are and in what way uncertainty affects the LIR and SCBA standards. Therefore, it is unknown if the current flood safety standards are representative for the posed flood risks, as for example flood consequences might be estimated wrongly. As a result, the flood defence improvement tasks derived from these standards might differ from the tasks required to comply with the criteria for optimal flood safety standards. Furthermore, these safety standards are also used as basis for dike improvement strategies, which is why uncertainty in the safety standards could also affect dike design.
The goal for this research is therefore:

To quantify the uncertainty of the Dutch flood safety standards for the primary flood defences of case study dike ring 43, by performing a scenario analysis.

The flood safety standards in the Dutch Water Act are given by the strictest standard derived from the three distinct risk analyses. The current flood safety standards for the 208 regular safety standard segments received a legal standard originating from either the LIR criterion (approximately 25% of the segments), SCBA criterion (approximately 25% of the segments) or a combination of these two (approximately 40% of the segments) (Slootjes & Wagenaar, 2016). The focus in this study is therefore on both the SCBA and LIR standards and the influence of uncertainty sources in the underlying safety standard calculation process. The group risk criterion is not considered in this study, as this criterion is not normative for the case study area (Slootjes & Wagenaar, 2016). A scenario uncertainty analysis is performed in this study by propagating uncertainty in the form of scenarios directly through the model chain to derive safety standards, rather than by using an analytical approach as was done by Gauderis et al. (2011). This study quantifies the safety standard uncertainty only for case study dike ring 43, as it is not feasible to consider the full model chain in the safety standard calculation process for multiple areas.

1.5 Research questions

Within this research, five research questions are answered to achieve the main research objective:

1) How well can the current flood safety standards for the primary flood defence system be reproduced by application of the documented calculation process for the safety standards?
2) Which uncertainty sources in the safety standard calculation process are of most influence on the derived standards?
3) How can the uncertainty of the main sources be quantified and propagated through the calculation process for the safety standards?
4) In what way do individual uncertainty sources influence the LIR and SCBA standards and which spatial characteristics affect the influence?
5) How uncertain are the flood safety standards due to the combined most important sources of uncertainty?

The answers to the first three research questions provide a solid reference set of flood safety standards, a systematic foundation for the choice which uncertainty sources to include in the uncertainty analysis and afterwards a way to quantify the uncertainty of these uncertainty sources. The fourth research question gives insight in the processes and characteristics which determine the influence of the uncertainty sources on the flood safety standards and identifies spatial characteristics affecting the uncertainty of the safety standards and the influence of uncertainty sources. This also enables translation of case study results to other areas with primary flood defences in the Netherlands. Lastly, the fifth research question covers the mutual dependency of the uncertainty source influences and provides the overall uncertainty of the flood safety standards which is explained by the uncertainty sources included in the analysis.

1.6 Case study: Dike ring 43

This study focusses on a case study to answer the research questions. The chosen case study area is dike ring 43, a dike ring located in the middle of the Dutch river system. The motivation for this specific case study is based on several aspects.

Firstly, as the research objective clearly focusses on both the derivation of the SCBA and LIR standards, a case study area where the current standards were derived based on both the SCBA and LIR criterion is essential. Dike ring 43 meets this requirement (Slootjes & Wagenaar, 2016). Secondly, it has become clear that the flood protection level offered by the current primary flood defences in this area is relatively far below the level demanded by the newly derived protection standards. Within the Dutch Flood Protection Programme (Dutch: HWBP), flood defence improvement projects are defined for the safety standard segments. The Flood Protection Programme prioritises the improvement projects based on the difference between the current protection level and the level demanded by the new standards, which is why multiple projects within dike ring 43 are currently in preparation (HWBP, 2019a). The responsible waterboard for the primary flood defence system of dike ring 43 therefore faces both an urgent and complicated task to strengthen many of its flood defences to comply with the new flood safety standards. It has become clear that this task will require significant adjustments of the current primary flood defences and therefore becomes more expensive than previous reinforcements, putting pressure on the budgets assigned for the Flood Protection Program (HWBP, 2019b). To assure that improvement tasks match with the local flood risks and budgets are spent accordingly, it is useful to critically review the standards which have been established for this area, study the influence of uncertainties embedded in the calculation process and seek for possibilities to derive a justifiable safety standard for the local flood risks in dike ring 43. Hence, besides a general motivation to find the influence of uncertainty on the flood safety standards and assure that flood safety standards are representative, in dike ring 43 there is a specific sense of urgency related to the improvement tasks the waterboard currently faces.

1.7 Report structure

This report starts with a brief description of case study dike ring 43 in chapter 2. Afterwards, chapter 3 elaborates on the followed research steps in this study to answer the research questions. Chapter 4 provides the results for each of these research steps. The report continues with a discussion of the followed methods and a translation of the case study results to more general statements in chapter 5. The report is finalised in chapter 6 with the conclusions and several recommendations for further study and possible approaches to enhance the safety standard derivation methodology.

2 Dike ring 43 and its flood safety standards

This chapter describes the characteristics of the case study area considered in this research and introduces the legal flood safety standards that have been established for this area.

2.1 Surface water system

Dike ring 43 is situated centrally within the Dutch Rhine/Meuse delta (see Figure 2-1). Dike ring 43 is approximately 70 km long from east to west and is between 3 and 15 km wide, which makes it one of the larger Dutch dike rings. Flood hazards for this dike ring are dominated by high river discharges of the rivers Rhine and Meuse. Dike ring 43 is located between three branches of the River Rhine: The River Waal along the southern border, the River Nederrijn/Lek along the northern border and the Pannerden Canal on the eastern border (see Figure 2-2). These three river branches are all part of the Dutch main surface water system and the primary flood defence system of dike ring 43 protects the hinterland against flood hazards originating from these three river branches. The western border of this dike ring is made up by the “Diefdijk”; a levee separating dike ring 43 and dike ring 16 on the western side. It prevents flood water propagation from dike ring 43 into dike ring 16 in case of a dike breach along dike ring 43.

Figure 2-1: Location of dike ring 43 in the Netherlands

The rivers bordering this dike ring flow westwards, which is shown by the east-west elevation slope in this dike ring (see Figure 2-3). The dike ring is situated entirely above mean sea level (Dutch: “NAP”), with elevations ranging from 1m+NAP along the western border of the dike ring to approximately 11m+NAP along the eastern ends (Vergouwe et al. 2014).

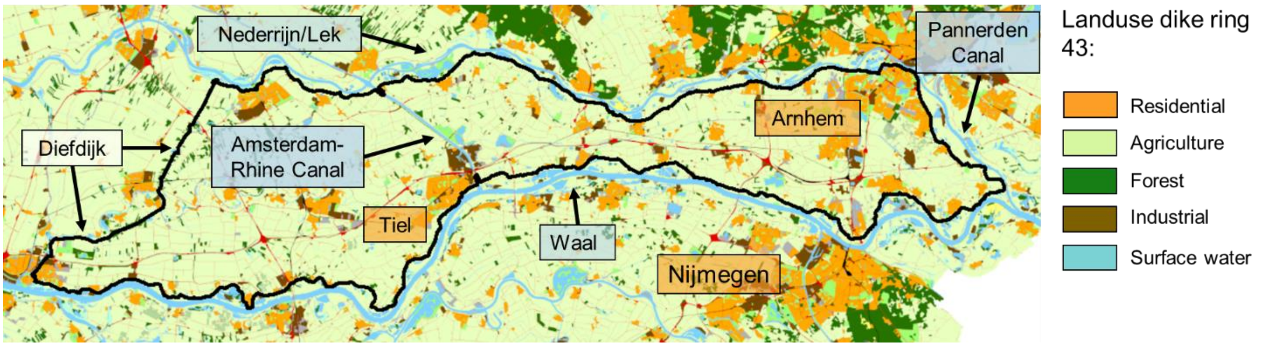

Figure 2-2: Landuse of dike ring 43, along with indication of the primary surface water bodies and urban centres

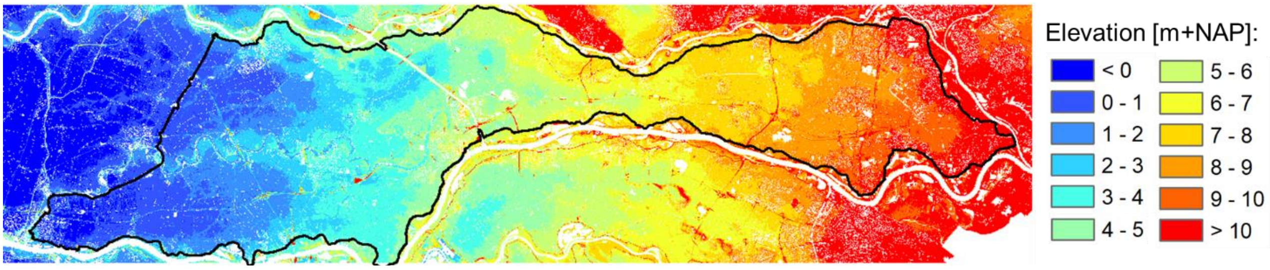

Figure 2-3: Elevation map of dike ring 43

Besides the three Rhine branches bordering this dike ring, there are also several notable interior surface water bodies. The Amsterdam-Rhine Canal connects the rivers Waal and Nederrijn/Lek, cutting through dike ring 43 and creating an eastern and western part of this dike ring. Another notable surface water body is the river Linge. This river originates from the Pannerden Canal, flows westward through Dike ring 43, is pumped beneath the Amsterdam-Rhine Canal via a siphon structure and flows onward into dike ring 16 through a sluice system in the Diefdijk (see Figure 2-4).

Figure 2-4: Locations of some the main hydraulic structures of dike ring 43: 1) Linge bypass sluice below the Amsterdam-Rhine Canal; 2) Linge discharge sluice in the Diefdijk; 3) Spill flow works at Dalem; 4) Shipping locks at the Amsterdam-Rhine Canal

2.2 Land use, economic activity and population

The interior of dike ring 43 contains a variety of land use types. Urban areas are mainly centred adjacent to the major rivers in the area, directly next to the primary flood defences. The total population of dike ring 43 is approximately 360.000 (CBS & Kadaster, 2019b). The largest urban centres are situated in the eastern part of the dike ring, between the cities of Arnhem and Nijmegen, where in recent years many urban expansion projects have taken place and large residential areas are located. Other notable residential areas are the smaller cities of Tiel and Culemborg, which are both located west of the Amsterdam-Rhine Canal. Besides many predominantly small urban areas, the land use of this dike ring is dominated by agricultural areas and grasslands. The area contains few large industrial areas, with the harbour zone at Tiel as notable exception. Several major infrastructure links run through dike ring 43, such as cargo and passenger rail links and 4 national highways. These infrastructure links run both east-west and north-south through this dike ring.

2.3 Flood defence system and flood safety standards

The primary flood defence system of dike ring 43 is made up of a chain of dikes and several hydraulic structures, which together make up a continuous network of flood defences encircling this dike ring. The northern, eastern and southern borders are made up of flood defences directly bordering the primary water bodies (Waal, Pannerden Canal and Nederrijn/Lek), while the Diefdijk is surrounded by land on both sides under normal conditions. The dikes along the northern, eastern and southern border are predominantly constructed from material which was historically available nearby, resulting in a variable composition of dike cores from coarser (sandier) material to finer and clayey material (Berendsen, 1993). Some notable hydraulic structures part of the flood defence system of dike ring 43 are the two shipping locks at the Amsterdam-Rhine canal and the spill flow works at Dalem, at the southwest tip of dike ring 43 (see Figure 2-4).

Together with the Linge discharge sluice in the Diefdijk, the spill flow works at Dalem can be used to release flood water in the western part of dike ring 43, to limit the flood consequences on both sides of the Diefdijk. The primary flood defence system encircling dike ring 43 is under the new flood safety standards divided in 6 different safety standard segments, which all received a separate safety standard based on the new calculation process (see Figure 2-5). The Diefdijk, which functions as the western border of dike ring 43 is considered part of the primary flood defence system of adjacent dike ring 16 and hence not part of dike ring 43. The safety standards for the Diefdijk have been defined differently and is therefore not considered in this study. Table 2-1 shows the current flood safety standards for the 6 segments. For each of the safety standard segments in the Netherlands, two different types of standards were derived: a lower limit and an alert standard. The lower limit standard describes the maximum permissible probability of flooding to still meet the LIR and SCBA criteria. The alert standard is defined to guide the initiation of intervention planning. For a more elaborate explanation for the function of the two distinct standards, refer to ENW (2017) and Slootjes & van der Most (2016a).

The derived standards are aggregated into safety standard classes which follow a 1-3-10 systematics (1/1000, 1/3000, 1/10000 etc.). This class-aggregation was applied to account for uncertainty in the safety standard derivation (Slootjes & Van der Most, 2016a). Table 2-1 makes clear for dike ring 43 that the derived alert and lower limit safety standard classes are equal for 5 of the 6 safety standard segments. The normative criterion based upon which the standards in the Dutch water Act are derived however does vary over the six segments. For 2 segments the standard is based on the LIR criterion (43-5 and 43-6), for 2 segments based on the SCBA criterion (43-1 and 43-3) and for 2 segments the two criteria resulted in the same safety standard class (43-2 and 43-4). Safety standard segments along the northern side of dike ring 43 are predominantly based on the SCBA criterion, while the standards along the southern side of the dike ring are derived mainly based on the LIR criterion.

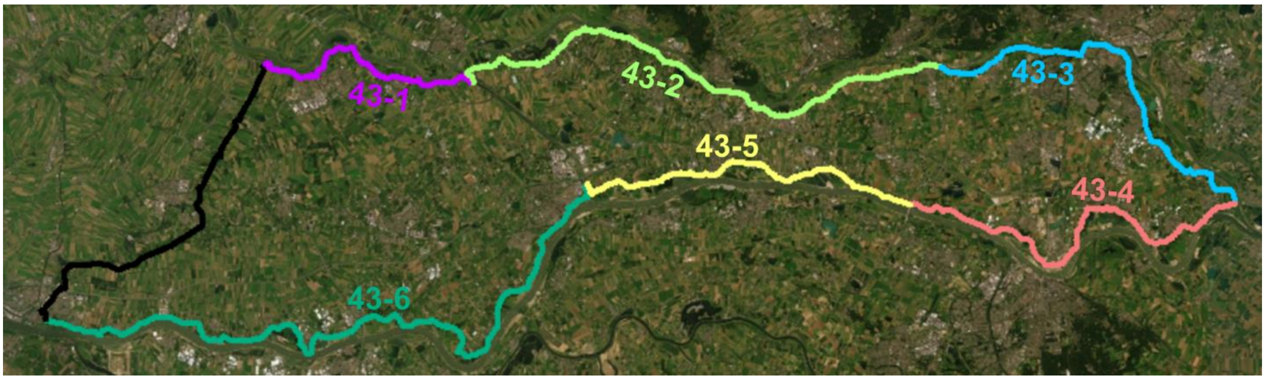

Figure 2-5: Dike ring 43 along with its 6 safety standard segments and the Diefdijk as western border

Table 2-1: Safety standard segments of dike ring 43, along with the flood safety standards and normative criterion (Slootjes & Wagenaar, 2016)

Safety standard segment	Lower limit standard class [y^{-1}]	Alert standard class [y^{-1}]	Normative criterion
43-1	1/10.000	1/30.000	SCBA
43-2	1/3.000	1/10.000	LIR & SCBA
43-3	1/10.000	1/30.000	SCBA
43-4	1/10.000	1/30.000	LIR & SCBA
43-5	1/10.000	1/30.000	LIR
43-6	1/10.000	1/30.000	LIR

3 Methods

This chapter presents the methods used in this study. Figure 3-1 gives an overview of the followed research steps and gives for each step the paragraph in which the used methods in this step are described. The five green highlighted main research steps each correspond with the five research questions defined in paragraph 1.5.

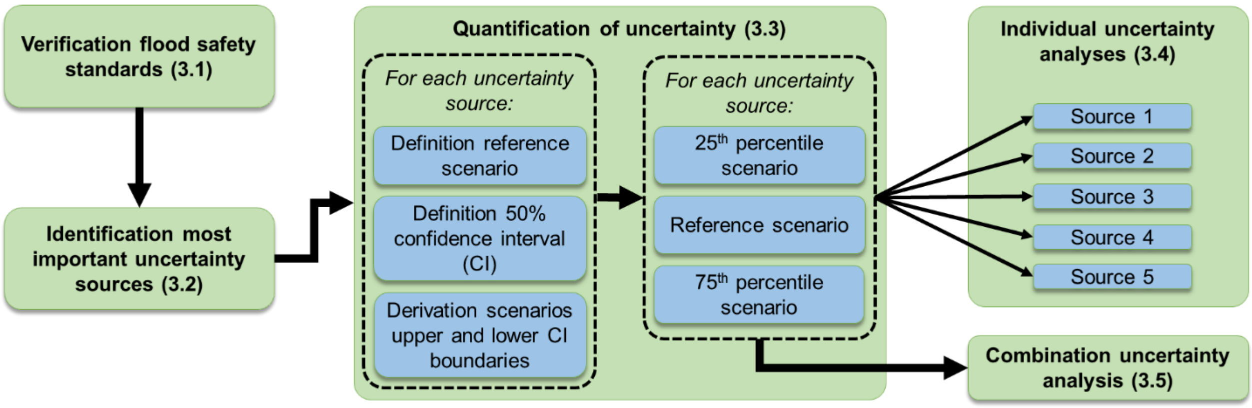

Figure 3-1: Schematic overview of the main research steps in this study and the sequence in which they are carried out, along with the accompanying paragraphs in which the step is further described.

3.1 Verification flood safety standards dike ring 43

The first step in this research was to generate a set of verification flood safety standards for dike ring 43, which can be used in the uncertainty analysis as reference situation. The current safety standards are obviously known already, but the safety standard derivation is a complex and not always well documented process. This may cause differences between the values calculated for the legal standards in the Dutch Water Act (by Slootjes & Wagenaar, (2016)) and the calculated values in this study. A verification of the standards therefore assures that these standards are based on the exact same process as the standards calculated in the uncertainty analysis. Furthermore, these verification calculations provide an overview of the main components of the safety standard calculation process, as preparation for the next step in this research.

The methodology followed in this study to derive safety standards was set-up in a way which as accurately as possible matches the methodology followed to derive the legal flood safety standards. The basic procedure is described by Slootjes & Van der Most (2016a). Figure 3-2 schematically shows the primary steps to derive the safety standards. The following paragraphs describe these steps, the involved models, data and approaches followed in this study.

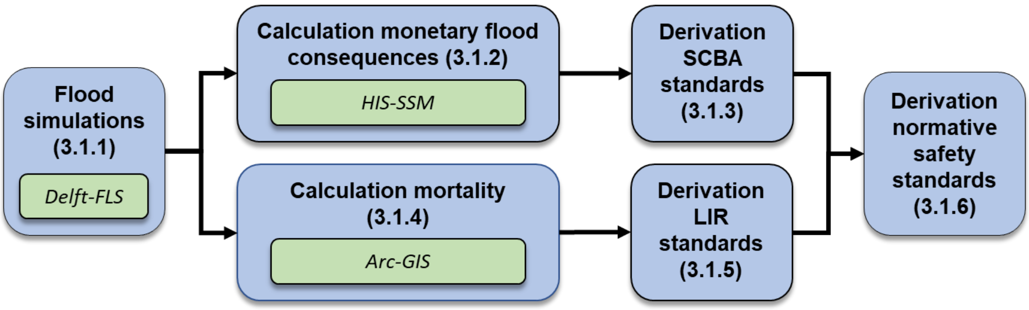

Figure 3-2: Schematisation of the primary steps in the general calculation methodology of the safety standards (blue) and the used models in this study (green)

3.1.1 Flood simulations

3.1.1.1 Flood scenarios

The first step consists of a set of flood simulations for different flood scenarios, used to determine the potential flood characteristics in case of failure of the flood defence systems encircling dike ring 43. As the potential number of locations where the flood defence system can fail is very large, a limited number of representative flood scenarios was used. Together, these provide a full coverage of the potential flood hazards in dike ring 43 and should give a good representation of all flood patterns which might occur. To cover the uncertainty in breach location, the primary flood defence system of dike ring 43 was divided in 15 different dike ring segments, each with one representative breach location. The 15 dike ring segments were defined for an earlier flood risk study (the VNK2 project, Projectbureau VNK2 (2011)). The breach location for each dike ring segment was chosen at the location where the induced flood damage is at its maximum (Rijkswaterstaat Waterdienst, 2008). The flood pattern resulting from one breach location represents the flood pattern which would occur regardless of the exact breach location within the respective dike ring segment (described in Projectbureau VNK2 (2011)). Figure 3-3 depicts the locations of the 15 breach locations along with their names as they are used in this report.

To cover the uncertainty in hydraulic conditions for which a flood defence could fail during a high water event, for each of the 15 breach locations flood scenarios were considered for two different hydraulic boundary conditions: test level (TL) conditions and test level +1 decimal height (TL+1D) conditions. For dike ring 43, TL conditions are defined as the outside hydraulic conditions (water levels) with a 1/1250 annual occurrence probability, while TL+1D conditions correspond to hydraulic conditions (water levels) with a 1/12500 annual occurrence probability. A decimal height is therefore defined as the additional water level above TL conditions for which the annual occurrence probability decreases with a factor 10. The standards for dike ring 43 in the Dutch Water Act have thus been derived based on 30 flood scenarios in total (15 locations at 2 hydraulic conditions).

These flood simulations are extensive and time-consuming operations. Therefore, for only 4 flood scenarios new flood simulations were made for the verification of the safety standards. The resulting flood characteristics for these 4 scenarios were compared to the flood characteristics for these scenarios given by the Dutch national information platform for water and floods (Dutch abbreviation: LIWO) (Rijkswaterstaat, 2019). LIWO contains flood characteristics data for almost all Dutch flood scenarios. The 4 considered flood scenarios are simulations under TL and TL+1D conditions for breach locations Bemmel and Oosterhout (see Figure 3-3). These breach locations are situated far upstream, which implies that floods would propagate for a long time westward through the hinterland towards the western border of dike ring 43. These are among the scenarios with the largest flood pattern and require the full extent and input of the flood simulation model. Hence, these are the most important flood scenarios to verify. Comparison made clear that the flood characteristics from the 4 made flood simulations correspond exactly to the LIWO data.

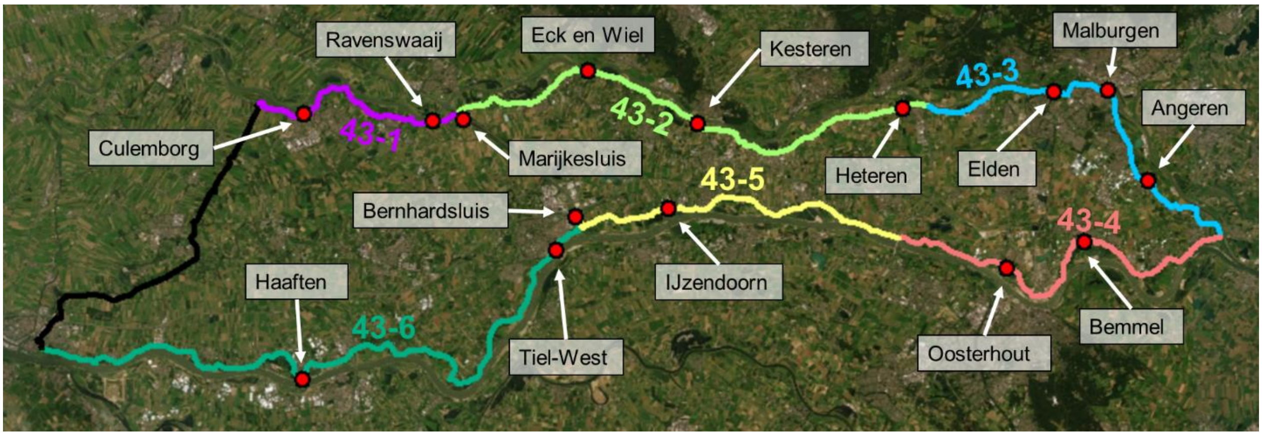

Figure 3-3: Breach locations in dike ring 43

3.1.1.2 Delft-FLS

Flood simulations in this study were made with the 2D hydrodynamic flood simulation model Delft-FLS. Delft-FLS is a relatively old flood simulation program, developed at the end of the previous century by WL | Delft-Hydraulics. Delft-FLS solves the 2D shallow water equations with a finite difference scheme on a staggered rectangular grid (Stelling, 2002). The spatial resolution used in the simulations is 100x100m and Delft-FLS uses an automatic timestep estimator which calculates optimal calculation timesteps to prevent numerical errors and minimise computation time (WL Delft Hydraulics, 2001).

The Delft-FLS model used in this study for dike ring 43 was developed by the province of Gelderland and is currently owned by Waterboard Rivierenland. This is the same model that was used to derive the flood safety standards in the Dutch Water Act for all safety standard segments within the province of Gelderland. The 2D model schematisation covers a large part of the Dutch Rhine/Meuse River delta and includes both the rivers, flood defence system and floodable hinterland (see Figure 3-4). The model simulates both river flow and flood propagation through the hinterland, based on a user-defined breach. The Delft-FLS model uses the following main input data:

- Elevation data
- Roughness data
- Inflow boundary conditions upstream
- Outflow boundary conditions downstream
- Breach growth characteristics

The elevation data implemented in the Delft-FLS model was based on laser altimetry data from the Dutch AHN1-dataset (PDOK, Kadaster, 2019). The roughness data used in this study originates from the Dutch LGN5 dataset (Hazeu, 2005), in combination with standard roughness values for different land use types.

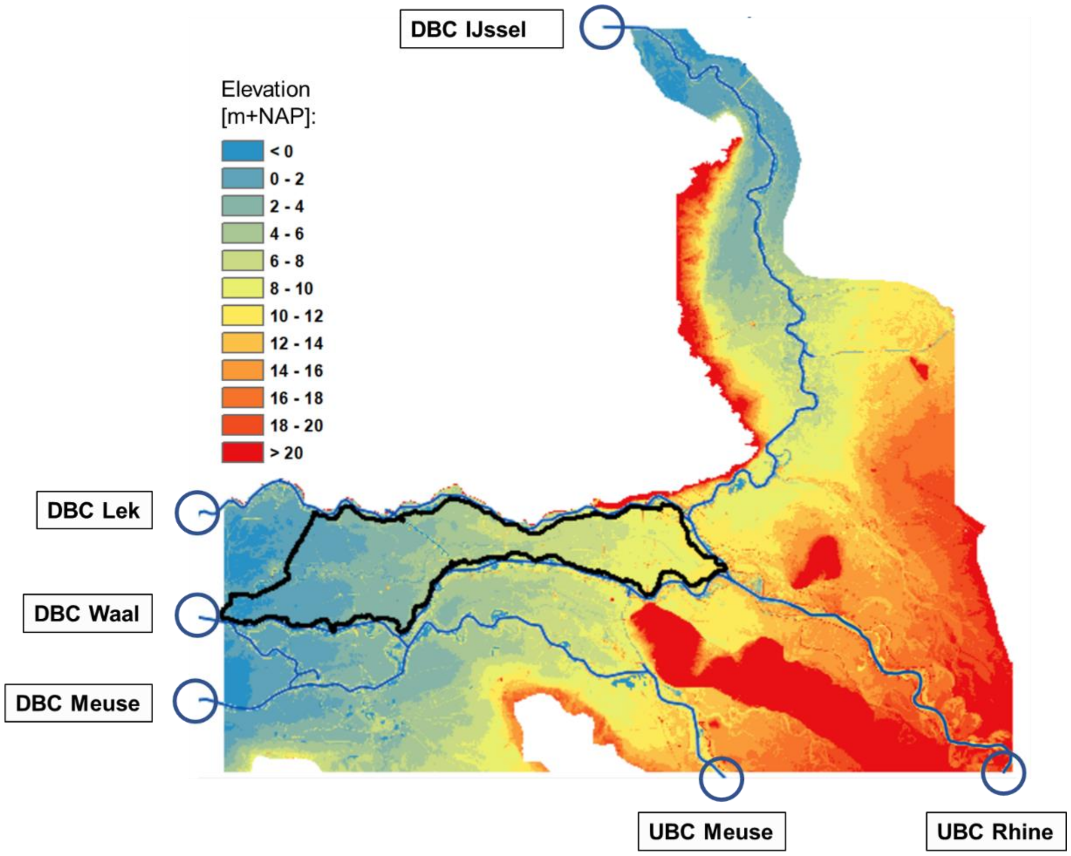

Figure 3-4: Extent of the Delft-FLS model. Elevation data and locations of the most important boundary conditions are shown (UBC = upstream boundary condition. DBC = downstream boundary condition). Dike ring 43 is highlighted in black

The model uses 6 primary hydraulic boundary conditions which describe the upstream Rhine and Meuse river inflow as discharge timeseries and the downstream river outflow boundary conditions via discharge water level relations (see Figure 3-4). These boundary conditions originate from the Dutch hydraulic boundary conditions 2006 (Ministerie van Verkeer en Waterstaat, 2007; Berger, 2008). All input data for Delft-FLS used for these verification calculations was available from Waterboard Rivierenland.

Delft-FLS does not contain an automatic breach growth module. For each flood simulation, predefined breach characteristics were implemented into the model. For the verification flood simulations, the same characteristics were used as for the calculation of the standards in the Dutch Water Act for the safety standard segments in the province of Gelderland. These describe the moment of breach initiation and the development of the breach width and depth in time. For all flood scenarios, the breach initiates when the outside water levels reach their peak at the breach location (De Bruijn & Van der Doef, 2011). After initiation, it is assumed that the breach deepens until the vertical scour has reached the surface level of the local hinterland (De Bruijn & Van der Doef, 2011). For the simulations in dike ring 43 this is assumed to occur within one hour after breach initiation. The breach width development after the initial vertical scour has finished was derived by the province of Gelderland with a simplified version of the Verheij-Van der Knaap equation for breach growth, established by Verheij (2003). The implemented breach growth curve is shown in Figure 3-5.

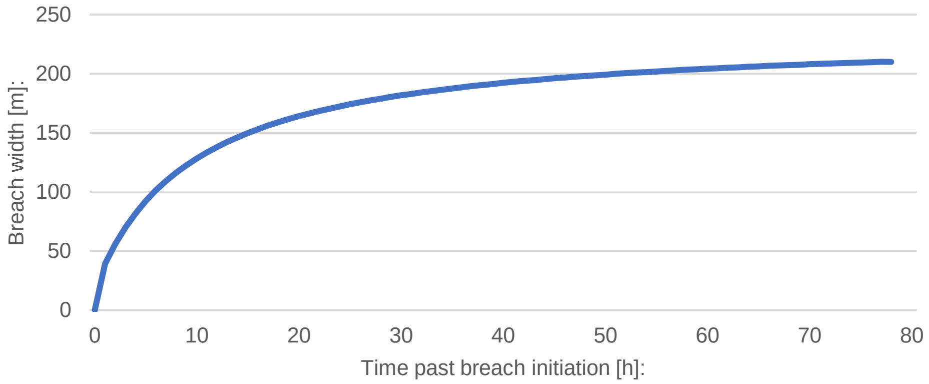

Figure 3-5: Breach development time series implemented in the flood simulation model, as derived by the Province of Gelderland (Slootjes et al. 2008)

For each flood simulation, Delft-FLS generates three types of output: grid-based maps of the flood rise rates, the maximum inundation depths and the maximum observed flow velocities. The rise rates were derived indirectly from the calculated inundation depths per timestep in an additional module. Delft-FLS registers the moment of transition between inundation depth classes (incremental depths) (WL Delft Hydraulics, 2001). Rise rates are calculated based on the transition between these classes, over the first 1.5m inundation depth. The choice for 1.5m is tied to the mortality functions, as explained by Jonkman (2007). Appendix A7 gives for one flood scenario an example of the three flood characteristic maps derived from Delft-FLS. Maps for all considered flood simulations in the verification calculation, along with descriptions and clarification of the flood characteristics are given by Vergouwe et al. (2014).

3.1.2 Calculation flood consequences

3.1.2.1 HIS-SSM

The flood characteristics derived from the 4 flood simulations made for this study correspond nearly exactly to the LIWO data for those 4 simulations. Therefore, for the flood consequence calculations the LIWO flood characteristics data was used as basis for all flood scenarios (the maximum inundation depths, maximum flow velocities and flood rise rates). The LIWO database contains flood data for 28 of the 30 flood scenarios discussed in paragraph 3.1.1.1. The remaining two flood scenarios (for breach locations Haaften and Heteren at TL+1D hydraulic conditions) were therefore not incorporated in these verification calculations. It is unknown whether these 2 missing scenarios were incorporated in the calculations carried out for the Dutch Water Act. The flood consequences for each flood scenario were calculated by application of the flood consequence calculation model HIS-SSM (version 2.5). HIS-SSM calculates for each flood scenario for all 100x100m grid cells the number of casualties for a flood event, the number of victims (residents whose house becomes inundated) and the economic damage, which are all used to calculate the flood safety standards based on the SCBA criterion. To calculate the extent of personal flood damage, HIS-SSM relies on population data for the year 2000. Monetised flood damage is calculated based on economic data, land occupation and asset data, mostly from 2000 as well (Gauderis & Kind, 2011).

3.1.2.2 Calculation personal damage

Within HIS-SSM, the number of flood victims is defined directly by the total number of residents in a grid cell. The number of casualties is calculated based on mortality functions. These functions define a relationship between the probability to pass away due to a flood event and the inundation depth. The functions used in HIS-SSM were initially derived by Jonkman (2007) and complemented by Maaskant et al. (2009a). The functions are based on empirical analysis of data from historical flood events from the 1950's in the Netherlands, the UK and Japan. Figure 3-6 shows the functions used in this study, which differ depending on the rise rate found in a grid cell.

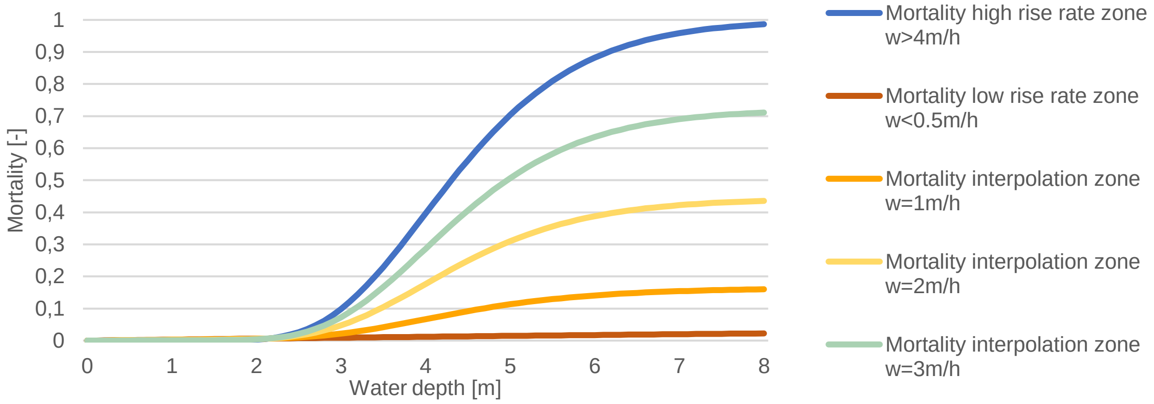

Figure 3-6: Mortality functions for low rise rates (<0.5m/h), high rise rates (>4m/h), as defined by Jonkman (2007) and mortality interpolation functions for rise rates (w) between 0.5 and 4m/h as defined by Maaskant et al. (2009a)

3.1.2.3 Calculation economic damage

The economic damage in HIS-SSM was calculated based on a series of functions which express a relationship between inundation depth and damage, as a percentage of the total value of the object/land. These functions have been defined for several different land use and asset categories, and are described in Kok et al. (2004) (Appendix A4 shows all damage functions). The functions were originally derived based on a combination of expert estimates and flood damage data from 2 historical floods in the Netherlands (flood events in 1945 and 1953) (Wagenaar et al. 2016) and are used for calculation of both direct damage and indirect damage, for instance due to post flood production losses and macro-economical effects (Kok et al. 2004). The maximum damage per category is for most categories based on replacement value of buildings and assets. For damage to business activities, added value data is used (Briene et al. 2002).

3.1.3 Derivation SCBA standards

The SCBA standards were derived in this study based on a cost optimum between reduced flood consequences (the benefits) and the required investment costs to achieve this reduction (the costs). This cost-benefit analysis was made separately for every safety standard segment. Flood consequences incorporate both economic and personal flood consequences (which is the social component in the social cost-benefit analysis) and were derived from the HIS-SSM outputs. The number of casualties given by HIS-SSM was corrected for the plausible effects of preventive evacuation of people. In accordance with Slootjes & Van der Most (2016b), the incorporated evacuation percentage was for the verification calculations set at 56% for the entire flood zone.

Personal damage was monetised and combined with the economic damage, to determine the total expected flood damage in monetary terms. The economic and personal damage is given by HIS-SSM for the year 2000, while the standards must be established for a time horizon until 2050 (Kind, 2011). Therefore, additional conversion steps were applied to project the flood consequences to the year 2050. Gauderis & Kind (2011) describes the applied conversions and parameters extensively.

Afterwards, for each safety standard segment, the total damage in 2050 for all flood scenarios within the segment were weighted (the scenarios for TL and TL+1D hydraulic conditions at the breach locations within the safety standard segment) with the following equation (Slootjes & Van der Most, 2016b):

$$D_{w,2050} = 0.6 * \left(\sum_{i=1}^{n} D_{i,TL,2050} * \frac{L_i}{L_{segment}}\right) + 0.4 * MAX(D_{i,TL+1D,2050}\ ; \ldots ;\ D_{n,TL+1D,2050}) \qquad (\mathbf{1})$$

In which:
$D_{w,2050}$= *Weighted total damage, projected towards 2050 [€]*
$D_{i,TL,2050}$ = *Total damage in 2050 for the TL flood scenario at breach location i.*
$D_{i,TL+1D,2050}$= *Total damage in 2050 for the TL+1D flood scenario at breach location i*
L_i= *Length of dike ring segment for which breach location i is representative [m]*
$L_{segment}$= *Length of the total safety standard segment [m]*
n = Number of dike ring segments within the safety standard segment

The weighted total damage derived with this equation is the direct input of the cost-benefit analysis. The required investment costs to decrease flood damage used in the cost-benefit analysis, are the investment costs required to improve the primary flood defences of a safety standard segment to a level where they can withstand hydraulic conditions with a 10 times smaller occurrence probability (one decimal height) than for TL-conditions. These estimated investment costs were derived based on the Dutch KOSWAT program, for which functions were derived which express the investment costs for a certain crest level increase. The derived functions account for many relevant aspects which influence dike investment costs, such as the location, relevant failure mechanisms, type of improvement and unit prices for required materials and labour. The full procedure is described extensively in De Grave & Baarse (2011). For the verification calculations in this study, these costs were used directly as calculated for the Dutch flood safety program by Rijkswaterstaat and were not derived in this study.

Slootjes & van der Most (2016b) showed that the optimal tradeoff between reduced flood consequences and required investment costs and hence the associated optimal flood probability can be approximated based on the found total flood damage and investment costs (Slootjes & Van der Most, 2016b):

$$P_{2050}^{alert} = \frac{1}{38}\frac{I(h_{10})}{D_{w,2050}} \qquad (\mathbf{2})$$

In which:
P_{2050}^{alert} *= Alert standard (annual flood probability in 2050) [1/year]*
$I(h_{10})$ *= Investment costs for dike improvement (crest level increase) with one decimal height [€]*
$D_{w,2050}$ *= Weighted total damage, projected towards 2050 [€]*
The factor 1/38 originates from the assumed discount rate, set at 5.5% (De Grave & Baarse, 2011).

This approximation equation gives the alert standards and was used both in this study and for the calculation of the alert standards tied in the Dutch Water Act (Slootjes & Van der Most, 2016b).

3.1.4 Calculation mortality values LIR

The LIR standard derivation methodology uses mortality calculations as well. For the LIR standard derivation, mortality values for each grid cell were calculated in the spatial data analysis program ArcGIS (instead of HIS-SSM used for the SCBA standard derivation). For each 100m x 100m grid cell, mortality values were calculated based on the LIWO flood characteristics data (maximum inundation depths, flow velocities and rise rates per grid cell) by application of the same mortality equations used by HIS-SSM to calculate the total number of casualties in a flood event (see Figure 3-6). For each flood scenario, a mortality grid map was derived. These maps were used to derive a map with weighted mortality values per safety standard segment, by applying the same weighing equation as shown by equation 1 for each grid cell (with mortality values instead of damage values). The weighted mortality values therefore represent the probability to become a flood casualty from any possible flood scenario within a safety standard segment.

Afterwards, the derived weighted mortality values were aggregated to a spatial resolution on neighbourhood level. LIR standards are always derived based on neighbourhood mortality values rather than grid cell mortality values. This approach prevents that small-scale extreme mortality values or errors result in exceptionally strict safety standards. These neighbourhoods originate from the neighbourhood dataset of the Dutch statistics bureau (CBS) for 2008 (CBS & Kadaster, 2019a). The neighbourhoods were defined based on differences in landscape, land use and socio-economic structure (CBS, 2019). Characteristics of these neighbourhoods relevant for flood risk vary greatly, such as the surface area (varies between 20 and 2000 ha) or the number of inhabitants (varies between 0 and 9000 inhabitants). Figure 3-7 shows the neighbourhood polygons for dike ring 43. For each neighbourhood a median mortality value was derived from all mortality cells within the neighbourhood, by exclusion of mortality values within 100m distance of surface water bodies, in accordance with Slootjes & Van der Most (2016b).

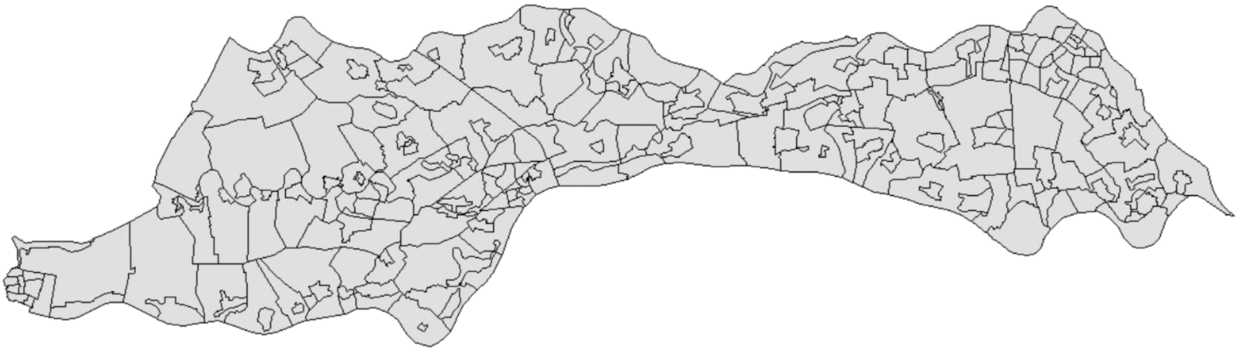

Figure 3-7: Neighbourhood polygons dike ring 43 (CBS & Kadaster, 2019a)

3.1.5 Derivation LIR standards

Eventually, the LIR standards for each safety standard segment were derived based on the neighbourhood where the highest weighted median mortality is found. The LIR standard is set such that the LIR requirements for the alert and lower limit standards are met (a maximum LIR of 1/100.000 per year for the lower limit standard and 1/200.000 for the alert standard (Slootjes & Van der Most, 2016a)). The alert and lower limit standards were calculated for each safety standard segment based on the following equation (derived from Beckers & De Bruijn, 2011):

$$P_f = \frac{LIR}{(1-E)*M} \qquad (\mathbf{3})$$

In which:
P_f *= Flood safety standard as annual flood probability [y^{-1}]*
LIR = Maximum allowed local individual risk value [y^{-1}] = 1/100.000 for lower limit standard and 1/200.000 for the alert standard (Slootjes & Van der Most, 2016a)
M = Weighted median mortality value in the normative neighbourhood [1/flood event]
E = Evacuation fraction [-] = 0.56

For one safety standard segment (43-1), it became clear that due to a wrong definition of the border between flood plains and hinterland, mortality values from the flood plain were sometimes incorporated in the derivation of the neighbourhood-based mortality. As a result, some neighbourhoods received a mortality value while they are in fact not inundated (see Figure 3-8). These neighbourhoods were omitted in the analysis and the neighbourhood with the highest correct median mortality value was used to derive the LIR standards (see Figure 3-8).

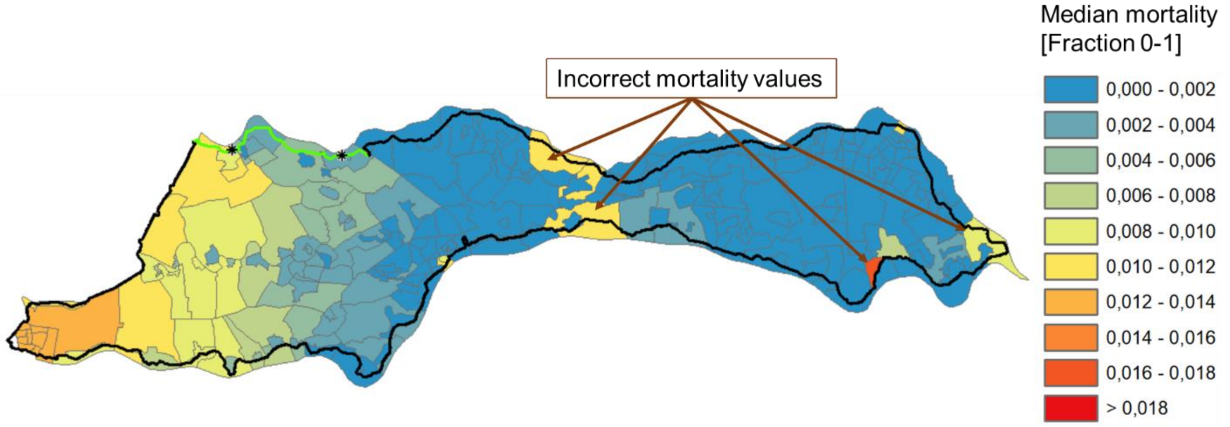

Figure 3-8: Median mortality map for safety standard segment 43-1 (highlighted green), in which the breach locations are depicted. Neighbourhoods with a mortality value assigned in the eastern part of the dike ring are incorrect. The correct mortality values are found in the western part.

The evacuation percentage used to derive the LIR standard with equation 3, is the same value as used in the SCBA standard calculation (56%). The median weighted mortality value of the normative neighbourhood in combination with the legally determined maximum allowed local individual risk (LIR) value gives the maximum allowed annual flood probability based on the LIR criterion.

The described approach to derive the LIR standard separately for each safety standard segment does not yet incorporate the fact that the flood hazard for many neighbourhoods in dike ring 43 originates from more than one segment (see Figure 3-9). Therefore, an additional correction was applied to assure that the total LIR in a neighbourhood (added up from all safety standard segments) does not exceed the maximum allowed LIR value. The standards for all 6 segments were set stricter by a factor equal to the ratio between the total LIR in the dike ring wide normative neighbourhood and the maximum allowed LIR. This factor was applied for all safety standard segments, regardless whether the flood risk posed by a segment contributes to the dike ring wide normative neighbourhood.

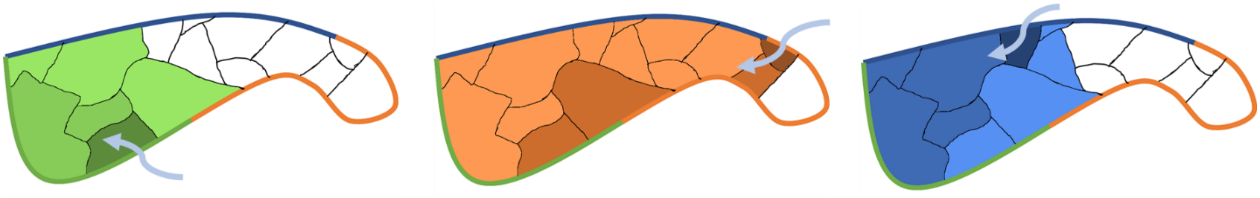

Figure 3-9: Fictional example of a dike ring with three safety standard segments and multiple neighbourhoods, where the total mortality in the western neighbourhoods originates from flood hazard posed by flood scenarios in all three safety standard segments.

3.1.6 Derivation normative safety standards

In the final step (Figure 3-2), the derived SCBA and LIR standards were aggregated into a safety standard class, according to the classification scheme defined by Slootjes & Van der Most (2016a) (see Table 3-1). The SCBA lower limit standard was not calculated but derived directly from the calculated alert standard and is always set one class stricter than the alert standard class. The normative safety standard for each of the 6 safety standard segments is the strictest of the SCBA and LIR safety standard class.

Table 3-1: Safety classes and corresponding interval of the calculated rough standards (Slootjes & Van der Most, 2016a)

Calculated rough protection standard [1/y]:	**Safety standard class [1/y]:**
> 1/550	1/300
1/550 – 1/1.700	1/1000
1/1.700 – 1/5.500	1/3000
1/5.500 – 1/17.000	1/10.000
1/17.000 – 1/55.000	1/30.000
1/55.000 – 1/170.000	1/100.000

3.2 Identification primary uncertainty sources

The verification safety standard calculations showed that many potential sources of uncertainty can be identified in the safety standard calculation process. Within this research, the next step was therefore to determine which uncertainty sources should be considered in the uncertainty analysis.

The literature review in paragraph 1.3 made clear that available literature does not provide a solid ground based upon which the primary uncertainty sources in the calculation process can be defined. Furthermore, the influence of individual uncertainty sources can vary for different areas. In this study, the primary uncertainty sources of influence on the standards for dike ring 43 were identified through expert elicitation. Afterwards, the results from the expert elicitation process were used to decide which uncertainty sources should be considered in the uncertainty analysis.

3.2.1 Selection of experts

To limit the influence of different types of individual expert bias on the overall result in an expert elicitation procedure, the number of consulted experts should ideally be as large as possible, but at least 4 experts should be consulted according to Van der Sluijs et al. (2004). The number of experts interviewed in this study was set at 6. These 6 experts were selected because of their acquaintance with the safety standard derivation process, its application and the interpretation of the derived standards. The following 6 experts were consulted:

- Herman van der Most (Deltares)
- Dennis Wagenaar (Deltares)
- Ruben Jongejan (Jongejan RMC)
- Durk Riedstra (Rijkswaterstaat)
- Michel Tonneijck (Royal HaskoningDHV)
- Peter Van der Scheer (Royal HaskoningDHV)

Three of these experts are member of the flood safety group within the Dutch expert network for flood protection. These experts have been closely involved in the development of the methodology to derive the current flood safety standards, each with their own expertise and affinity with the subject matter. One expert was involved in the calculation process of the standards as modeller and made many calculations in light of the new flood safety standards for various safety standard segments. He therefore has an excellent overview of the calculation process and the principles and characteristics of the calculations. One expert is an experienced professional within the subject of flood safety who is also a visiting lecturer at a university, amongst others covering the subject of flood probabilities and safety standards. One expert is an experienced professional within the application of flood safety standards in dike improvement programs and design of flood defences based on the new standards.

With these 6 experts of various backgrounds, the total group has a complete overview of the calculation process of the current safety standards and the associated potential sources of uncertainty.

3.2.2 Set-up interview sessions

The purpose of the interviews is to identify which uncertainty sources in the calculation process are likely of most significant influence on the flood safety standards for the segments of dike ring 43. This information was used to create a ranking of most influential uncertainty sources based on the expert opinions.

As a way of structuring the interview sessions and to assure that each expert considers all consecutive steps, components and uncertainty sources in the calculation process of the safety standards, each expert was provided with a list of predefined potentially relevant uncertainty sources in the calculation process. Warmink et al. (2010) stated that it is useful to provide a structured overview in which all types of uncertainty are incorporated, as uncertainty analysis studies often only consider easily quantifiable uncertainties. Furthermore, in case of uncertainty source identification by using expert elicitation it can otherwise strongly depend on the expert which uncertainties are mentioned.

This list of identified uncertainty sources was derived mainly based on reviewing available documentation of the safety standard calculation process (amongst others Slootjes & Van der Most (2016a); Gauderis & Kind (2011); Vergouwe et al. (2014) and De Bruijn & Van der Doef (2011)) and the verification safety standard calculations in paragraph 3.1. Table 3-2 shows the list of predefined uncertainty sources. The uncertainty sources incorporated in this list are both epistemic uncertainties and uncertainties related to natural variability of the system. Furthermore, they originate from all possible locations within the model chain (as defined by Warmink et al. (2010)) such as model-technical parameters, input data uncertainty and the model structure used to derive the standards.

For each of these uncertainty sources, the experts were asked to comment on the expected influence of the uncertainty source on the flood safety standards derived for dike ring 43. The experts each expressed their qualitative judgement about the uncertainty sources with a quantitative score based on a 5-point scale: 1 represents an expected minor influence on the eventually derived standards, while a score of 5 was awarded to uncertainty sources with the highest influence on the uncertainty of the derived standards. This method enables aggregating the scores of the individual experts into an overall score table, similar to the procedure used by Warmink et al. (2011). In their judgements, the experts were asked to incorporate both the uncertainty range of the uncertainty source, as well as the expected influence on the flood safety standards, as an aspect might be very uncertain, but might hardly influence the standards or vice versa. Considering these two aspects, the experts awarded one score for each uncertainty source. Besides commenting on the predefined uncertainty sources, the experts were also asked to comment on the completeness of the list, point to additional uncertainty sources which might not have been included in the predefined list and express their opinion on the current characteristics of the safety standard derivation methodology and the associated uncertainty. Appendix A1 gives a short overview of the set-up of the interview sessions.

3.2.3 Uncertainty ranking

After the 6 experts defined a score for each of the predefined uncertainty sources, the scores of the 6 experts were averaged, to generate a ranking of the uncertainty sources based on their expected influence on the flood safety standards for dike ring 43. During the interview sessions, not all of the experts used the highest scores, either because an expert argued that none of the uncertainty sources would be of significant influence on the safety standards or because an expert was reluctant to use the highest scores. The purpose of the expert interviews was to gather an uncertainty ranking based on expert judgements of the relative influence of uncertainty sources and not to receive a quantified uncertainty estimate. The awarded scores for 4 of the experts were therefore rescaled into a 5-point scale. The rescaling does not affect the ratio between the initial scores awarded to individual aspects, and the expert’s relative judgements remain the same. After the rescaling, an average score was calculated for each uncertainty source.

Table 3-2: Predefined uncertainty sources discussed with the experts in the interview sessions

Influencing SCBA or LIR standard?	Uncertainty source	Influencing SCBA or LIR standard?	Uncertainty source
LIR & SCBA	Peak discharge representing TL and TL+1D hydraulic conditions	LIR & SCBA	Mortality functions
LIR & SCBA	Hydrograph shape representing TL and TL+1D hydraulic conditions	LIR & SCBA	Evacuation percentages
LIR & SCBA	Downstream stage/discharge relation boundary conditions	SCBA	Population data
LIR & SCBA	Breach locations for representative flood scenarios	SCBA	Correction factor for population growth 2000-2011
LIR & SCBA	Moment of breach-initiation	SCBA	land use and asset data
LIR & SCBA	Breach development (width, depth & development time)	SCBA	Damage functions
LIR & SCBA	Elevation data	SCBA	Maximum damage values
LIR & SCBA	Land use data used for roughness estimations	SCBA	Correction factor for increased economic value 2000-2011
LIR & SCBA	Roughness values per land use class	SCBA	Correction factor for unaccounted damage and risk aversion
LIR & SCBA	Grid size Delft-FLS	SCBA	Monetisation values for casualties and victims
LIR & SCBA	Timesteps Delft-FLS	LIR & SCBA	Ratio reference flood scenario and extreme flood scenario
LIR & SCBA	Correctness Delft-FLS simulations	LIR	Neighbourhood-based mortality aggregation
LIR & SCBA	Derivation flood rise rate based on incremental inundation depths	SCBA	Economic growth scenario 2050
LIR & SCBA	Stability increased surface elevation lines	SCBA	Investment costs flood defence improvement
LIR & SCBA	Operation Lingewerken & Spill flow works at Dalem	SCBA	Discount rate
LIR & SCBA	Influence of the positive system effect	LIR & SCBA	Length of the current safety standard segments
LIR & SCBA	Influence of the negative system effect	LIR	Neighbourhood-based LIR redistribution over multiple safety standard segments

3.3 Quantification of uncertainty

After gathering a priority list with uncertainty sources in the safety standard derivation process, the third step in this research was to quantify the uncertainty of the most important uncertainty sources, to enable propagation through the calculation process and analyse the induced influence on the flood safety standards. Below, first an overview of the considered uncertainty sources is given, as well as the general method of uncertainty quantification followed in this study. Afterwards, each uncertainty source and the specific quantification method are discussed.

3.3.1 Uncertainty quantification approach

Based on the expert interview sessions from the previous research step, a ranking scheme of the most important uncertainty sources was established. The ranking scheme (see Table 4-4) does not enable defining a small selection of uncertainty sources which are significantly more important than the rest of the uncertainty sources. For feasibility grounds therefore the upper 5 uncertainty sources, which received the highest average expert scores, were further considered and incorporated in the uncertainty analysis:

- **Breach development** *(Influences LIR & SCBA standards*)
- **Mortality functions** (*Influences LIR standards and to a lesser extent SCBA standards*)
- **Evacuation percentages** (*Influences LIR standards and to a lesser extent SCBA standards*)
- **Damage functions** (*Influences SCBA standards*)
- **Investment costs for flood defence improvement** (*Influences SCBA standards*)

Of these 5 uncertainty sources, three influence both the SCBA and LIR standard calculation, while the damage functions and investment costs for the improvement of flood defences only influence the SCBA standard calculation. Figure 3-10 shows schematically which of the steps in the safety standard calculation process are primarily and directly affected by these uncertainty sources. Note that the mortality functions and evacuation percentages influence the SCBA standard calculation as well, but to a far lesser extent. The casualty-related monetary damage only accounts for approximately 10% of the total monetary damage for the scenarios of dike ring 43 (as observed during the verification calculations in this study).

Within the uncertainty analysis, in principle all 6 safety standard segment of dike ring 43 are considered for each of the 5 uncertainty sources. Two exceptions however are the breach development and investment costs. Paragraphs 3.3.2 and 3.3.6 discuss these exceptions.

The basic quantification approach followed for each uncertainty source was to establish confidence intervals around a certain most likely (reference) scenario, based on insights from literature or based on available data for dike ring 43. This approach enables an equivalent analysis of the individual uncertainty sources' influence on the flood safety standards. As reference scenario, it seems logic to consider the settings used in the verification calculations made in this study. These settings do however not necessarily represent the average or most likely scenario for the case study, as the safety standard calculation process currently does not give a location-specific representation of the reality but rather uses a consistent estimate. Multiple interviewed experts in this study pointed to this characteristic as well. This study tries to find an uncertainty bandwidth around the most plausible flood safety standards for dike ring 43. For the uncertainty quantification therefore for each uncertainty source, besides uncertainty quantification, the scenario used in the verification safety standard derivations was reviewed as well. In case literature insights or available data provided a more solid base for the definition of a most likely scenario, the verification scenario was altered to derive a reference scenario for the uncertainty analysis.

The uncertainty analysis in this study followed a scenario analysis approach, which is further introduced in paragraph 3.4. The uncertainty quantification therefore seeks for a limited number of distinct scenarios for each uncertainty source, from which the influence on the safety standards can be derived. The complexity and significant time consumption of the calculation process of the standards prohibits propagating many alternative scenarios through the calculation process. Uncertainty sources were therefore quantified such that a 50% confidence interval around the established reference scenario can be defined. As upper and lower limit of the 50% confidence interval, 2 alternative scenarios were defined: a 25th and a 75th percentile scenario, which can both be propagated through the safety standard derivation process to show the influence of these uncertainty sources. The choice for a 50% confidence interval was made because this gives a more practically useful result than for example a more extreme 90% confidence interval. The 25th and 75th percentile scenarios are still realistic and therefore give a more intuitive sense of a plausible uncertainty range around the reference standards than 5th & 95th or 1st & 99th percentile scenarios would.
The quantification of the 50% confidence interval for each uncertainty source is the result of this third research step.

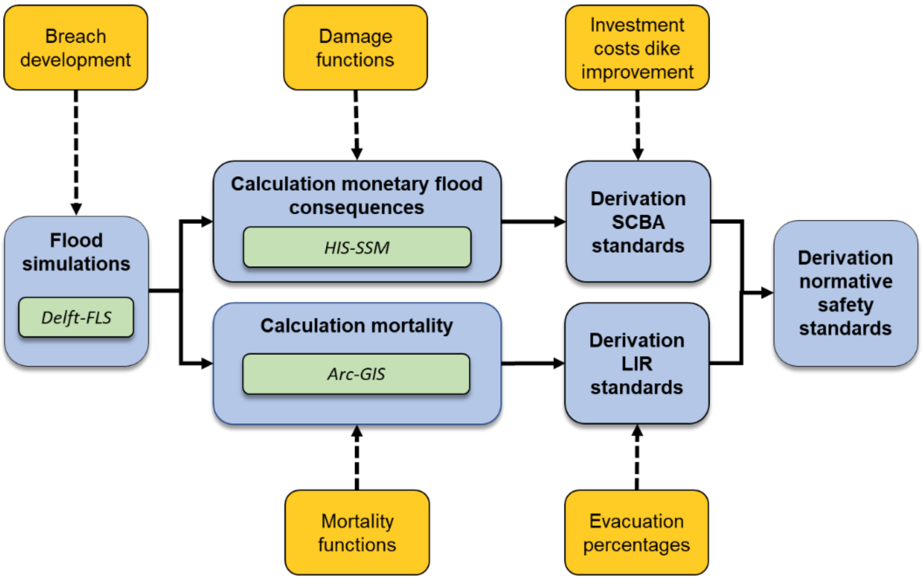

Figure 3-10: Flood safety standard derivation process schematisation and components where the considered uncertainty sources influence the process primarily.

3.3.2 Breach development

As mentioned in paragraph 3.1.1.2, the original approach to describe breach development over time for the safety standard segments in the province of Gelderland is derived from the Verheij-Van der Knaap equation (Verheij, 2003):

$$B(t) = 1{,}3\frac{g^{0{,}5}H^{1{,}5}}{u_c}\log\left(1+\frac{0{,}04g}{u_c}t\right) \qquad (\mathbf{4})$$

In which:
B(t) = Breach width at time t after the breach starts to grow in width
g = Gravitational acceleration constant = 9,81m/s^2
u_c *= Critical flow velocity for erosion of the dike material [m/s]*
H = Time-averaged head difference over the breach during the breach development phase [m]
t = Time after breach initiation [h]

This approximation equation was derived from measured breach development data by Verheij (2003). The equation is applicable to estimate breach development for both dikes with sandy and clayey compositions, based on the head difference over the breach and the erosion resistance of the material of which the dike is composed (for a further explanation see Verheij, (2003)).

The current safety standard calculation approach uses one breach growth function (see Figure 3-5) for all flood scenarios. The exact parameter configuration (H and U_c) resulting in the breach growth curve of Figure 3-5 is unknown. It is however mentioned by Gauderis et al. (2011) that it is common practice in these flood simulations to assume a sand dike. For a sandy interior (with $U_c = 0.2$m/s; (Verheij, 2003)) and a time-averaged head difference over the breach $H=2.8$m, the equation gives a close approximation of the breach growth function used in the original safety standard derivations. This single breach growth curve was applied for all flood scenarios of dike ring 43 in the original safety standard calculations, regardless of possible differences in dike composition for different locations along the Dutch river system or variety in head differences over the breach at different locations. The breach development function is therefore a clear source of uncertainty.

The breach development uncertainty due to uncertainty of the dike composition is included in the uncertainty analysis for this study. Uncertainty in dike composition was implemented in the Verheij-Van der Knaap equation via soil parameter U_c, which varies for different materials, depending on erodibility (such as sandy or clayey material). The uncertainty quantification approach used here is therefore based on a probability distribution of the value for U_c, which was then used to propagate uncertainty through the safety standard calculation process.

The influence of breach development uncertainty was in this study only considered for safety standard segment 43-6 due to the extensive model and processing times of the flood simulation model Delft-FLS. This segment was chosen, as the normative neighbourhood for this segment is only inundated by floods originating from this segment (see appendix A8). For safety standard segments where the normative neighbourhood can be flooded from multiple segments, the effects would be less clear if only the breach development in the flood scenarios relevant for one single safety standard segment is analysed.

Safety standard segment 43-6 consists of 2 dike ring segments, each with one representative breach location: Tiel-West and Haaften (see Figure 3-11). For the verification calculations, three flood scenarios were considered along this safety standard segment: for TL and TL+1D hydraulic conditions at Tiel-West and TL conditions at Haaften.

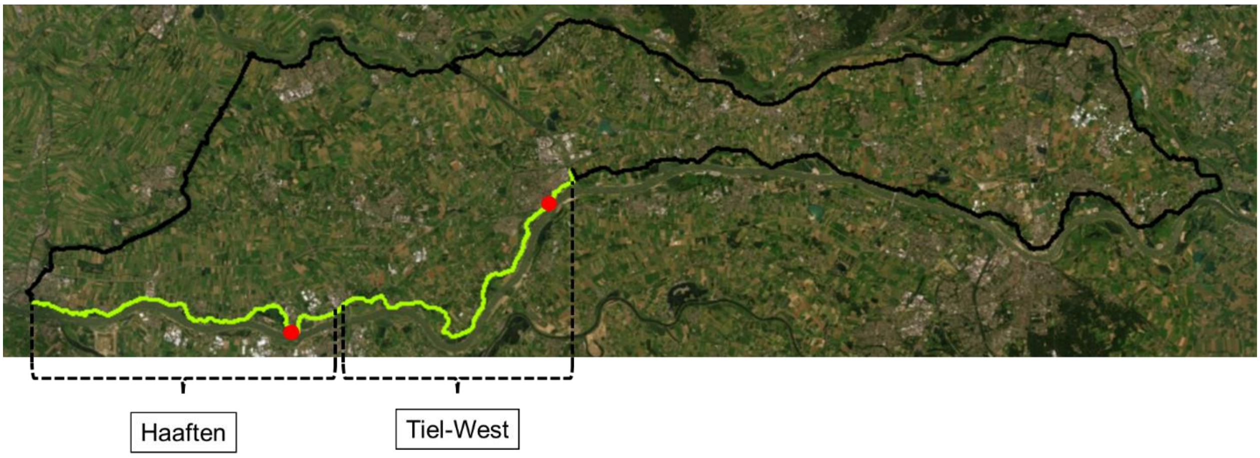

Figure 3-11: Safety standard segment 43-6 highlighted in green with its two dike ring segments Haaften and Tiel-West. The two representative breach locations for these dike ring segments are shown as red dots.

The uncertainty in dike composition in this area was quantified by considering the dike composition over the entire safety standard segment. Two separate data sources were used for the uncertainty quantification of the dike material. For dike ring segment Haaften (see Figure 3-11), technical cross-section drawings which show the internal dike composition were analysed. These are available for intervals of 100m, based on the last major dike reconstruction works in the area in the 1990's (Waterschap Rivierenland, 2014). Figure 3-13 gives an example of the cross-sectional data, while Appendix A3 provides additional examples. For dike ring segment Tiel-West, detailed cross sections were not readily available. For this dike ring segment, information about the dike composition was obtained from core drill samples of the dike interior at 9 locations spread over this dike ring segment. The core drill data is publicly available via Dinoloket, the Dutch platform where data from soil and underground measurements is stored (TNO, 2019). Figure 3-12 gives an example of the data, appendix A3 shows all core drill sample data that was used.

For both data sources, estimations were made of the ratio between the amount of sandy and clayey material of which these dikes consist. This ratio was used to quantify the uncertainty of U_c for the dikes in the area. As detailed information about the critical flow velocities of the specific dike material in these dikes is lacking, typical U_c-values for clayey and sandy material were used to translate the found clay/sand ratios into average values for U_c. In accordance with Verheij (2003), a typical critical flow velocity of 0,2m/s for sandy dike material and 0,5m/s for clayey dike material was assumed.
Analysis of the dike composition data points out that the variety is significant over the safety standard segment (see appendix A3). Table 3-3 shows the minimum, maximum and most commonly found sand/clay ratios in the area. These typical sand/clay ratios were translated into typical values for U_c, by averaging the assumed U_c-values for sandy and clayey material for these ratios. For both dike ring segments, the datasets showed a very similar variation of the composition of the dike interior. Therefore, no further differentiation was made between these two sections for the quantification of the uncertainty.
From the characteristic sand/clay ratios, the variation of the sand/clay ratio was described statistically via a triangular distribution. Triangular probability distributions describe the probability density of U_c over a finite domain. The dike composition data enabled defining an absolute minimum, maximum and most commonly found value for the area. A triangular distribution therefore is a suitable representation of the probability of the average U_c-value along this safety standard segment. The fitted triangular distribution for U_c was used to define a 50% confidence interval for U_c around the mean value. This confidence interval was eventually translated into a confidence interval for the breach growth curve, by use of the Verheij-Van der Knaap equation (equation 4 in paragraph 3.3.2).

Table 3-3: Minimum, maximum and most commonly found sand/clay ratios for safety standard segment 43-6 and accompanying average U_c-values

Sand/clay composition ratio:	Average U_c-value [m/s]
0/100 (maximum)	0,50
20/80 (Most common)	0,44
80/20 (minimum)	0,26

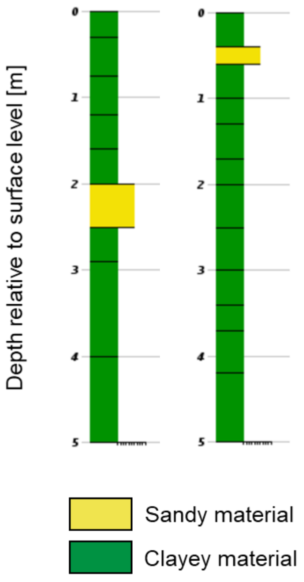

Figure 3-12: Example of 2 core drill samples used to quantify U_c for dike ring segment Tiel-West (TNO, 2019)

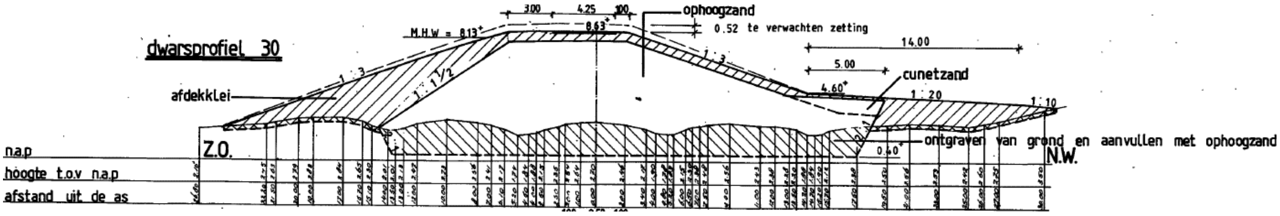

Figure 3-13: Example of cross-sectional dike composition data used to quantify uncertainty of U_c for dike ring segment Haaften. This example shows a mainly sandy dike composition (Waterschap Rivierenland, 2014).

3.3.3 Mortality functions

The mortality functions used in the flood safety standard derivation approach give an estimation of the number of casualties which should be expected in case of a large-scale flood event. The used mortality functions for flood casualty estimations originate from Jonkman (2007) (also used in the verification safety standard calculations). Jonkman (2007) derived three separate mortality functions for three different zones of the flooded hinterland, distinguished by the observed rise rates, flow velocities and inundation depths. These functions were defined based on mortality datasets in these distinguished zones, primarily originating from the Dutch coastal floods in 1953. Maaskant et al. (2009a) extended the set of functions with a fourth interpolation function:

In the zone with high flow velocities and inundation depths (the breach zone):

$$\boldsymbol{F_B(d) = 1}; \quad for\ dv \geq 7m^2/s\ \&\ v \geq 2m/s \qquad (\boldsymbol{5})$$

In the zone with high rise rates and inundation depths:

$$\boldsymbol{F_{FR}(d) = \phi_n\left[\frac{\ln(d) - \mu_N}{\sigma_N}\right]} \qquad with{:}\ \mu_N = 1.46 \quad \sigma_N = 0.28;$$

$$for\ d > 2.1m\ \&\ w > 4.0m/h \qquad (\boldsymbol{6})$$

In the zone with lower inundation depths or low rise rates:

$$\boldsymbol{F_{SR}(d) = \phi_n\left[\frac{\ln(d) - \mu_N}{\sigma_N}\right]} \qquad with{:}\ \mu_N = 7.60 \quad \sigma_N = 2.75;$$

$$for\ d < 2.1m\ \ or\ w < 0.5m/hr \qquad (\boldsymbol{7})$$

In the remaining zones, the following linear interpolation equation is used (Maaskant et al. 2009a):

$$\boldsymbol{F_{RZ}(d) = F_{SR} + (w - 0.5)\frac{F_{D,FR} - F_{D,SR}}{3.5}} \qquad (\boldsymbol{8})$$

<u>In which:</u>
$F_{D,B}$ = mortality in the breach zone [1/flood event]
$F_{D,FR}$ = mortality in the zone with high rise rates [1/flood event]
$F_{D,SR}$ = mortality in the zone with low rise rates [1/flood event]
$F_{D,RZ}$ = mortality in the remaining zone [1/flood event]
d = Inundation depth [m]
v = flow velocity [m/s]
w = water level rise rate [m/h]
ϕ_n= lognormal distribution function
μ_N & σ_N are the mean and standard deviation of the lognormal distribution

These mortality functions are uncertain due to multiple aspects, many of which are discussed by Jonkman (2007) and Maaskant et al. (2009a). It was not feasible to quantitatively include all uncertain aspects in this uncertainty analysis as these uncertain aspects impact the mortality functions differently, which restricts defining clear confidence intervals of the functions. The influence of these uncertain aspects on the safety standards was therefore qualitatively analysed, to determine how the uncertainty of the mortality functions can best be quantified and incorporated in this study.

Mortality uncertainty primarily influences the LIR standards. The flood characteristics acquired from the verification safety standard calculations described in paragraph 3.1.1 provide useful insights into which aspects of the mortality functions are of most influence on the LIR standards. Figure 3-14 shows which of the four mortality functions were used in the mortality calculations for different parts of the flood zone, based on the flood characteristics observed locally. It becomes clear that the areas where the highest mortalities were observed in the verification safety standard calculations are dominated by the interpolation rise rate function (equation 8). These areas also contain the normative neighbourhood from which the LIR standard of segment 43-6 is derived. This insight shows that especially the uncertainty of the interpolation function can impact the LIR standards.

In this specific zone, especially the used interpolation approach between the high (>4m/h) and low (<0.5m/h) rise rate functions is prone to uncertainty, as described by Maaskant et al. (2009a). The uncertainty related to the interpolation function was therefore incorporated in the uncertainty analysis of the flood safety standards.

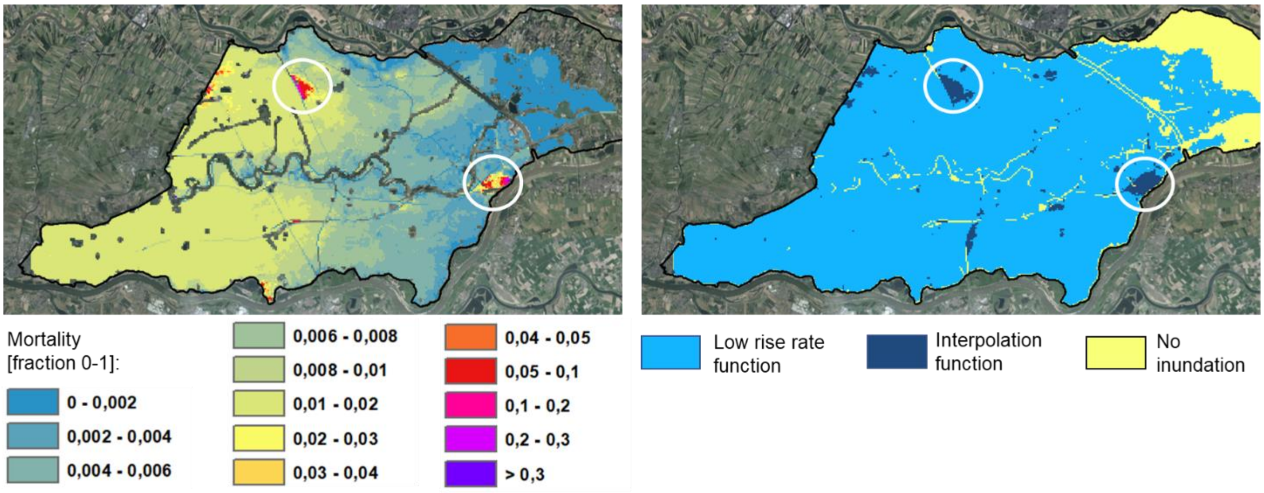

Figure 3-14: Left: Mortality map from the verification safety standard calculations for safety standard segment 43-6, in which the areas with the highest mortality are white encircled. Right: Mortality function zonation map, showing which of the mortality functions was used. Again, the areas with the highest mortality are white encircled.

Jonkman (2007) argued based on the data he used that the threshold for application of the function for high rise rates could be chosen anywhere between 0,5 m/h and 4 m/h. Maaskant et al. (2009a) chose to interpolate linearly between the two functions for rise rates between 0.5 and 4m/h (see equation 8). This assumption could however differ significantly in reality. Quantification of this uncertainty is hard, as additional usable mortality data does not exist. As quantification of this uncertainty source it can therefore only be said that any type of transition between the two functions could be a plausible representation of the reality. As a result, a 50% confidence interval of the interpolation function was given through an educated guess. The concept by Maaskant et al. (2009a) to interpolate linearly between the high and low rise rate functions defined by Jonkman (2007) is intuitively realistic, as slight changes in flood circumstances would likely not cause abrupt changes in mortality rates. The linear interpolation scenario is therefore used as reference scenario in the uncertainty analysis.

The 50% confidence interval of the interpolation function was set based on best guess curves. The best guess curves (shown in Figure 3-15) are defined at an equal distance from the reference scenario. As any interpolation between 0,5 and 4m/h is in theory possible, a symmetrical 50% confidence interval around the reference curve is the best possible guess. The alternative functions both start and end at the same location, as it is again unrealistic that mortality would change abruptly in reality for slight changes in rise rate.

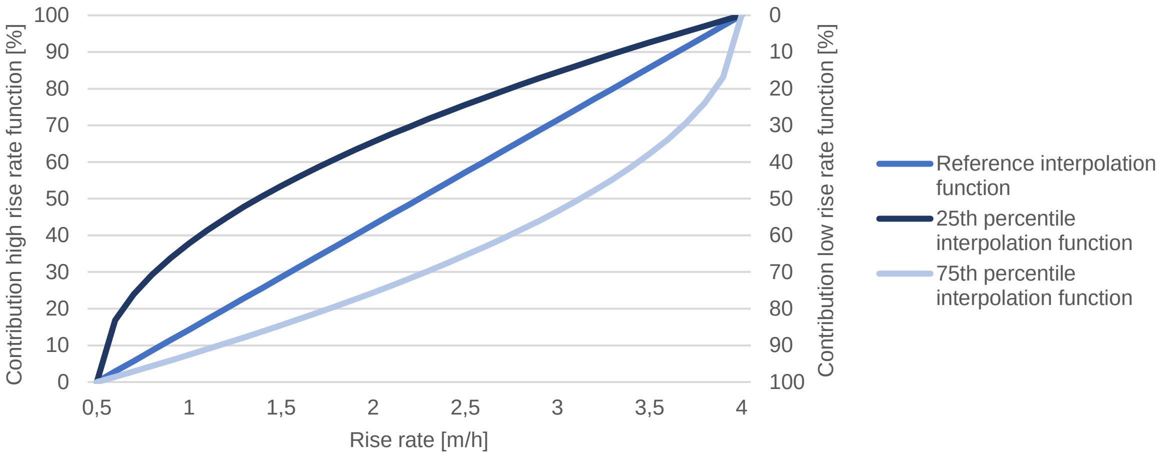

Figure 3-15: Reference and best guess 50% confidence interval for the interpolation between the mortality functions for high and low rise rates (equations 6 and 7). This figure shows the interpolation functions as contribution percentage of the high and low rise rate functions by Jonkman (2007). The 75th percentile scenario corresponds with a more dominant high rise rate function, while the 25th percentile scenario corresponds with a more dominant low rise rate function.

Further review of the currently used mortality functions gave reason to additionally make an adaptation to the verification high rise rate mortality function, based on studies by Asselman (2005) and Jonkman (2007). The data used to derive the high rise rate mortality function originates from 1953. In the areas with high rise rates, many buildings collapsed in the floods of 1953. Jonkman (2007) shows that there is a linear relationship between building collapsibility and mortality in the data from 1953. Asselman (2005) showed that improved building quality in the Netherlands since 1953 would reduce the collapsibility of buildings under those flood circumstances by almost 60%. Jonkman (2007) has therefore also derived a high rise rate mortality function which corrects for the reduced collapsibility of buildings in modern times. The adapted mortality function therefore gives a better representation of the expected mortality for modern-day floods in the Netherlands. Therefore, the adapted function was used as reference scenario for the high rise rate mortality function in this study. Figure 3-16 shows the differences between the functions.

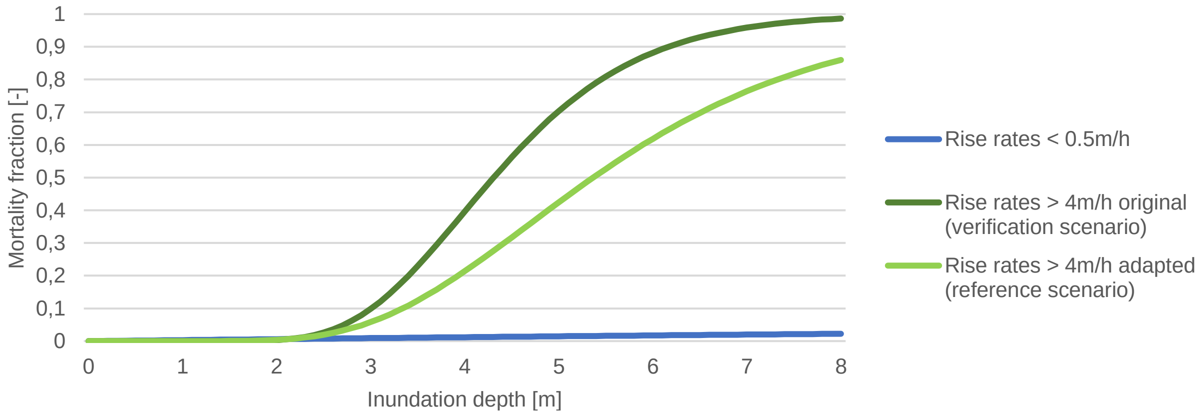

Figure 3-16: Mortality functions for low rise rates and high rise rates as defined by Jonkman (2007) and the adapted high rise rate function as defined by Jonkman (2007). This adapted function was used as reference scenario for the high rise rate mortality function.

3.3.4 Evacuation percentages

As mentioned earlier in paragraph 3.1, the current calculation process for the flood safety standards accounts for a preventive evacuation percentage of 56%. This percentage was defined for the upper reaches of the Dutch river network and corrects the mortality to account for evacuation possibilities before onset of a flood. This percentage was chosen based on expert estimates which were made prior to the new safety standard derivation methodology (Slootjes & Van der Most, 2016b). Experts defined plausible evacuation bandwidths for different geographical areas in the Netherlands and 56% is the lower limit of the bandwidth assumed realistic for the Dutch upper river areas. The current reference percentage is therefore a conservative estimate representing a badly executed evacuation process (Slootjes & Van der Most, 2016b).

The percentage of the population which would evacuate before the onset of a flood and hence the presence of people during the flood event itself is uncertain due to a variety of aspects which determine the required and available time for evacuation. Kolen (2013) discusses many different aspects, such as the threat and imposed available evacuation time, the citizen response to evacuation orders, decision making by authorities and the area characteristics. The lead time before a flood defence is expected to fail is a key aspect, which also influences authorities' decision making and evacuation orders (Kolen, 2013). This key aspect was considered in the evacuation uncertainty quantification approach for this study. The available time before flood defence failure amongst others depends on the flood defence failure mechanism (Barendregt et al. 2005) and the predictability of a flood event (Kolen, 2013).

To quantify the uncertainty of the preventive evacuation percentages due to uncertainty in the available evacuation time, a probability distribution of the number of available days was used. Maaskant et al. (2009b), cited in Kolen (2013) earlier established a probability distribution of the number of available days, based on expert estimates specifically for the upper reaches of the Dutch river network in which dike ring 43 is situated (see Figure 3-17). For this study, the day-based estimates were translated into a continuous hour-based distribution over the interval between 0 and 5 days, to enable defining a 50% confidence interval of the time availability. The assumption was therefore made that the day-based probability estimates can be distributed evenly over the interval between 12 hours before and after the considered day (For instance a 50% probability of 2 days of preventive evacuation time was distributed linearly between 36 and 60 hours on the hour-based distribution).

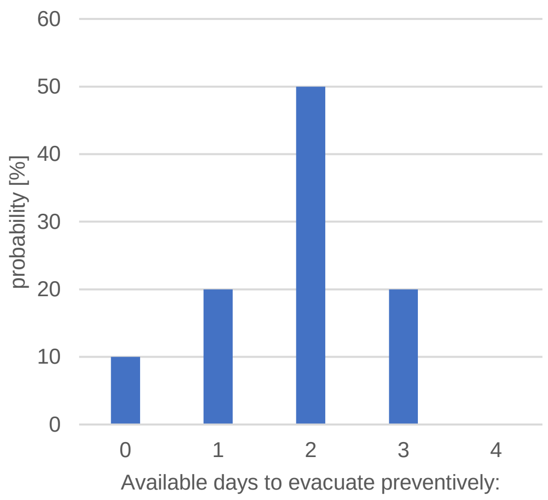

Figure 3-17: Expert estimates of available time for the upper reaches of the Dutch Rhine system, as given by Maaskant et al. (2009b)

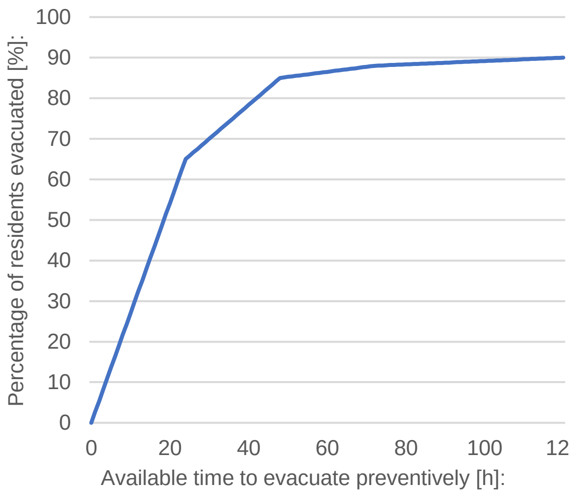

Figure 3-18: Relation between the percentage of residents evacuated and available hours for preventive evacuation, based on data by Kolen (2013)

Afterwards, the time-availability distribution was translated into a preventive evacuation percentage probability distribution. This was done by means of available model estimates for the expected evacuation percentage, depending on the number of available days to evacuate preventively. These estimates were made with evacuation model “Evacuaid”, described by Kolen (2013) (see Figure 3-18). These percentages were derived for the upper reaches of the Dutch Rhine and were determined based on a reference (most likely) scenario for the aspects which determine the success of evacuation, such as human behaviour in traffic. The evacuation percentages calculated by the model account for a non cooperation percentage of 10% among residents, which would not cooperate in organised evacuation. Regardless of the available evacuation time, evacuation percentages in Figure 3-18 therefore do not exceed 90%. A 10% disobedience percentage is in line with experiences during the evacuation for the high river waters in dike ring 43 in 1995 (Kolen, 2013). The derived preventive evacuation probability distribution was used to define a reference scenario for the preventive evacuation percentage, as well as a 50% confidence interval around the reference scenario.

Additionally, in the uncertainty analysis of this study another aspect related to the available evacuation time was considered: the possibility to evacuate an area after a flood defence has failed, but before exposure to the flood water. Kolen (2013) refers to this type of evacuation as “acute evacuation”. In the current safety standard derivation process, acute evacuation is not accounted for. After a dike breaches, the presence of people over the hinterland is assumed to remain constant.

The relevance of acute evacuation has amongst others been analysed by Mevissen, (2010). Furthermore, some of the experts consulted in this study mentioned that in relation to evacuation uncertainty, this aspect is important to consider as well to give a more realistic representation of flood consequences. People will not passively stay at home knowing that they will sooner or later be flooded. Furthermore, the LIR standards are currently defined based on the annual probability to become a casualty due to flooding at a certain location, in which evacuation possibilities are accounted for (Slootjes & Van der Most, 2016a). It can therefore be well argued to include acute evacuation as well in the calculations. Accounting for enhanced evacuation time within the evacuation fraction was already proposed earlier by Maaskant et al. (2009a) as possible adaptation of the method to determine the number of casualties in a flood event.

Especially in dike ring 43 the effect of acute evacuation could be significant. As shown in Figure 3-19 in an example, the time between dike failure and time of arrival of the inundation front highly varies throughout the dike ring. Due to the relatively low flow velocities and the presence of many increased surface elevation lines in this dike ring, some areas would only become inundated after multiple days. It is highly questionable whether residents would still be present in areas where flood water arrives days after a breach has initiated, especially with the modern-day communication methods and quick spread of news.

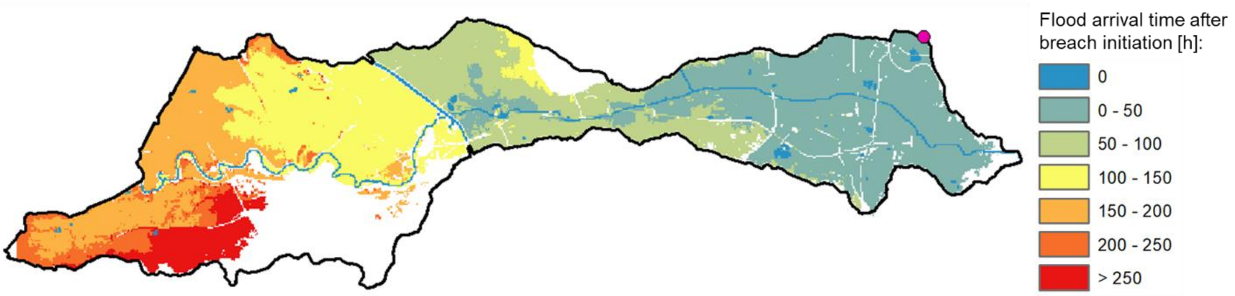

Figure 3-19: Flood arrival times for dike ring 43 after breach initiation for the flood scenario with a breach at Malburgen (pink dot) under TL-hydraulic conditions

The effect of acute evacuation was incorporated in the uncertainty analysis as an additional adaptation of the reference evacuation percentages. This was done by calculating the cell-based acute evacuation time available for each of the 28 considered flood scenarios (as Figure 3-19 gives an example for one scenario). This acute evacuation time was added up to the available preventive evacuation time, for which a 50% confidence interval was derived above. The total evacuation time (preventive + acute) was translated into evacuation percentages by using the relation between available time and evacuation percentage introduced above to quantify the uncertainty of the preventive evacuation percentages (see Figure 3-18).

So, as quantification of the 50% confidence interval of the evacuation percentages, a reference (50th percentile) scenario was established based on the acute + 50th percentile preventive evacuation time available. The 25th and 75th percentile scenarios around this reference scenario were derived from the uncertainty of the available preventive evacuation time through the above established probability vs. available time relation.

This quantification method implicitly assumes that evacuation time before the flood onset is as effective as evacuation time after the flood onset. This will in reality depend on the degree of evacuation planning by responsible organisations, as discussed by (Mevissen, 2010).

3.3.5 Damage functions

The damage functions currently used in the safety standard derivation are described by Kok et al. (2005). These functions express a relationship between inundation depth and the percentage of the total value of buildings, assets or land use covers which is lost in those circumstances (becomes invaluable). In total 11 different functions are currently used for the various land use categories in the land use datasets (shown in appendix A4).

For the uncertainty analysis in this study, the uncertainty associated with the damage functions was quantified based on an approach introduced by Egorova et al. (2008). Their approach was applied earlier by De Moel et al. (2012 & 2014) for uncertainty analyses in flood damage and flood risk estimates. Their approach is to describe the uncertainty of the depth damage functions statistically via beta distributions. This approach is motivated by the fact that the damage factor derived from the damage function always has a value between 0 and 1. Beta probability distributions are defined on this exact interval as well. Furthermore, beta distributions allow both high and low probability densites over the interval. Therefore, the uncertainty can be varied for different inundation depths.

A recent study by De Bruijn et al. (2015) has investigated the original damage functions by Kok et al. (2005). For some of these functions, De Bruijn et al. (2015) argued that these functions are based on errors or do not comply with reality. As the uncertainty analysis in this study tries to find an uncertainty bandwidth around the most plausible flood safety standards, these errors present in the current functions were corrected first to define a reference scenario.

Two of the original functions by Kok et al. (2005) were corrected: the function for industry and for vehicles. Figure 3-20 shows the adaptation of these functions relative to the original functions, in accordance with De Bruijn et al. (2015). The function for the damage category vehicles becomes significantly steeper, while the function for industry is split into three separate and steeper functions for offices, commercial areas and (general) industrial areas. Besides these two functions which contained errors in the old version, De Bruijn et al. (2015) also discusses other adaptations, related to altered definitions of categories or functions for revised data. Those adaptations were not applied in this study, to be able to assess the influence of uncertainty in the damage functions on the flood safety standards in isolation, rather than involving revised definitions and data in the analysis as well. One of the interviewed experts in this study has shown in an unpublished study that with all suggested adaptations, the total flood damage would increase on average 20% compared to the damage in the verification flood safety standards. This increase is approximately equal to the increase found by adapting only the industry and vehicle functions. Neglecting the other suggested assumptions does therefore not affect the uncertainty influence of the damage functions.

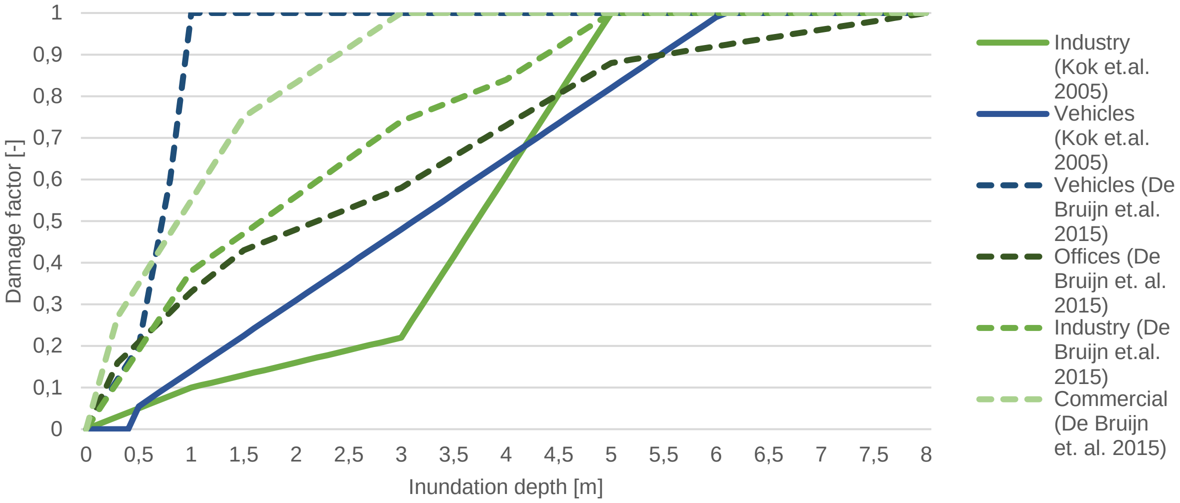

Figure 3-20: Adaptation damage functions for Industry and vehicles according to De Bruijn et al. (2015)

The partially adapted set of original functions was used as reference scenario for the uncertainty quantification, for which the techniques proposed by Egorova et al. (2008) were applied. In their approach, it is assumed that the variance of the beta distributions for all damage functions (and thus the uncertainty) is zero where the damage factor is equal to 0 or 1. Over the interval in between, the uncertainty has a shape as shown in Figure 3-21. This variance function shape is a plausible assumption as the onset of damage is often quite certain, with increased uncertainty for larger inundation depths. Due to the distinctive categories of each damage function, the uncertainty of the damage factor decreases again towards damage factors closer to 1.

The magnitude of uncertainty (represented by the variance of the beta distribution) is indicated by a characteristic k-value, proposed by Egorova et al. (2008) (see Figure 3-21). In accordance with De Moel et al. (2012 & 2014) a k-value of 0.1 was used in this study to describe the uncertainty around each reference function. De Moel et al. (2012) supports this value by comparing the functions by Kok et al. (2005) to functions derived for another study. The magnitude of deviation of those functions from the functions by Kok et al. (2005) roughly matches the magnitude of deviation described by a beta distribution with a k-value of 0.1. Furthermore, the areas studied by De Moel et al. (2012 & 2014) are similar in size and land use characteristics as dike ring 43.

Finally, the beta distributions for each function were used to define alternative depth damage functions corresponding to the 50% confidence interval around the (adapted) reference functions.

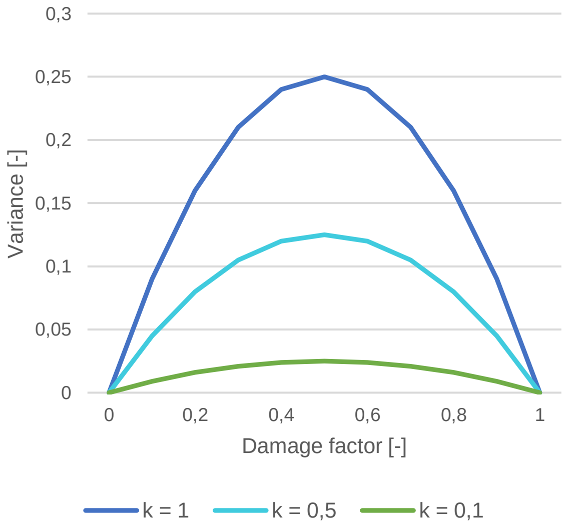

Figure 3-21: Shape of the beta distribution variance for several values of k

3.3.6 Investment costs flood defence improvements

The investment costs for flood defence improvements impact the SCBA standards, as these determine for which level of flood probability the expected flood damage evens the required costs to reduce flood probabilities accordingly. As stated in paragraph 3.1.3, the investment costs are defined for every safety standard segment as the costs required to strengthen the flood defence system with one decimal height. De Grave & Baarse (2011) gives an extensive description of the process followed to derive these investment costs. In short, the procedure consists of two main steps: deriving the optimal dike improvement strategy and making an accompanying cost estimate. De Grave & Baarse (2011) defined homogeneous dike sections, for which the optimal dike improvement strategy was determined at discrete magnitudes of crest level increase. These optimal strategies were derived automatically, amongst others based on the available space and the properties of the dike (see De Grave & Baarse (2011)). Afterwards, automatic cost estimates were made for these discrete steps. The current cost estimates were based on extensive datasets for specific cost components in dike improvement projects, based on know-how from engineering firms. The discrete cost estimates were aggregated in a continuous cost curve (costs vs. crest level increase). This curve is used to determine the investment costs required for flood defence improvement of one decimal height (De Grave & Baarse (2011)). The required investment costs are determined based on many non-location specific principles, estimations and correction factors for additional costs. Furthermore, automatically determined best suitable dike improvement methods are in practice often not standard and highly uncertain. As a result, the derived exponential cost curves are uncertain.

Within this study, the uncertainty of the investment costs was quantified based on uncertainty quantification in recently made cost estimates for dike improvement projects within dike ring 43. This data is therefore especially suitable for the case study. There are three major flood defence improvement projects for which cost estimates were made by cost experts from Royal HaskoningDHV as involved engineering consultant in the three projects. The three project stretches of primary flood defence are each situated in a different safety standard segment (Figure 3-22). The uncertainty was therefore only quantified and included in the uncertainty analysis in this study for safety standard segments 43-4, 43-5 and 43-6.

An absolute cost estimate per km of flood defence is given for these projects, as well as a variation coefficient (Table 3-4). This variation coefficient describes the uncertainty of the cost estimate due to uncertainty in the underlying cost components. The variation coefficients for these three projects differ. Cost experts from Royal HaskoningDHV argued that variation in uncertainty over these projects is mainly related to the different characteristics of the dike improvement strategy. For instance, the basic design for the improvements in safety standard segment 43-6 involves many constructive measures like sheet piles, for which the investment cost uncertainty is relatively low. One of the most prominent sources of uncertainty in these cost estimates relates to the use of ground for adaptation of the dike profile. Can layers of the old dike profile be reused? Is cleaning of soil required? How is the soil quality? The project-specific composition of measures in the improvement project and local characteristics (such as the presence of underground pipes or the presence of private property) determine the relative uncertainty of the cost estimates.

*Table 3-4: Average investment costs per km as used in the verification safety standard calculations, cost estimates per km in the three safety standard segments based on current strengthening projects and variation coefficients derived based on the cost estimates for these projects. * Note that these absolute values cannot be compared directly*

Safety standard segment	Investment costs per km in verification safety standard calculations*	Investment costs per km in the current dike improvement projects*	Variation coefficient
43-4	€ 6.051.000,-	€ 10.335.000,-	0.22
43-5	€ 8.042.000,-	€ 13.477.000,-	0.24
43-6	€ 6.086.000,-	€ 19.786.000,-	0.16

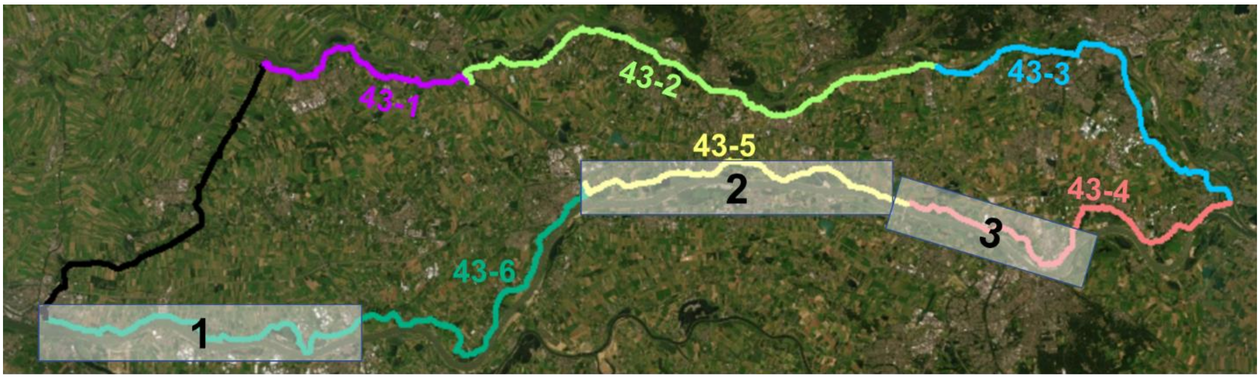

Figure 3-22: Locations of the three dike improvement projects considered in the quantification of dike improvement cost uncertainty. (1): Project "Gorinchem-Waardenburg" in safety standard segment 43-6; (2): Project "Neder-Betuwe" in segment 43-5; (3): Project "Wolferen-Sprok" in segment 43-4

It makes sense to use these absolute cost estimates to derive an altered 50th percentile scenario for this source of uncertainty, as the most suitable set of measures and accompanying cost estimates are derived based on more in-depth analysis of the local characteristics than the estimates used in the verification safety standard calculations. This is however not straightforward, as the two different cost estimates cannot be compared directly due to fundamental differences in the purpose and characteristics of the estimates. Appendix A10 further discusses these differences. To quantify the uncertainty of the cost estimates, the values used in the verification safety standard calculations were therefore kept as reference scenario. The 50% confidence interval around this value was derived based on the variation coefficients defined in the cost estimates for the current dike improvement projects. With this approach it is assumed that the uncertainty is not significantly influenced by the absolute cost estimates or the magnitude of dike improvement. This assumption was made as the relative uncertainty of investment costs for dike improvement programs is likely strongest influenced by the location and type of measure. As the locations for the different types of cost estimates are equal, the proposed measures should in basis correspond (although in different magnitude).

The uncertainty of the cost estimates was quantified through the derivation of normal distributions of the cost estimates per kilometre of flood defence. The mean of the normal distributions was for each safety standard segment given by the absolute cost estimates used in the verification safety standard calculations. The standard deviation for the three safety standard segments was derived from the variation coefficients in Table 3-4. Figure 3-23 shows that a normal distribution is a reasonable representation of the uncertainty. The distribution of cost estimates made by the cost experts is only slightly right-skewed.

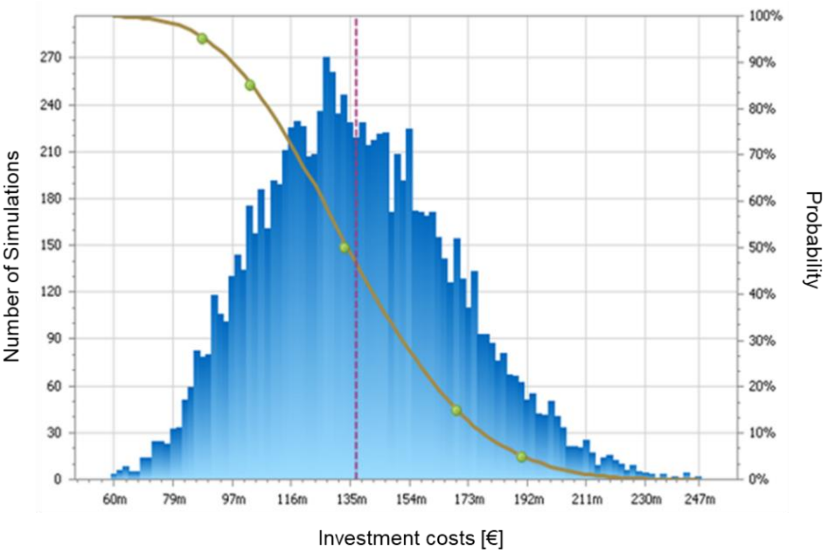

Figure 3-23: Probability density function and cumulative probability distribution of the expected investment costs for the Wolferen-Sprok dike improvement project currently in preparation. The figure is based on 10000 probabilistic cost estimations, made by cost experts at Royal HaskoningDHV. (m stands for million euros in this figure)

3.4 Influence individual uncertainty sources on flood safety standards

This paragraph explains the method used to propagate the individual uncertainty sources through the calculation process of the safety standards. The goal of this fourth research step is to show in what way individual uncertainty sources influence the flood safety standards.

3.4.1 Scenario analysis

The general approach for the individual uncertainty analysis followed a scenario analysis. Separately for each uncertainty source, three distinct scenarios were propagated through the safety standard derivation process. The scenarios were defined in the third research step (see paragraphs 3.3 & 4.3). These correspond to the reference (most likely) scenario and the upper limit (25th percentile) and lower limit (75th percentile) scenarios for the 50% confidence interval around the reference scenario.

For consistency in the uncertainty analysis, the 25th percentile scenarios for all uncertainty sources were defined such that these either result in more severe flood consequences or higher investment costs compared to the reference scenario. The 75th percentile scenarios always results in less severe flood consequences or lower investment costs. Table 3-5 provides an overview of all scenarios in the uncertainty analysis, as well as the settings for the current safety standards and the deviations in the established reference scenarios. The defined scenarios were all propagated through the safety standard calculation process as described in paragraph 3.1. The sole adaptations are shown in Table 3-5.

After propagation, additionally an indicator was derived to aid the analysis of the uncertainty influence and enable comparison of uncertainty source influences between different safety standard segments. The indicator expresses the absolute 50% confidence interval of the alert standard as percentage of the reference alert standard. The indicator therefore expresses the relative size of the 50% confidence interval.

Below, for each of the individual uncertainty sources a small explanation of the scenario propagation approach is given.

3.4.2 Breach development

The breach development uncertainty was propagated through the calculation process for both the LIR and SCBA standards. The three breach development scenarios (see Table 3-5) were defined based on data for safety standard segment 43-6 (discussed in paragraph 3.3.2 & 4.3.1). The scenarios were therefore only propagated through the safety standard calculation process for segment 43-6 and the safety standard effects were only quantified for this segment.

In accordance with the verification calculations carried out earlier in this study, three different flood scenarios were considered: A flood scenario at TL-hydraulic conditions of the river discharges (1/1250 annual reoccurrence probability) for both Haaften and Tiel-West breach locations, as well as a flood scenario for Tiel-West under TL+1D conditions (1/12500 annual reoccurrence probability). In total 9 new flood simulations (three flood scenarios for three breach development scenarios) were made in Delft-FLS and propagated in the safety standard calculation process shown in Figure 3-2. For each of these 9 new flood simulations the operation times of the hydraulic structures which influence the flood pattern were optimised as well (syphon below the Amsterdam-Rhine Canal, discharge sluices in the Diefdijk and the spill flow works at Dalem, see Figure 2-4). These structures must be operated at the right time to reduce flood consequences in the hinterland. The operation times are influenced directly by the breach development curve as the flood propagation front and rises rate are affected.

Afterwards, based on the flood simulations made with the alternative breach development scenarios, the validity of the earlier assumed stable average head difference (H=2.8m) for the two breach locations and the different breach development scenarios was verified. This simplification gives a reasonable representation of the reality, see appendix A6 for further explanation.

Table 3-5: Overview of the scenarios incorporated in the individual uncertainty analysis, the type of flood standard for which the influence was studied and the safety standard segments for which the influence was studied. The Verification scenario contains the settings used by Slootjes & Wagenaar (2016a) to derive the standards currently defined in the Dutch water Act.

Uncertainty source:	Verification scenario:	25th percentile scenario	Reference scenario:	75th percentile scenario:	Influence analysed for:
Breach development	U_c = 0.2 m/s; Breach width = 210m (Figure 4-5)	U_c = 0.36 m/s; Breach width = 99m (Figure 4-5)	U_c = 0.41 m/s; Breach width = 86m (Figure 4-5)	U_c = 0.44 m/s; Breach width = 78m (Figure 4-5)	- LIR & SCBA standard - Segment 43-6
Mortality functions	Original functions by Jonkman (2007) & Maaskant et al. (2009a) (Figure 4-6 a)	Original functions corrected for reduced building collapsibility & high rise rate favoured interpolation (Figure 4-6 b)	Original functions corrected for reduced building collapsibility (Figure 4-6 c)	Original functions corrected for reduced building collapsibility & low rise rate favoured interpolation (Figure 4-6 d)	- LIR standard - All 6 segments
Evacuation percentage	Everywhere 56%	70% + location-specific influence acute evacuation (Figure 4-7)	83% + location-specific influence acute evacuation (Figure 4-7)	86% + location-specific influence acute evacuation (Figure 4-7)	- LIR standard - All 6 segments
Damage functions	Original functions by Kok et al. (2005)	25th Percentile functions (see appendix A5)	Functions by Kok et al. (2005), with 2 adapted functions (see Figure 3-20)	75th Percentile functions (see appendix A5)	- SCBA standard - All 6 segments
Investment costs flood defence improvements	Estimations by automated cost-functions, automatically chosen site-specific designs	25th percentile costs based on uncertainty current improvement projects (see Table 4-6)	Investment costs as used in the verification calculations	75th percentile costs based on uncertainty current strengthening projects (see Table 4-6)	- SCBA standard - Segments 43-4, 43-5 and 43-6

3.4.3 Mortality functions

The three defined alternative mortality function scenarios (graphically shown in Figure 4-6) were propagated through the safety standard calculation process for the LIR standards only and for all 6 safety standard segments of dike ring 43-6. The monetised number of casualties accounts on average only for 10% of the total monetary flood damage relevant for the SCBA standard calculations. This shows that the role of the mortality function uncertainty on the SCBA standards is very small. Therefore, the influence on the SCBA standards was not considered in this study.

3.4.4 Evacuation percentage

The alternative evacuation scenarios listed in Table 3-5 were propagated only for the LIR standards. For the same reason as the mortality functions, the effect of evacuation percentage uncertainty is very small on the derived SCBA standards, which justifies considering only the influence of the evacuation percentages on the LIR standards. The influence of the three scenarios was studied for each of the six safety standard segments.

As the evacuation percentages vary for the different flood scenarios in the uncertainty analysis, the original approach to determine the LIR standards (based on paragraph 3.1.4 & 3.1.5) was slightly adjusted. The LIR standards are always derived on the spatial scale of safety standard segments, based on multiple different flood scenarios. Therefore, the alternative evacuation scenarios were implemented in the LIR derivation by calculating for each of the 28 flood scenarios the cell-specific mortality value, corrected for the cell-specific evacuation percentages. Afterwards, the derived mortality values for the individual flood scenarios were combined in the same way as described in paragraph 3.1.4 to calculate the median weighted mortality value for each neighbourhood. This implies that evacuation is not any more incorporated in equation 3 (paragraph 3.1.5), but one step earlier in the calculation process. The rest of the safety standard derivation process remains unchanged.

3.4.5 Damage functions

The influence of the damage functions was propagated only through the SCBA standard derivation process, as the LIR standards are not influenced by this uncertainty source. The influence of the three scenarios was studied for each of the six safety standard segments.

In accordance with De Moel et al. (2014), the set of damage functions defined in the three scenarios was sampled as a whole. This means that for the 25th percentile damage function scenario, for each land use category the 25th percentile function was sampled from the established beta distributions, and similarly for the other two scenarios.

3.4.6 Investment costs flood defence improvements

Flood defence investment costs only influence the SCBA safety standards, hence the associated uncertainty was only propagated through the SCBA standard derivation process. The uncertainty was quantified and therefore propagated only for safety standard segments 43-4, 43-5 and 43-6. Uncertainty of the investment costs is given per km flood defence based on the currently prepared dike improvement projects in these three segments. The total investment costs for the three segments as implemented in the SCBA standard derivations (equation 2 in paragraph 3.1.3) were derived by multiplication of the costs per km with the length of the three safety standard segments. It is therefore implicitly assumed that the uncertainty in the sections where the current dike improvement projects are carried out is representative for the entire safety standard segment in which it is situated.

3.5 Combined influence uncertainty sources on flood safety standards

In the fifth research step, the uncertainty scenarios were combined for multiple uncertainty sources, to give a plausible range of the calculated flood safety standards. This step also provides insight in the interaction between the individual uncertainty sources.

For two of the five individual uncertainty sources only the influence on the SCBA standards was considered, for two other sources the influence on the LIR standards was studied and for one source the influence on both LIR and SCBA standards was considered (see Table 3-5). For the combination uncertainty analysis, the 5 uncertainty sources were therefore grouped according to their influence on the LIR standards (breach development, mortality functions and evacuation percentages) and the SCBA standards (breach development, damage functions and investment costs for flood defence improvement).

The approach to study the combined uncertainty influence followed an often applied approach to show the range of uncertainty resulting from multiple sources of uncertainty (e.g. Merz & Thieken, 2009). The approach was to combine the scenarios for the individual uncertainty sources in a finite number of unique scenario combinations. These combinations were propagated through the safety standard calculation process, after which the derived values give an expression of the range of plausible flood safety standards. For both the LIR and SCBA standards, three scenarios were established for each of the influential individual uncertainty sources (paragraph 4.3). As a result, in total 27 unique combinations were analysed for both the LIR and SCBA standards. The combination uncertainty analysis focussed on safety standard segment 43-6. This is the only segment for which each of the five individual uncertainty sources was quantified.

4 Results

Chapter 4 presents the results of the five main research steps. The paragraphs in this chapter follow the same structure as methods chapter 3.

4.1 Verification flood safety standards

This paragraph shows the derived safety standards for the 6 safety standard segments. These were compared to the safety standards shown in Slootjes & Wagenaar (2016). Both the SCBA and LIR standards, as well as the accompanying safety standard classes are discussed.

4.1.1 SCBA standards

From the calculated flood consequences with HIS-SSM and the required investment costs to decrease the flood probability, the resulting SCBA alert standards were calculated and shown in Table 4-1. The table also shows the SCBA alert flood safety standards as given by Slootjes & Wagenaar (2016), from which the legal flood safety standards were derived. It becomes clear that the calculated values for all safety standard segments correspond closely to the values given by Slootjes & Wagenaar (2016). Deviations are for all segments less than 1%, which points to a likely identical approach followed in this study and followed for the derivation of the safety standards in the Dutch Water Act. This means that both the flood simulations, flood consequence calculations and post-processing steps (see paragraph 3.1.3) are likely executed identically. The strictest values were derived for safety standard segment 43-3, while the least strict values were derived for segments 43-5 and 43-6. These segments are both characterised by a moderate expected flood damage, while the required investment costs in flood defence improvement projects would be relatively high, resulting in less strict optimal annual flood probabilities.

Table 4-1: Optimal alert SCBA standards for dike ring 43, as derived in this study as well as the standards given by Slootjes & Wagenaar (2016). The difference between these two is shown relative to the standards by Slootjes & Wagenaar (2016)

Safety standard segment	Damage in 2050 [€]	Investment costs 1 decimal height [€]	Alert standard found in this study [y^{-1}]:	Alert standard found by Slootjes & Wagenaar (2016) [y^{-1}]:	Difference [%]
43-1	*28 Billion*	*52 Million*	**1/20519**	**1/20400**	**0.6%**
43-2	*35 Billion*	*92 Million*	**1/14375**	**1/14300**	**0.5%**
43-3	*65 Billion*	*86 Million*	**1/28712**	**1/28500**	**0.8%**
43-4	*78 Billion*	*159 Million*	**1/18612**	**1/18500**	**0.6%**
43-5	*47 Billion*	*183 Million*	**1/9643**	**1/9600**	**0.4%**
43-6	*46 Billion*	*284 Million*	**1/6154**	**1/6100**	**0.9%**

4.1.2 LIR standards

4.1.2.1 Calculation normative mortality values

An important intermediate result in the LIR standard derivation is the calculation of the median mortality value per neighbourhood for each of the 6 safety standard segments. Figure 4-1 shows the derived median mortality map for segment 43-4, along with the cell-based weighted mortality values from which the median value was aggregated for each neighbourhood. Appendix A8 contains similar maps for all 6 safety standard segments. These figures make clear that the highest mortality values are for each of the 6 segments found along increased surface elevation lines in dike ring 43, such as the dikes along the Amsterdam-Rhine canal and the Diefdijk along the western border of dike ring 43. These areas are all characterised by both quickly rising flood water and relatively high maximum inundation depths, as propagating flood water is halted against these increased surface elevation lines. The mortality functions used to calculate the mortality (see paragraph 3.1.2) explain this strong relation between flood rise rate, inundation depth and mortality. As a consequence, the median mortality values are also highest in those areas. For instance, for safety standard segments 43-3,43-4 and 43-5 it becomes clear that the median mortality value is highest in the neighbourhood “Rijswijk”, which is a small neighbourhood located in this zone with high flood rise rates (see Figure 4-1). Areas with flow velocities exceeding 2m/s hardly emerge in the flood simulations, which explains why the areas around the breach location are often not characterised by high mortality values, as one might expect.

The neighbourhood-based mortality maps also show that the neighbourhood definitions have a strong influence on the LIR standards derived from these maps. If neighbourhood polygons are sufficiently small to include only grid cells with high mortality values, the median mortality value becomes high as well, resulting in strict LIR standards. As soon as small areas with lower mortality values are included as well, the median mortality drops quickly. Figure 4-2 gives an example of the strong sensitivity of the normative neighbourhood and LIR standard to the definition of these neighbourhood polygons. This example shows that would the neighbourhoods have been defined slightly different, this would significantly influence the LIR standards in this example.

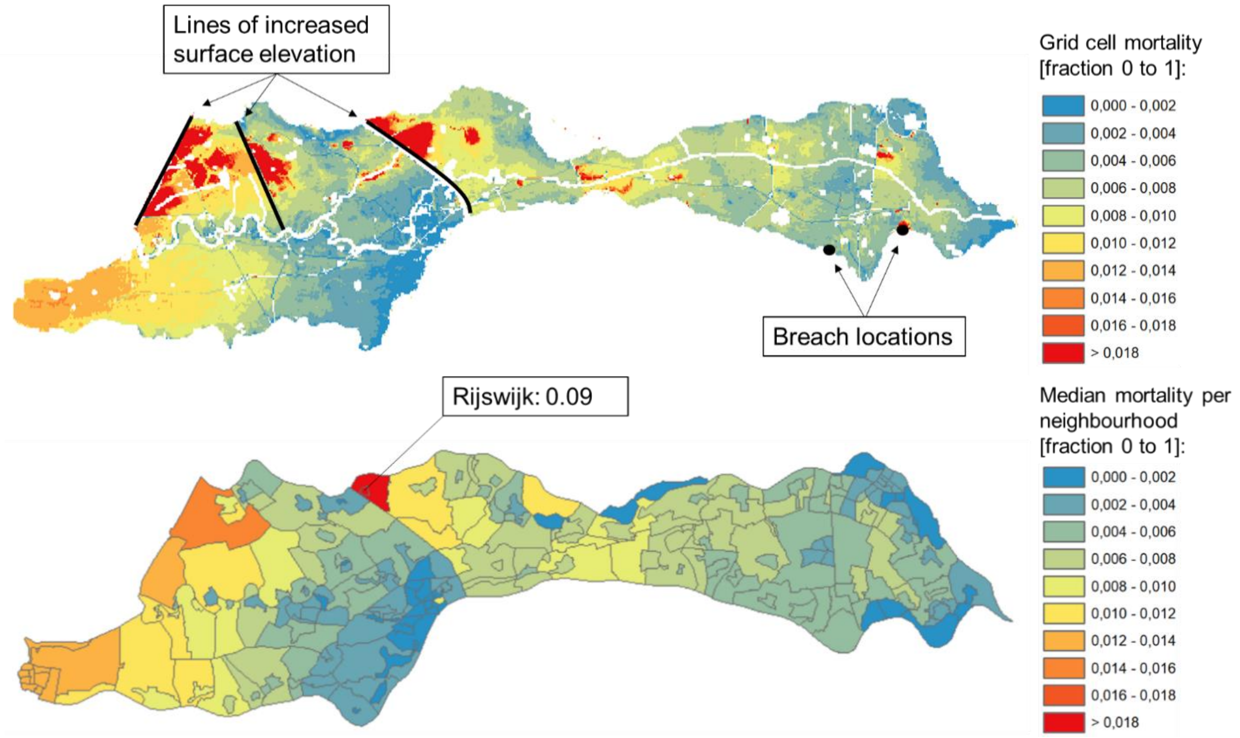

Figure 4-1: Cell-based weighted mortality values (Top) and aggregated median mortality values (bottom) per neighbourhood for safety standard segment 43-4, with the normative neighbourhood pointed out

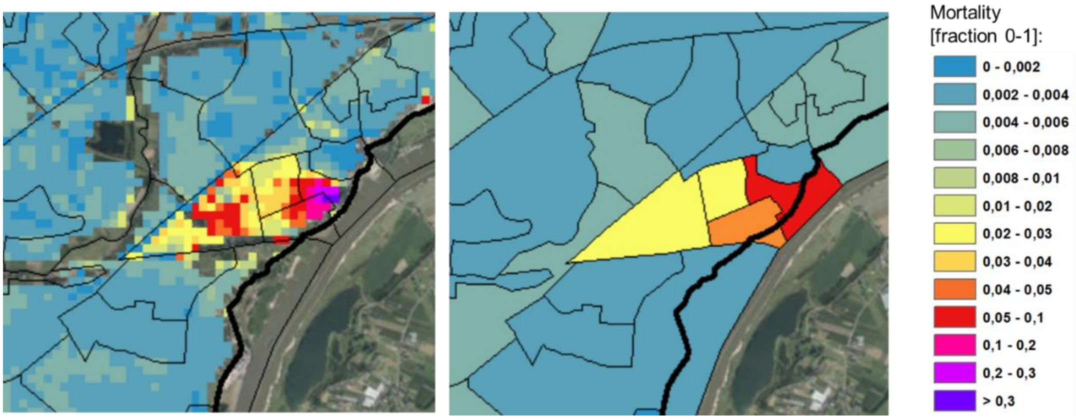

Figure 4-2: Example of the effect of neighbourhood polygon definition on the LIR standards. On the left side the mortality values calculated per grid cell are shown and on the right side the median mortality values per neighbourhood are shown.

4.1.2.2 Calculated LIR standards

From the neighbourhood with the highest median weighted mortality, the associated LIR standards were derived for each safety standard segment (see Table 4-2). It becomes clear that contrary to the SCBA standards, the calculated LIR standards do deviate from the values given by Slootjes & Wagenaar (2016). For all segments, the calculated standards are stricter than the standards derived by Slootjes & Wagenaar (2016). For segments 43-1, 43-2 and 43-6 the difference is relatively small and lies around 7%, while for segments 43-3, 43-4 and 43-5 the difference is more significant and lies around 30% to 40%.

Table 4-2: LIR alert standards for each safety standard segment as derived from this study, as well as standards given by Slootjes & Wagenaar (2016). The difference between these two is shown relative to the standards by Slootjes & Wagenaar (2016)

Safety standard segment	**Alert standards in this study [y^{-1}]:**	**Alert standards by Slootjes & Wagenaar (2016) [y^{-1}]:**	**Difference [%]**
43-1	**1/4773**	**1/4500**	**6.1%**
43-2	**1/6543**	**1/6100**	**7.3%**
43-3	**1/8149**	**1/5900**	**38.1%**
43-4	**1/32683**	**1/25200**	**29.7%**
43-5	**1/34290**	**1/26000**	**31.9%**
43-6	**1/18798**	**1/17700**	**6.2%**

4.1.3 Derivation normative safety standards

From the calculated LIR and SCBA standards in the previous paragraphs, the associated safety classes and normative safety standards for the 6 safety standard segments are given in Table 4-3, along with the normative criterion (LIR or SCBA). It becomes clear that the derived classes hardly deviate from the classes in the Dutch Water Act, despite the differences in the calculated LIR standards for some segments. The aggregation level of the safety standard classes has resulted in the same classes for all but one segment: 43-5. The lower limit class became one level stricter there.

The verification calculations show that the current flood safety standards cannot be fully replicated based on the existing documentation of the calculation process for the flood safety standards. The SCBA standards calculated in this study closely match the values given by Slootjes & Wagenaar (2016), with deviations under 1% for all 6 safety standard segments. The LIR standards on the other hand deviate more significantly, with deviations up to 40% for three segments. The overall image provided by the LIR standards in Slootjes & Wagenaar (2016) however remains the same in this study, as the same segments receive the strictest standards and the order of magnitude of the calculated values corresponds between both studies. The implications of these deviations of the calculated standards into safety classes is negligible, as all but one segment receives a different lower limit class in this study.

The results provide likely and less likely explanations for the found deviations. As the SCBA standards matched closely between the studies, the underlying steps to derive those values are likely identical in this study (flood simulations Delft-FLS, consequence calculation HIS-SSM and the applied fixed parameter values in the final processing steps in the SCBA standard calculations (see paragraph 3.1.3)). The LIR standards were derived based on the same flood simulations and mortality functions as used for the SCBA standard calculations and hence do not deviate. An explanation for the found differences in the LIR standards is therefore most likely found in the final operations of the LIR standard derivation; the processing of calculated mortality values. This study followed the available documentation about the procedure to derive the LIR standards. No obvious reason for deviations could be found. Undocumented operations in the process to derive the LIR standards could therefore be an explanation for the deviations. Several experts interviewed in this study already pointed to the possibility of incomplete documentation for the LIR standard calculation process and mentioned possible deviations from the standard approach for specific safety standard segments. Notable analogy between the three segments where the standards calculated in this study deviate strongest from the standards by Slootjes & Wagenaar (2016), is that the normative neighbourhood is the same for these three segments (see appendix A8). This supports the hypothesis that deviations in the final processing steps of calculated mortality values could provide an explanation. For instance, it is possible that the normative neighbourhood differs in this study compared to Slootjes & Wagenaar (2016).

Table 4-3: Derived safety standard classes for the 6 safety standard segments of dike ring 43 from this study and from Slootjes & Wagenaar (2016), for the SCBA and LIR alert and lower limit standards. The only deviation is highlighted yellow in this table.

This study:	**43-1**	**43-2**	**43-3**	**43-4**	**43-5**	**43-6**
Alert safety class SCBA [y^{-1}]:	1/30000	1/10000	1/30000	1/30000	1/10000	1/10000
Lower limit safety class SCBA [y^{-1}]:	1/10000	1/3000	1/10000	1/10000	1/3000	1/3000
Alert safety class LIR [y^{-1}]:	1/3000	1/10000	1/10000	1/30000	1/30000	1/30000
Lower limit safety class LIR [y^{-1}]:	1/3000	1/3000	1/3000	1/10000	1/30000	1/10000
Normative criterion:	SCBA	LIR & SCBA	SCBA	LIR & SCBA	LIR	LIR
Slootjes & Wagenaar (2016):						
Alert safety class SCBA [y^{-1}]:	1/30000	1/10000	1/30000	1/30000	1/10000	1/10000
Lower limit safety class SCBA [y^{-1}]:	1/10000	1/3000	1/10000	1/10000	1/3000	1/3000
Alert safety class LIR [y^{-1}]:	1/3000	1/10000	1/10000	1/30000	1/30000	1/30000
Lower limit safety class LIR [y^{-1}]:	1/3000	1/3000	1/3000	1/10000	1/10000	1/10000
Normative criterion:	SCBA	LIR & SCBA	SCBA	LIR & SCBA	LIR	LIR

4.2 Identification primary uncertainty sources

This paragraph discusses the results of the expert interviews conducted with 6 flood safety and safety standard experts. The full results of each interview session are shown in Appendix A2. The uncorrected scores awarded by each expert to the individual uncertainty sources are listed there, along with discussion points and remarks made by the experts for several uncertainty sources. Each expert was also asked to comment on the completeness of the list of uncertainty sources and name possibly overlooked sources of uncertainty. This has not led to the definition of additional sources of uncertainty and the initially defined list (see Table 3-2) has remained the same throughout the expert elicitation process.

4.2.1 Uncertainty priority ranking

Based on the rescaled expert scores, an overall uncertainty priority ranking was derived based on the average score from all responded experts (see Table 4-4). The results point out that the experts mainly consider the uncertainty sources present in the calculation of the flood consequences as the most prominent sources, as for example the evacuation percentages, mortality functions and damage functions received the highest scores. Multiple experts motivated the higher scores and argued that these three aspects both contain a high degree of uncertainty while also significantly influencing the derived safety standards. The only uncertainty source related to the flood simulation, which received the second highest average score, is the breach development uncertainty. Also, three uncertainty sources which influence either solely the LIR standard or SCBA standard score relatively high, such as the neighbourhood-based mortality aggregation approach. These are both choice-based uncertainties, and not necessarily cause a deviation of the objectively optimal LIR standard. Experts however expressed that other choices could significantly affect the resulting standards. Uncertainty sources which received a relatively low average score are often related to the data used in the flood simulation and damage calculation models, as well as technical uncertainties within the models, such as the used timestep and grid size of the flood simulation model Delft-FLS.
The 6 experts were all relatively unified in their opinions. The uncertainty sources in the highest positions of the ranking table were by all experts ranked among the most important uncertainty sources. The rescaling of the expert scores therefore has also hardly influenced the derived ranking. One notable exception is the neighbourhood-based mortality aggregation, which would have ended up among the most important sources without rescaling.

Table 4-4: Uncertainty source ranking based on the expert interviews

Uncertainty source	Average score	Standard deviation	Number of respondents
Evacuation percentages	**4,0**	0,7	4
Breach development (width, depth & development time)	**4,0**	1,1	5
Mortality functions	**3,9**	0,7	5
Damage functions	**3,9**	1,0	5
Investment costs flood defence improvements	**3,7**	1,0	5
Neighbourhood-based LIR redistribution over multiple safety standard segments	**3,6**	1,5	5
Neighbourhood-based mortality aggregation	**3,5**	0,5	2
Correction factor for unaccounted damage and risk aversion	**3,4**	1,2	4
Peak discharge representing TL and TL+1D hydraulic conditions	**3,3**	0,9	6
Discount rate	**3,3**	0,9	4

Economic growth scenario 2050	**3,2**	0,9	6
Moment of breach initiation	**2,9**	0,8	6
Operation Lingewerken & Spill flow works at Dalem	**2,9**	1,1	5
Length of the current safety standard segments	**2,8**	0,2	3
Ratio reference scenarios and extreme flood scenario	**2,7**	0,5	5
Influence of the positive system effect	**2,6**	1,4	4
Hydrograph shape representing TL and TL+1D hydraulic conditions	**2,5**	0,7	6
Influence of the negative system effect	**2,5**	0,5	2
Derivation flood rise rate based on incremental inundation depths	**2,5**	0,9	5
Stability increased surface elevation lines	**2,4**	0,7	5
land use and asset data	**2,4**	1,4	5
Monetisation values for casualties and victims	**2,3**	0,5	5
Breach locations for representative flood scenarios	**2,3**	1,5	6
Downstream stage/discharge relation boundary conditions	**2,3**	0,7	5
Correction factor for increased economic value 2000-2011	**2,2**	1,2	5
Maximum damage values	**2,1**	0,5	5
Grid size Delft-FLS	**1,5**	1,3	5
Correction factor for population growth 2000-2011	**1,4**	0,6	4
Roughness values per land use class	**1,4**	0,8	6
Correctness Delft-FLS simulation itself	**1,4**	1,0	4
Land use data used for roughness estimations	**1,2**	0,8	6
Elevation data	**1,2**	1,0	6
Timesteps Delft-FLS	**1,1**	1,0	5
Population data	**0,9**	0,9	5

The column with the number of respondents presented in Table 4-4 points to another insight gathered from the interview sessions. As respondents did not award a score to uncertainty sources for which they found that they lacked specific knowledge, the number of respondents gives an idea of how acquainted the experts are with an uncertainty source. The acquaintance of the experts with the various components and uncertainty sources in the safety standard calculation process varies. Several times during the interview sessions, experts explained their specific knowledge of the derivation process was quite specific and therefore could not judge about sources of uncertainty outside of their specific knowledge field. One expert explained that the complexity and extensiveness of the calculation process has resulted in a highly fragmented knowledge of the calculation process over different experts. Most experts have in-depth knowledge of some specific components within the process and very few people have a full overview of all principles and approaches in each step of the process. This underlines the importance of a thorough analysis of all uncertainty sources within the safety standard calculation process.

4.3 Quantification of uncertainty sources

4.3.1 Breach development

Based on the quantification approach and findings from the dike composition data discussed in paragraph 3.3.2, a triangular probability distribution for soil parameter U_c was found, depicted in Figure 4-3 as cumulative distribution. This distribution gives a rough expression of the uncertainty of the erosion resistance of the dike interior along safety standard segment 43-6.

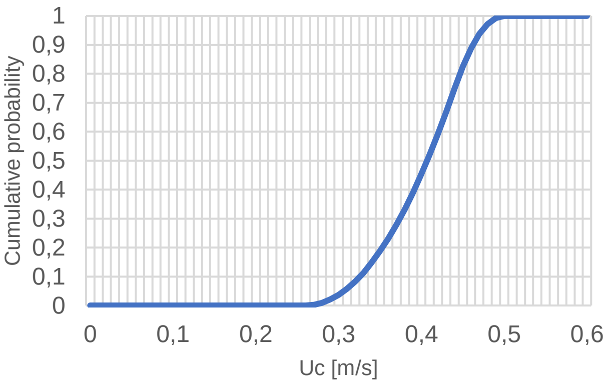

Figure 4-3: Cumulative probability of the critical flow velocity for dikes in safety standard segment 43-6, based on a triangular probability density function.

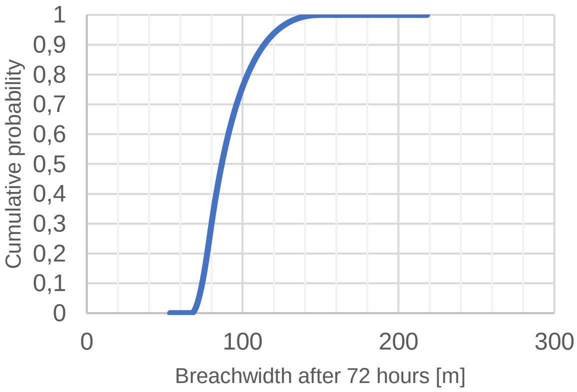

Figure 4-4: Cumulative probability distribution of the breach width after 72 hours of development, based on the probability distribution of U_c for safety standard segment 43-6

Based on the Verheij-Van der Knaap equation (equation 4 in paragraph 3.3.2), the probability distribution of U_c was translated into a probability distribution of the breach width after 72 hours of breach development (see Figure 4-4). This figure makes clear that breach widths for safety standard segment 43-6 would likely vary between approximately 70m and 150m based on this equation. The breach development curve used in the current safety standard calculation process (as applied in the verification calculations in this study) is based on the dike interior data therefore likely an unrealistic estimation for this area. The currently used breach development curve, which results in a breach width of 210m after 72 hours, is more representative for dikes with a sandy interior. This does not comply with the more clayey compositions primarily found in this area.

Based on these distributions, the 50% confidence interval for the breach growth curve is given (see Figure 4-5). It becomes clear that the confidence interval is relatively small, as the breach width after 72 hours differs only about 20m between the upper and lower limit of the 50% confidence interval (see Table 4-5). This is explained by the properties of the Verheij-Van der Knaap equation and the role of erodibility parameter U_c in the equation. The breach width development slows down stronger when moving from U_c = 0,2m/s to U_c = 0,25m/s than when moving from U_c = 0,35m/s to U_c = 0,4m/s. The same absolute difference in erodibility does not have the same influence on the breach width development in the Verheij-Van der Knaap equation. Moving from full sandy soils to soils with some clay can quickly decrease the erodibility, while further increase of the clay content less quickly slows down the erosion process.

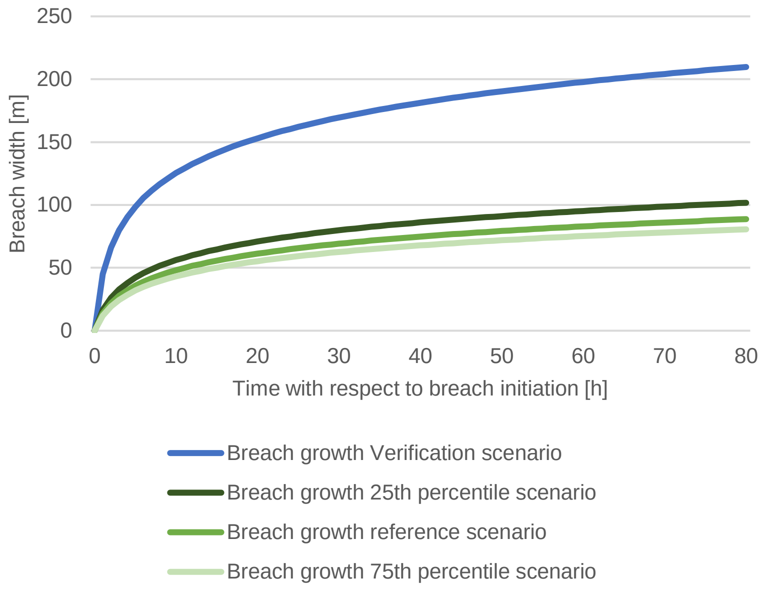

Figure 4-5: Breach growth curves for 50% confidence interval around the average curve, along with the breach growth curve used in the verification calculations.

Table 4-5: U_c-value and breach width after 72 hours for the 50% confidence interval.

	Average U_c-value	Breach width after 72h:
25th percentile	0,364 m/s	99 m
50th percentile (reference)	0,407 m/s	86 m
75th percentile	0,440 m/s	78 m

4.3.2 Mortality functions

The uncertainty of the mortality functions was quantified in paragraph 3.3.3 based on the interpolation function between the functions for high and low rise rates and the original reference scenario was adapted to correct for reduced building collapsibility since the 1950’s. Figure 4-6 shows the defined confidence interval of the mortality functions based on these two aspects. The reference scenario set of mortality functions was derived based on the original functions, adapted for the reduced building collapsibility. The 25th and 75th percentile function sets deviate from this reference set based on the discussed best-guess alternative interpolation scenarios (see paragraph 3.3.3). The 25th percentile set of interpolation functions favours the high rise rate mortality function and the 75th percentile set of interpolation functions favours the low rise rate mortality function. As becomes clear in the figure, the interpolated mortality functions are therefore not distributed evenly over the rise rate interval between 0,5 and 4m/h.

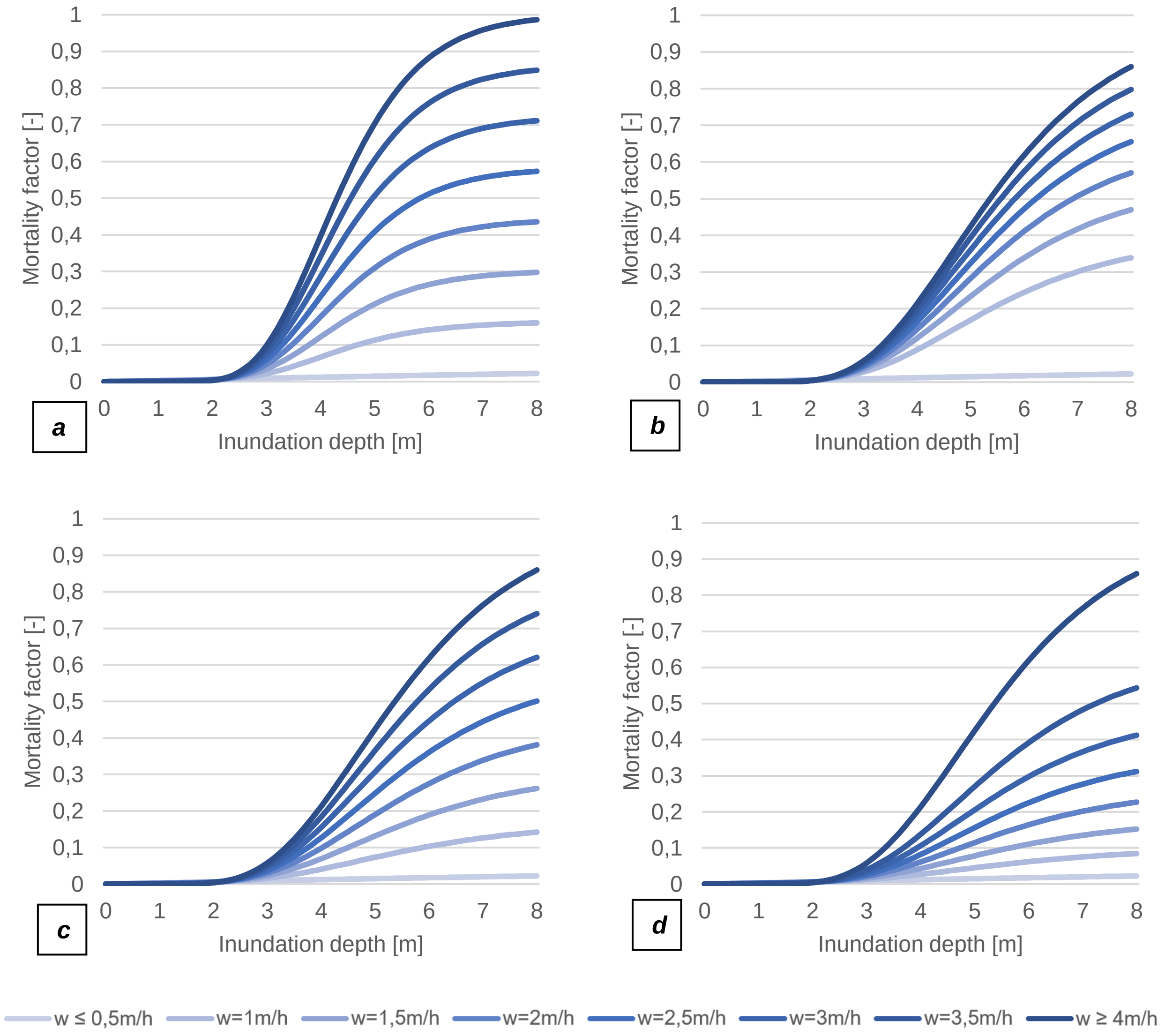

Figure 4-6: Mortality functions for flood rise rates (w) between 0,5 and 4m/h, defined for the 50% confidence interval in the uncertainty analysis: a) Original functions used in the verification calculations; b) 25th percentile functions; c) 50th percentile (reference) functions; d) 75th percentile functions

4.3.3 Evacuation percentages

Figure 4-7 shows the probability distributions of the evacuation percentages as gathered based on the data discussed in paragraph 3.3.4. The figure shows probability distributions for different flood arrival times after breach initiation, as the acute evacuation possibility creates location-specific evacuation percentages. It becomes clear that the evacuation percentage increases roughly exponential for increased cumulative probabilities. For increasing flood arrival times past breach initiation, evacuation percentages more quickly approach 90%, as more time is available for evacuation. Furthermore, at locations where flood water would not arrive instantly, expected evacuation percentages do not start at 0%, as the possibility of acute evacuation in those areas allows people to evacuate even in the event of an unexpected breach.

A first insight given by Figure 4-7 is that the derived reference (50th percentile) evacuation scenario gives evacuation percentages of approximately 83% for the areas where acute evacuation is not possible. The current (verification) scenario assumes 56% as evacuation percentage, which is clearly lower than what should be expected based on the quantification approach followed in this study. Some of the experts consulted earlier in this study argued that the percentage of 56% is likely too conservative, and one expert mentioned that the choice for this low percentage was influenced by governmental organisations which would be responsible for evacuation management in case of a flood event. These organisations could consider these percentages as an obligation to achieve, which creates an incentive to be rather conservative about the evacuation percentage incorporated in the calculations.

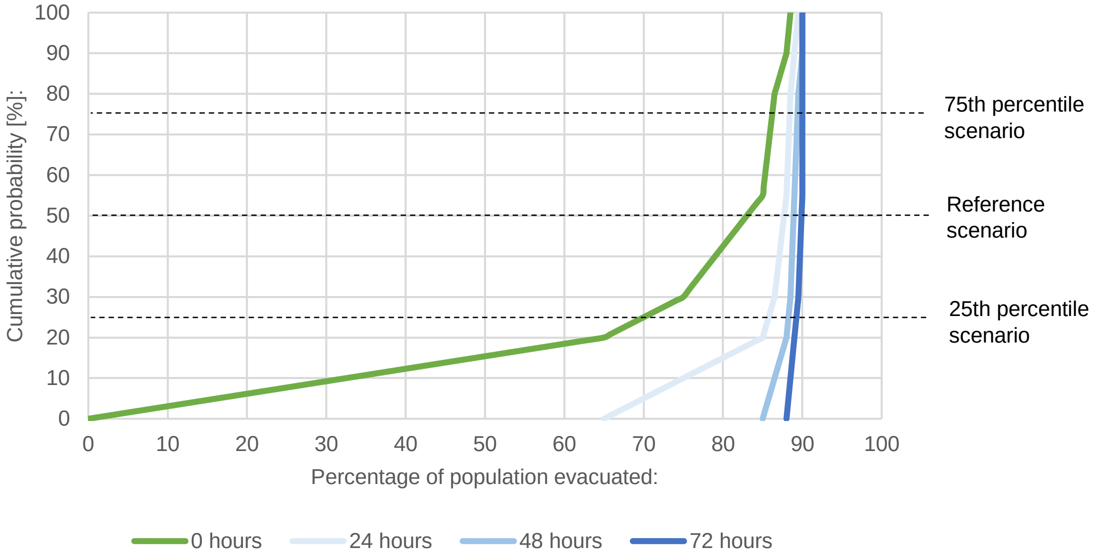

Figure 4-7: Cumulative probability distribution of the evacuation percentage of the population, for 4 different flood arrival times. The line for "0 hours" shows the distribution when acute evacuation is not possible, the other three lines show the distribution when acute evacuation is incorporated as additional evacuation time, for three different flood arrival times after breach initiation

Based on the location-specific probability distributions shown in Figure 4-7, for each of the considered flood scenarios for dike ring 43 the 50% confidence interval evacuation percentages were derived. Figure 4-8 gives an example for the flood scenario at breach location Malburgen for TL hydraulic conditions. It becomes clear that due to the incorporation of acute evacuation possibilities in the reference scenario, the evacuation percentage in significant parts of the flood zone approaches 90%, regardless of the uncertainty of the available preventive evacuation time. Areas where flood arrival times are small show more variation between the 25th and 75th percentile scenarios.

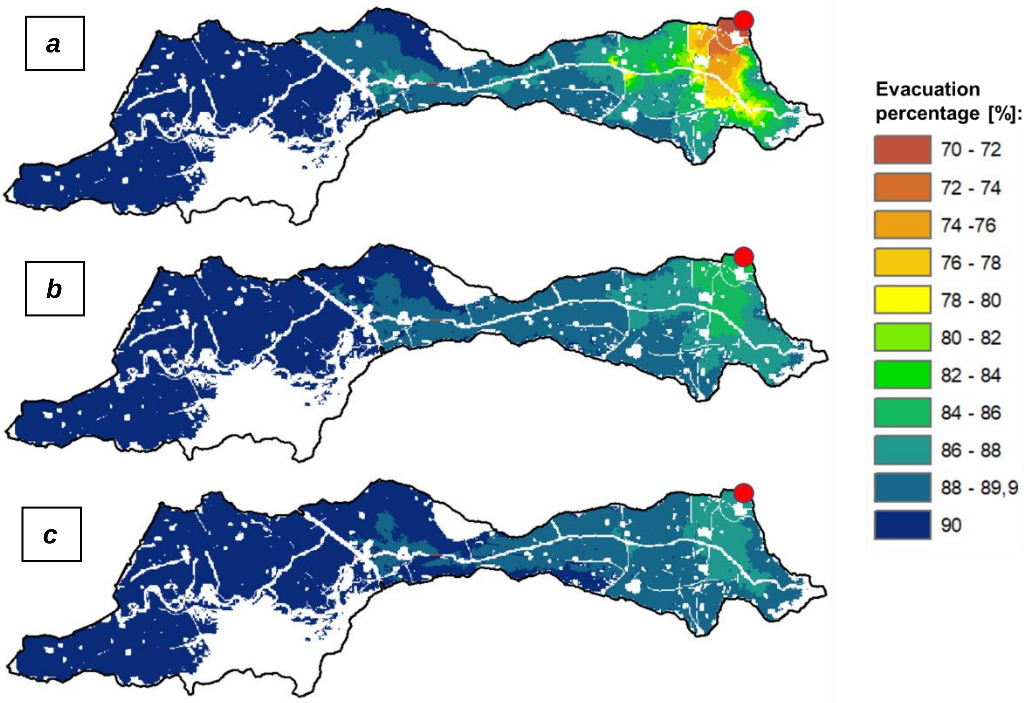

Figure 4-8: Evacuation percentage scenarios for breach location Malburgen (red dot) at TL-hydraulic conditions: a) 25th percentile; b) 50th percentile; c) 75th percentile

4.3.4 Damage functions

Figure 4-9 gives for two of the damage functions the quantified uncertainty following the procedure by Egorova et al. (2008). All individual functions are shown in appendix A5. The figures show in accordance with Egorova et al. (2008) that the uncertainty is largest for damage factors around 0.5 and uncertainty is zero at damage factors of 0 and 1. Compared to the reference damage functions, the 25th and 75th percentile functions shown in the figures give damage factors approximately 0.1 higher or lower under conditions where the reference damage factors are around 0.5. Hence, the damage deviates approximately 20% around the reference situation for the 50% confidence interval under those circumstances.

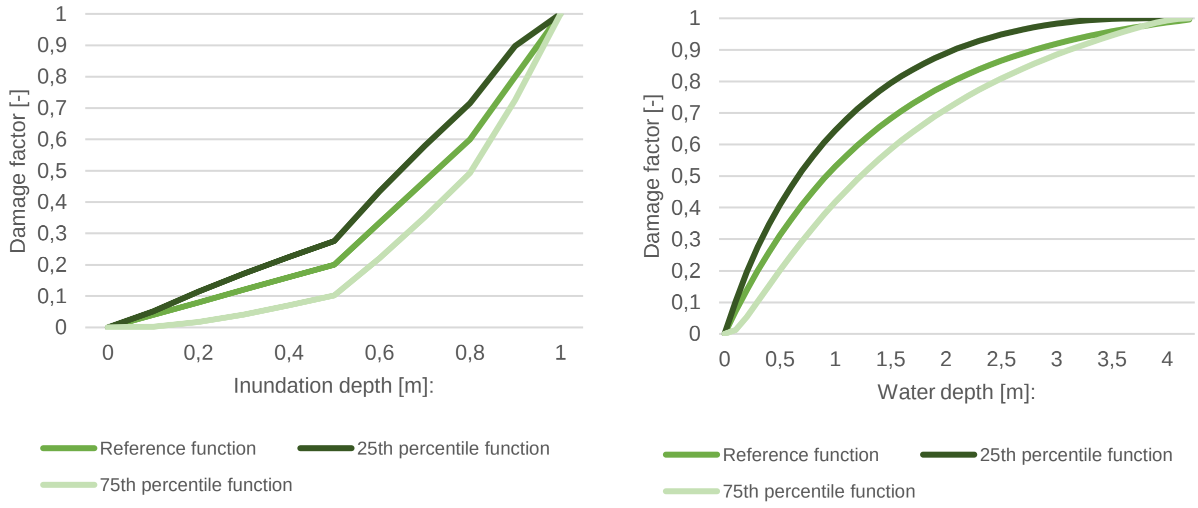

Figure 4-9: Uncertainty of the damage function for the category “vehicles” (left) and the category “low residential buildings” (right) for a k-value of 0.1

4.3.5 Investment costs flood defence improvements

Based on the cumulative normal distributions set up for safety standard segments 43-4, 43-5 and 43-6 (Figure 4-10), the 50% confidence interval was defined around the reference scenario. Table 4-6 gives an overview of the absolute investment costs corresponding to the 50% confidence interval. The variation in steepness of the three curves is explained by the different variation coefficients and by the varying mean investment costs per km over the three segments. The 25th and 75th percentile investment costs deviate approximately 10% to 16% from the 50th percentile (reference) costs for the three considered segments. Logically, the segment with the highest variation coefficient (43-5) in this quantification approach gives the largest percentual difference from the 50th percentile scenario.

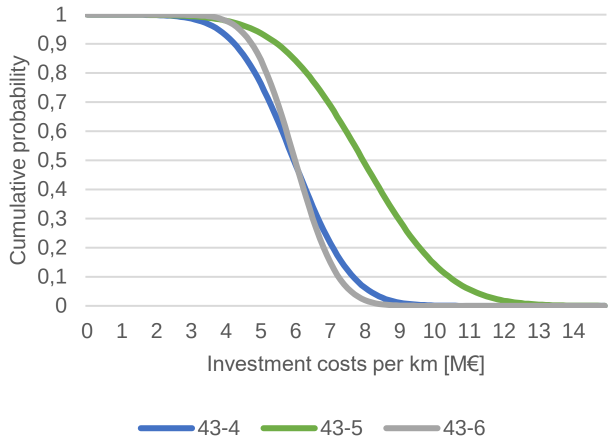

Figure 4-10: Cumulative probability distributions for the investment costs per km flood defence for safety standard segments 43-4, 43-5 and 43-6.

Table 4-6: 50% confidence interval for the investment costs per km for safety standard segments 43-4, 43-5 and 43-6. The percentages express the percentual deviation from the 50th percentile value.

	Investment costs per km [Million euro]		
Scenario:	43-4 ***(26,3km)***	43-5 ***(22,8km)***	43-6 ***(46,6km)***
25th percentile	€ 6.95 *(+14.9%)*	€ 9.34 *(+16.2%)*	€ 6.74 *(+10.8%)*
Reference	€ 6.05	€ 8.04	€ 6.09
75th percentile	€ 5.15 *(-14,9%)*	€ 6.74 *(-16,2%)*	€ 5.43 *(-10,8%)*

Uncertainty in investment costs has been quantified earlier by De Grave & Baarse (2011). Their approach was to derive a high and low investment cost estimation, by investigating a scenario with more pessimistic and more optimistic assumptions and parameter values in the automatic cost estimations. Those two alternative scenarios were set as 10th and 90th percentile cost estimation in a continuous triangular probability distribution for the uncertainty in investment costs for dike improvement. Their quantified uncertainty of the investment costs is only available for the primary flood defence system of dike ring 43 completely, which prohibits direct comparison of the found confidence intervals. De Grave & Baarse (2011) estimated that the 10th and 90th percentile total investment costs are respectively 13% lower and 35% higher than the most likely cost estimation (the mode of their triangular distribution). This indicates that their triangular distributions are strongly right-skewed. In this study, a normal distribution was used, and Figure 3-23 showed that the probability distribution of investment costs is only slightly right-skewed. Figure 3-23 is based on 10000 probabilistic cost estimations, whereas the uncertainty estimations by De Grave & Baarse (2011) are based on three expert-based cost estimates. A normal distribution therefore likely provides a better representation of the uncertainty in investment costs than a skewed triangular distribution as applied by De Grave & Baarse (2011).

4.4 Influence individual uncertainty sources on flood safety standards

This paragraph discusses the results of the fourth step in this research. The alternative scenarios established for the 5 uncertainty sources were propagated through the safety standard calculation process and give insight in the induced effects. The following subsections present the results of the uncertainty analysis, separately for each of the five uncertainty sources. These subsections focus mainly on the differences between the 6 safety standard segments. The final subsection summarizes the identified (spatial) characteristics which determine the influence of the uncertainty sources for these different segments. An overview of all safety standards resulting from the individual uncertainty analysis is shown in Table 4-7, along with the relative width of the 50% confidence interval. For an overview of the differences between the propagated scenarios refer to Table 3-5. This paragraph presents and discusses the alert safety standards. The lower limit standards are directly related to the alert standards and the described uncertainty influence in this chapter applies the same for the lower limit standards. Hence it does not give added value to present both the alert and lower limit standards.

4.4.1 Breach development

From the made flood simulations, Figure 4-11 shows the effects of the distinguished breach growth scenarios on the inundation characteristics in dike ring 43. The figure points out that decreased breach growth significantly influences both the maximum inundation depths and flood rise rates in the inundated area. Notable is the fact that the rise rates at most locations are stronger influenced by the breach growth than the inundation depths. The explanation is that the inundation depths for all scenarios keep increasing (albeit at a smaller pace) until the spill flow works at Dalem are opened to release flood water. Furthermore, it becomes clear that both the inundation depths and rise rates are influenced strongest in the area north of the river Linge (which can be recognised as the meandering east-west pattern in Figure 4-11). This is explained by the secondary dikes bordering the Linge river, which divide the flood zone in compartments during inundation and prevent the area north of the river Linge from inundating until the crest level of these secondary dikes is reached. For smaller breaches and decreased inflow volumes the southern compartment therefore still fills up, but overflow into the compartment north of the river Linge is decreased and hence results in strong reductions of inundation depths and rise rates there.

Propagation of the flood characteristics for the distinguished breach growth scenarios through the calculation process for the safety standards gives safety standards for segment 43-6 as shown in Figure 4-12. Logically, for areawide decreased inundation depths and rise rates in the reference scenario, both the LIR and SCBA standards decrease significantly compared to the verification scenario. It becomes clear that the difference between the verification scenario and the reference scenario is larger for the LIR standards than for the SCBA standards. This is explained by the stronger reduction in rise rates than inundation depths. Inundation depths are by far most influential for the flood damage, while the rise rate is an additional important factor for the calculation of the mortality and LIR in the area. The rise rates especially decreased strongly in the areas directly behind the breach location in Tiel (see Figure 4-11). This is reflected in the strong decrease of the median mortality in the neighbourhood which was normative in the verification safety standard calculations (see Figure 4-13). For the 25th, reference and 75th percentile breach growth scenarios, the normative neighbourhood moves as the flood characteristics in the westernmost areas of the dike ring are less influenced by the breach growth curve (see Figure 4-11 & Figure 4-13).

As shown in Figure 4-12, the difference between the verification and reference standards is significant, while the 50% confidence interval is rather small for both the LIR and SCBA standards. This is explained by three aspects: firstly, it became clear before that the 50% confidence interval of the breach growth curve, given by the Verheij-Van der Knaap equation, is relatively small for the clayey dike compositions predominantly found along safety standard segment 43-6. The low value assumed for U_c in the verification scenario gives a significantly stronger breach growth.

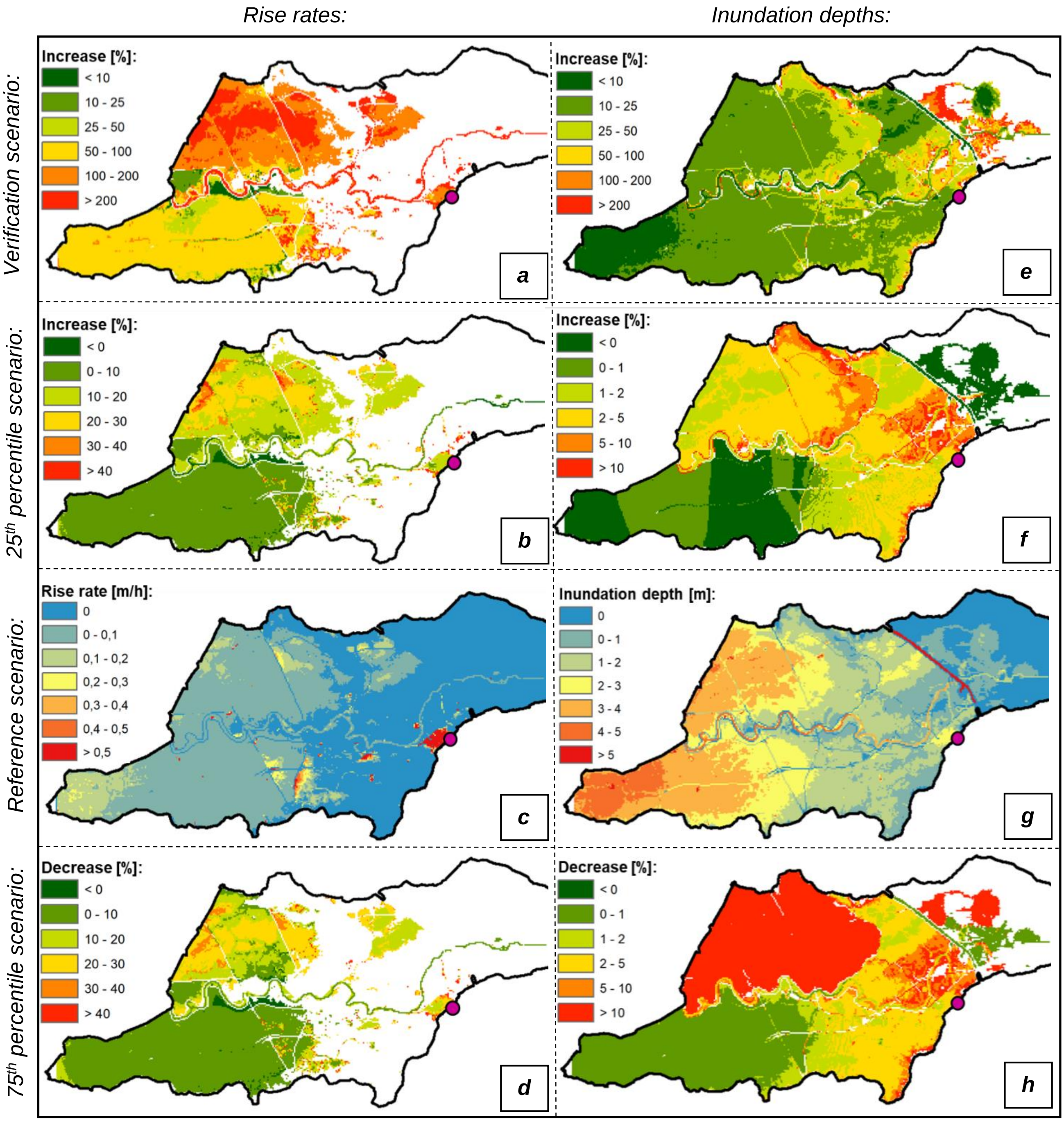

Figure 4-11: Flood rise rates (left column) and inundation depths (right column) for the verification breach development scenario and the three established alternative breach development scenarios, for breach location Tiel-West (purple dot). Sub-figures (c) and (g) give the absolute rise rates and inundation depths for the reference scenario, while the other figures all give the percentual increase or decrease of the rise rates/inundation depths from the reference scenario to the other scenarios. (a): Rise rates verification scenario; (b) Rise rates 25th percentile scenario; (c): Rise rates reference scenario (d): Rise rates 75th percentile scenario; (e): Inundation depths verification scenario; (f): Inundation depths 25th percentile scenario; (g): Inundation depths reference scenario; (h): Inundation depths 75th percentile scenario. Note that the legends differ for these sub-figures.

Secondly, specifically relevant for the SCBA standards, Figure 4-11 makes clear that the inundation depth is for large areas marginally influenced by the alternative breach development scenarios. The spill flow works at Dalem (see Figure 2-4) prevent a further increase of inundation depths. Inundation depths are therefore not highly influenced by the breach growth, hence the SCBA standards neither. Thirdly, specifically relevant for the LIR standards are the characteristics of the normative neighbourhoods for the different scenarios. Some neighbourhoods of Tiel behave like a small bathtub due to the presence of the river dikes, an elevated railway and the naturally higher elevated city centre of Tiel. This results in high rise rates and inundation depths for a dike breach along this bathtub area. The mortality in this area is therefore also very sensitive for variations of the breach growth. Slower breach growth moves the normative neighbourhood towards the west of the inundated area (see Figure 4-13). These neighbourhoods are situated far from the breach locations and are less sensitive to variations in breach growth, as shown in Figure 4-13.

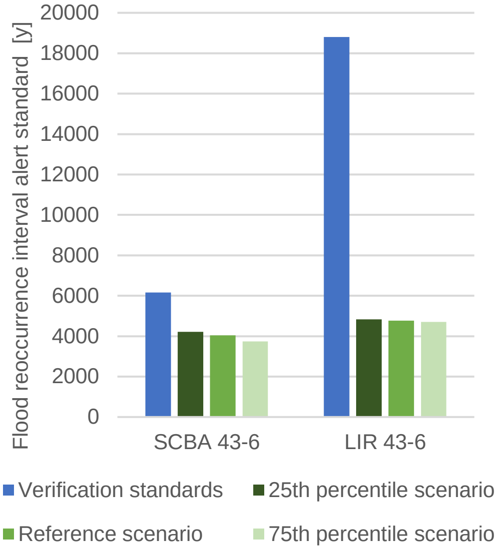

Figure 4-12: Overview of the LIR and SCBA standards for the three breach development scenarios for safety standard segment 43-6, along with the verification standards.

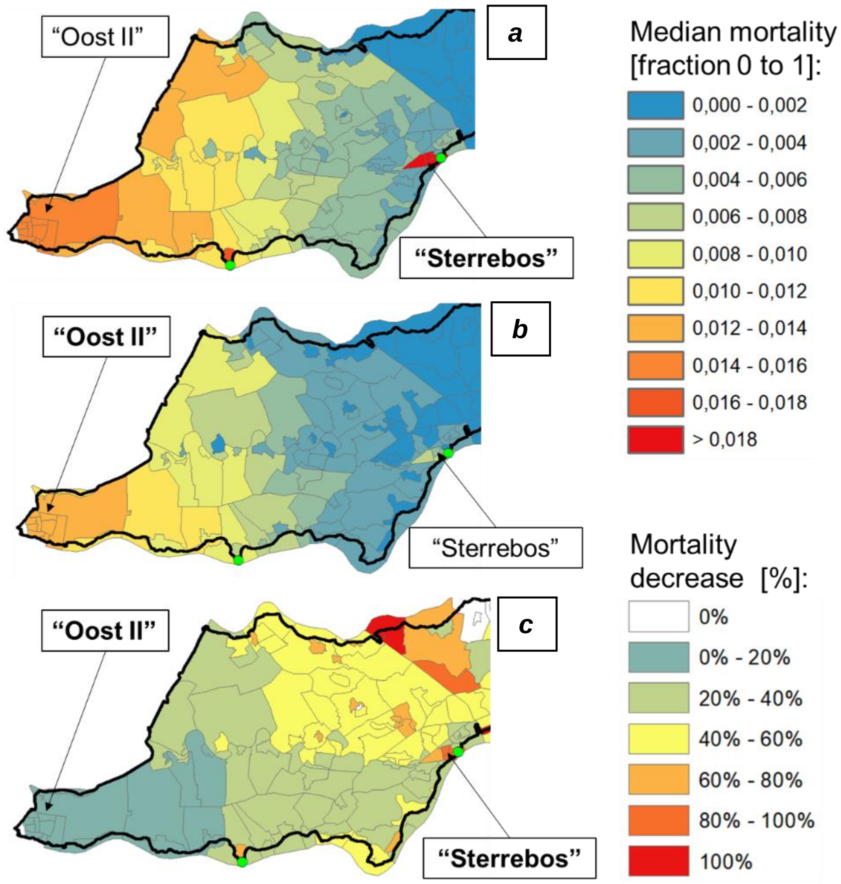

Figure 4-13: Median mortality per neighbourhood for safety standard segment 43-6 in the verification scenario (a), for the reference scenario (b) and the percentual decrease between these two scenarios (c). The location of the normative neighbourhood in the verification scenario (Sterrebos) and in the three other scenarios (Oost II) is indicated as well. Breach locations are indicated as green dots.

4.4.2 Mortality functions

The LIR alert standards calculated based on the 25th percentile, reference and 75th percentile scenarios differ significantly over the 6 safety standard segments (see Figure 4-14). Firstly, it became clear that in the reference scenario, the LIR standards are less strict for most segments compared to the verification standards. The standards derived for the 50% confidence interval give a large spread around the reference standards for most segments. Most notable however is the significant difference in effect over the 6 segments, which is explained by the flood characteristics in the normative neighbourhoods for the individual segments.

Firstly, when comparing the verification standards to the reference standards from the uncertainty analysis, it stands out that the difference varies over the 6 segments. Inundation characteristics in the normative neighbourhoods for segments 43-4, 43-5 and 43-6 are much more violent than for the other three segments (pointed out by the higher median mortality for those segments, see appendix A8). The correction for reduced building collapsibility therefore has much more effect for those segments.

Secondly, it is notable that the standards for segment 43-1 are hardly affected by any of the three defined mortality scenarios. Flood characteristics are relatively mild for this segment. As a result, the median mortality value in the neighbourhood dominant for this safety standard segment is determined by the low rise rate mortality function. Therefore, the standards are in principle not influenced by the three scenarios, as only the mortality functions for the high rise rates and the intermediate zone differ from the verification calculations. Because the 6 LIR standards are intertwined and depend on each other (as explained in paragraph 3.1.5), the standards for this safety standard segment could even become stricter in the 75th percentile scenario, the opposite of the other segments.

Lastly, it is also notable that the safety standard for segment 43-2 is influenced by the 25th percentile scenario, while it is hardly influenced by the 75th percentile scenario. The explanation is that the normative neighbourhood for this safety standard segment changes for different scenarios. The neighbourhoods normative in the reference and 25th percentile scenarios are strongly influenced by the mortality function interpolation. For the 75th percentile scenario, the median mortality in this neighbourhood drops below the median mortality of other neighbourhoods where the mortality interpolation is less or not of influence at all. As a result, the 75th percentile and reference scenarios do not differ, while the 25th percentile scenario does.

For segments 43-4, 43-5 and 43-6 the normative neighbourhood does not change over the three scenarios and is the same as in the verification standards (the neighbourhoods are shown in appendix A8). Therefore, the 25th percentile, reference and 75th percentile scenarios all give a significantly different LIR alert standard for those segments.

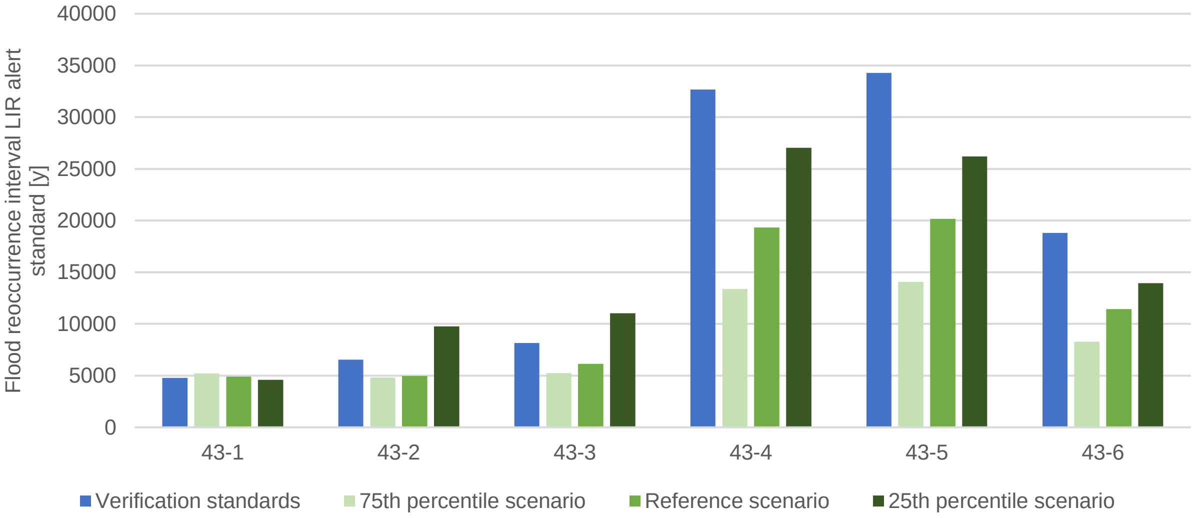

Figure 4-14: LIR alert standards for the 6 safety standard segments of dike ring 43, for three considered alternative mortality function scenarios, along with the verification standards

4.4.3 Evacuation

After incorporation of the 3 defined alternative evacuation scenarios within the safety standard calculation process, new LIR standards were calculated. Figure 4-15 shows that evacuation significantly affects the LIR standards.

Firstly, the difference between the verification standards and the reference scenario is large, with alert standards on average 70% less strict than the verification standards. The original evacuation percentage of 56% assumed in the verification calculations is much lower than the percentages derived in the uncertainty quantification. The differences between verification standards and the reference scenario are strongest for the segments where the normative neighbourhood in the verification standards is flooded a long time after breach initiation. For those segments (43-1, 43-3 and 43-4), acute evacuation possibilities add up to the already high preventive evacuation percentages in the reference scenario. As a result, the neighbourhood normative for the LIR standards also changes for some evacuation scenarios, as shown for segment 43-1 in Figure 4-16 (figures for all segments are shown in Appendix A9)

The effect of the uncertainty in preventive evacuation time becomes clear as well. For all safety standard segments except 43-4, the standards are 20% to 50% stricter in the 25th percentile scenario compared to the reference scenario. In the 75th percentile scenario, standards are between 4% and 13% less strict compared to the reference scenario. The difference in effect between moving from the 25th percentile to the reference scenario and moving from reference to 75th percentile scenario is explained by the non-linear cumulative probability function of the preventive evacuation percentages (see Figure 4-7).

The relative size of the 50% confidence interval (also see Table 4-7) differs over the 6 segments. This difference is explained by two factors. Firstly, there is the variation in normative neighbourhoods for the 6 safety standard segments. The effect of uncertainty in preventive evacuation time is very small if a normative neighbourhood is situated at a location where flood water arrives after many hours (as the availability of acute evacuation time already gives very high evacuation percentages). This explains why the effect is relatively large for segments 43-2 and 43-6, where flood water arrives almost instantly after breach initiation (see Appendix A9). Segments 43-1 and 43-4 are recognised by relatively long flood arrival times, which is why the effect of uncertainty of the evacuation percentage is smaller there. Besides this effect, the interdependence between the safety standards for the 6 safety standard segments influences the effects as well. For segment 43-4 this explains why the standards can even become stricter for the 75th percentile evacuation scenario.

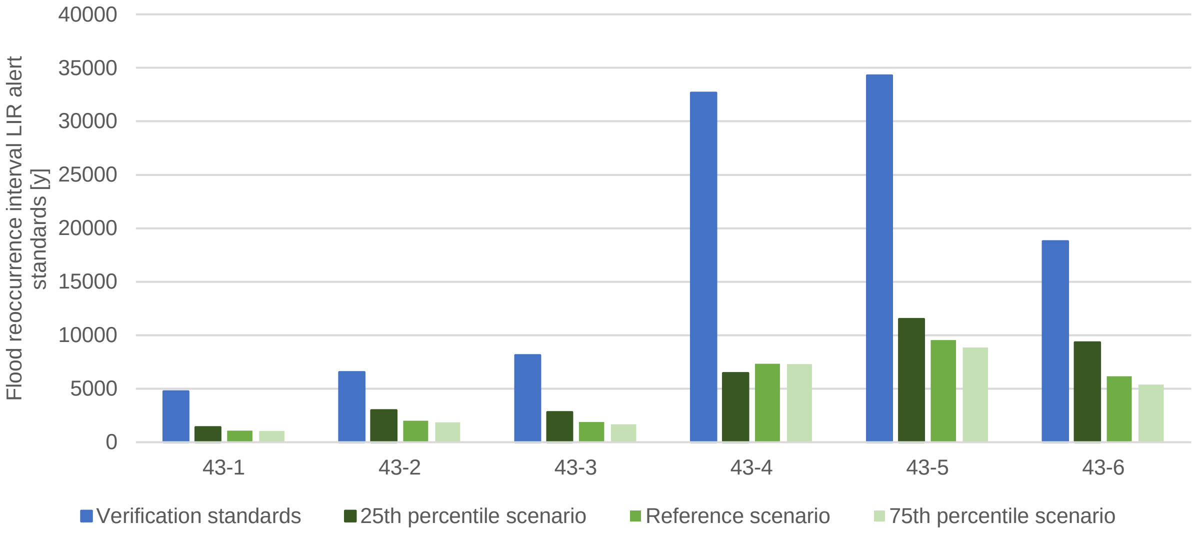

Figure 4-15: Alert LIR standards for the 6 safety standard segments of dike ring 43 for three considered alternative evacuation scenarios, along with the verification standards

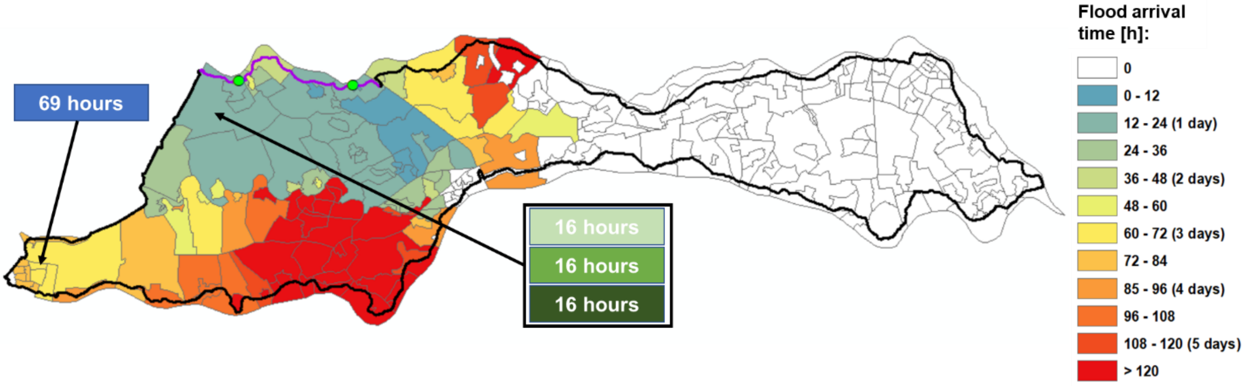

Figure 4-16: Flood arrival times after breach initiation, for safety standard segment 43-1. The flood arrival times in the LIR normative neighbourhoods for the verification standard (blue box) and the three alternative evacuation scenarios (green boxes) are shown as well. (dark green = 25th percentile scenario, middle green = reference scenario, light green = 75th percentile scenario)

4.4.4 Damage functions

For each of the three damage function scenarios, new SCBA alert standards were calculated (see Figure 4-17). Firstly, it became clear that the adaptations of two of the original damage functions to correct for proven errors (the reference scenario) results in stricter SCBA standards than the verification standards. Especially the total damage for industrial areas increased significantly for the considered flood scenarios compared to the situation in which the damage functions all originate from Kok et al. (2005). There is on average 20% more flood damage in the reference situation. The alert standards therefore on average increased 20% as well, due to the linear relationship between flood damage and safety standards in equation 2 (paragraph 3.1.3).

The relative width of the 50% confidence interval is approximately 30% to 40% (see Table 4-7). This characteristic slightly varies for the 6 safety standard segments, which is explained by the differences in flood patterns and land use relevant for the total damage. Furthermore, the percentage of the total damage caused by monetised casualties and flood victims slightly differs over the 6 segments, which also affects the potential influence of adapted damage functions on the SCBA standards. For instance, the influence of damage function uncertainty is smallest for segment 43-6, which is also where the monetised casualty damage accounts for the highest percentage of the total damage of all safety standard segments.

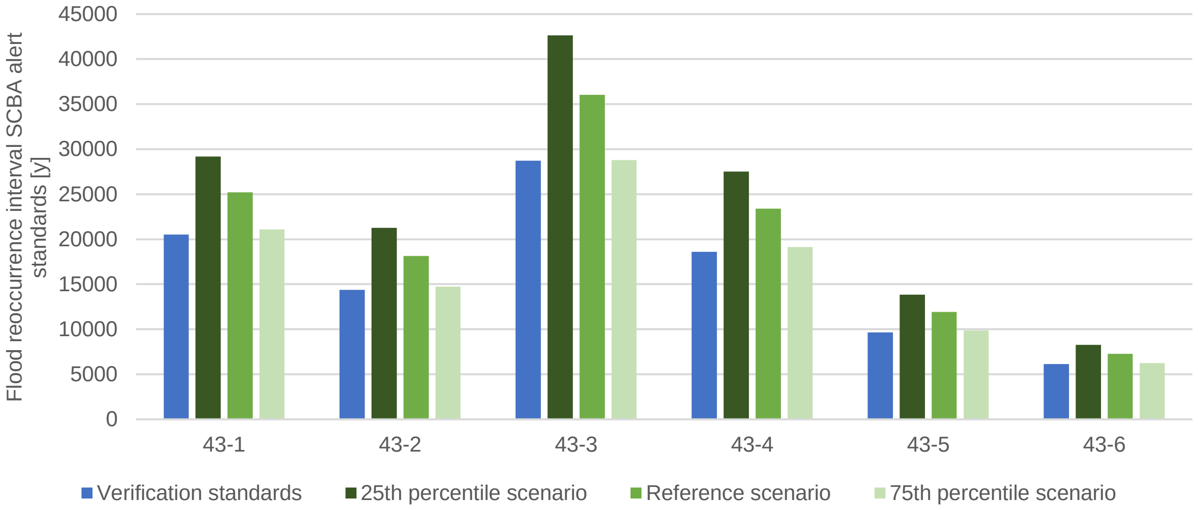

Figure 4-17: SCBA alert standards for the safety standard segments of dike ring 43, calculated for three alternative scenarios of damage function sets, along with the verification standards.

4.4.5 Investment costs for dike improvement

The SCBA flood safety standards calculated based on the three distinct scenarios are shown in Figure 4-18. The investment costs directly and linearly influence the SCBA flood safety standards, as should be expected based on the SCBA standard calculation equation (equation 2 in paragraph 3.1.3). Opposed to the other 4 uncertainty sources, the 75th percentile scenario results in stricter safety standards. This is logically explained as reduced investment costs imply that the optimal cost-benefit annual flood probability is larger. The relative width of the 50% confidence interval of the safety standards (Table 4-7) is equal to the width of the 50% confidence interval of the investment costs: approximately 20 to 30%. Of the three segments, the uncertainty in flood defence investment costs gives the largest relative safety standard uncertainty for safety standard segment 43-5. The explanation for varying relative uncertainty over the three considered segments is therefore the same as the explanation for uncertainty variance in the investment costs over these segments, as was discussed in paragraph 3.3.6.

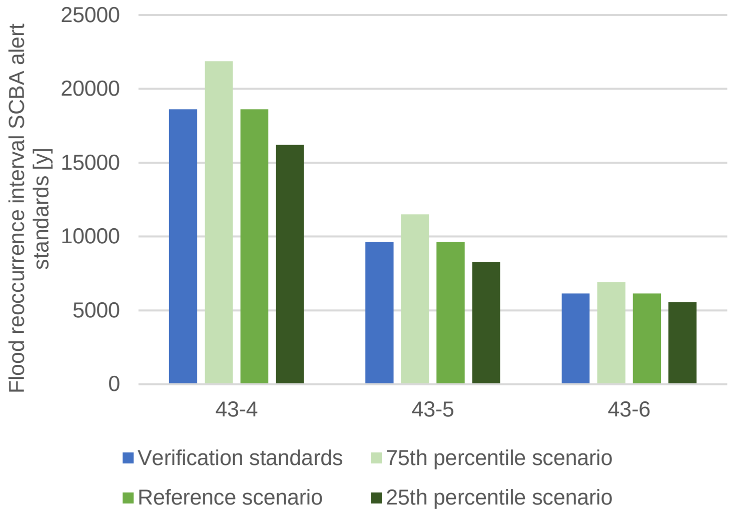

Figure 4-18: SCBA alert standards for three of the six safety standard segments of dike ring 43, for different scenarios of uncertain flood defence investment costs, along with the verification standards.

4.4.6 Uncertainty influence variation over the safety standard segments

The analysis in the previous subsections of the individual uncertainty sources enabled defining some general statements on the importance of the individual uncertainty sources and the spatial characteristics which determine the effects of these uncertainty sources. This provides an answer to the fourth research question. First focussing on the LIR safety standards, it became clear that in general the uncertainty of the mortality functions most significantly influences the flood safety standards of dike ring 43 (see the relative confidence interval widths in Table 4-7), which was for most safety standard segments relatively large. The influence of the evacuation scenarios was mostly smaller but still significant, while the breach development uncertainty was of minor influence on the safety standards (based on segment 43-6).

For both the mortality functions and the evacuation scenarios, the influence variation over the 6 safety standard segments depends strongly on the flood characteristics of the normative neighbourhood. The rise rates in this area determine whether the mortality function uncertainty impacts the safety standards, while the flood arrival time determines to what extent evacuation percentage uncertainty affects the safety standards. As the mortality function uncertainty and evacuation percentage uncertainty do not equally influence the entire flood zone, the normative neighbourhood is variable for different uncertainty scenarios as well. The results indicate that this aspect affects the uncertainty source influence as well. The flood arrival time and location of the normative neighbourhood determine the influence of breach development uncertainty as well, based on the results for segment 43-6.

The SCBA flood safety standards derived in the uncertainty analysis generally showed less variability than the LIR safety standards. This indicates that the derivation of SCBA standards with the current safety standard calculation process is more robust than the derivation of LIR standards. For the safety standard segments where comparison between the relative width of the confidence intervals was possible, it became clear that the damage function uncertainty is of most significant influence, slightly more than the uncertainty in investment costs. Breach development uncertainty is of smallest influence for the SCBA standards (based on the results for segment 43-6). The influence of these three uncertainty sources is determined mainly by the relative uncertainty in the sources itself, rather than by other factors like flood characteristics. The SCBA standards are therefore not only influenced by different uncertainty sources than the LIR standards but are also influenced for different reasons.

The fundamental differences between the calculation of the SCBA standards and LIR standards are the main explanation for the fact that the relative width of the 50% confidence interval varies significantly over the segments for the LIR standards, while being much more constant for the SCBA standards. Uncertainty sources relevant for the SCBA standards influence the flood damage and investment costs directly, as the standards are derived based on weighing the total costs and benefits for each segment. Possible spatial variance of the effects is therefore not relevant for the SCBA standards. Uncertainty sources relevant for the LIR standards influence the standards less directly, as these are derived based on the flood characteristics in a single neighbourhood. Spatial variance of the effects is therefore clearly more important, hence the effects of the relevant uncertainty sources can stronger vary over the different safety standard segments.

Table 4-7: Overview of all alert standards calculated in the uncertainty analysis and the expression of the 50% confidence interval (CI) as percentage of the 50th percentile, as indicator of the influence of uncertainty sources on the safety standards.

Scenario	43-1	43-2	43-3	43-4	43-5	43-6
	Breach Development LIR					
Verification	1/4773	1/6543	1/8149	1/32683	1/34290	1/18798
25th percentile	-	-	-	-	-	1/4825
50th percentile	-	-	-	-	-	1/4775
75th percentile	-	-	-	-	-	1/4700
Relative width 50% confidence interval	-	-	-	-	-	*2,6%*
	Mortality functions LIR					
Verification	1/4773	1/6543	1/8149	1/32683	1/34290	1/18798
25th percentile	1/4603	1/9763	1/11020	1/27045	1/26214	1/13956
50th percentile	1/4909	1/4954	1/6129	1/19336	1/20168	1/11446
75th percentile	1/5220	1/4808	1/5249	1/13390	1/14055	1/8273
Relative width 50% confidence interval	*13%*	*100%*	*94%*	*71%*	*60%*	*50%*
	Evacuation percentage LIR					
Verification	1/4773	1/6543	1/8149	1/32683	1/34290	1/18798
25th percentile	1/1410	1/2994	1/2823	1/6470	1/11511	1/9326
50th percentile	1/1095	1/1998	1/1887	1/7335	1/9535	1/6175
75th percentile	1/1049	1/1874	1/1675	1/7304	1/8856	1/5389
Relative width 50% confidence interval	*33%*	*56%*	*61%*	*11%*	*28%*	*64%*
	Breach development SCBA					
Verification	1/20519	1/14375	1/28712	1/18612	1/9643	1/6154
25th percentile	-	-	-	-	-	1/4222
50th percentile	-	-	-	-	-	1/4044
75th percentile	-	-	-	-	-	1/3737
Relative width 50% confidence interval	-	-	-	-	-	*12%*
	Damage functions SCBA					
Verification	1/20519	1/14375	1/28712	1/18612	1/9643	1/6154
25th percentile	1/29190	1/21264	1/42641	1/27529	1/13854	1/8285
50th percentile	1/25216	1/18131	1/36027	1/23393	1/11928	1/7275
75th percentile	1/21073	1/14725	1/28804	1/19120	1/9875	1/6254
Relative width 50% confidence interval	*32%*	*36%*	*38%*	*36%*	*33%*	*28%*
	Investment costs SCBA					
Verification	1/20519	1/14375	1/28712	1/18612	1/9643	1/6154
25th percentile	-	-	-	1/16204	1/8301	1/5555
50th percentile	-	-	-	1/18612	1/9643	1/6154
75th percentile	-	-	-	1/21861	1/11506	1/6899
Relative width 50% confidence interval	-	-	-	*30%*	*33%*	*22%*

4.5 Combined effect uncertainty sources on flood safety standards

This section describes the effect on the flood safety standards when the uncertainty sources are combined. This fifth research step provides insight in the plausible range of LIR and SCBA standards which could be expected when the described uncertainty is considered and provides an answer to the fifth research question.

4.5.1 Combined uncertainty LIR standards

After propagation of the 27 unique combinations of the individual uncertainty source scenarios, LIR standards were derived for safety standard segment 43-6 (Table 4-8). The results provided several insights. Firstly, it became clear that the combination scenario in which the three (adapted) reference scenarios were combined, results in an alert flood safety standard of 1/1284 per year. The strictest and least strict standards derived from the 27 combinations are respectively 1/2080 per year and 1/1190 per year. The combination which results in the strictest standards originates from the three 25th percentile scenarios and vice versa for the least strict standard. The strictest and least strict combination scenarios are made up by the three individual scenarios which individually gave respectively the strictest and least strict standards as well (see paragraph 4.4).

Notable is the fact that this spread is relatively small considering that the individual uncertainty sources showed a large relative width of the confidence interval by themselves. Furthermore, it became clear that the least strict standard was given by three different combinations. Both observations are explained by one particular phenomenon. For most combinations of breach development and evacuation scenarios, the mortality scenario does not have any influence on the LIR standards. This might seem odd considering the results in paragraph 4.4.2, which showed that the mortality functions individually clearly can have significant influence. This is explained by the interaction between the three uncertainty sources. The uncertainty in the mortality functions was for this study quantified through the interpolation method between the high and low rise rate mortality functions (elaborated in paragraph 3.3.2). The mortality function uncertainty therefore especially influences the areas of the inundation zone which are characterised by intermediate rise rates between 0,5 and 4m/h. The distinguished breach development scenarios all 3 resulted in strongly reduced rise rates compared to the verification scenario that was used as basis in the analysis of the individual uncertainty influences. Therefore, the median mortality values derived for the normative neighbourhood can under these circumstances become fully dominated by the low rise rate mortality function rather than the interpolation function. This explains why the mortality function uncertainty no longer influences the LIR standards. Besides this characteristic, both the breach development and evacuation scenario influenced the neighbourhood which becomes normative for the LIR standards, as was observed in the analysis of the individual uncertainty sources as well. Combined, these effects explain why for the 25th percentile evacuation scenario the mortality is of influence, while for the reference and 75th percentile scenarios there is no influence (as another neighbourhood is normative).

Based on the results in Table 4-8 gathered for segment 43-6, several statements were defined: Firstly, the found relative spread in LIR standards is quite small (the spread is approximately 70% of the standard in the combination reference scenario), compared to the confidence interval spreads for the individual uncertainty sources (breach development 2.6%, mortality 50% and evacuation 64%, see Table 4-8). Secondly, the uncertainty of the evacuation percentages explains most of the uncertainty appointable to the three considered uncertainty sources. Thirdly, the influence of mortality function uncertainty is generally of less influence and strongly depending on the breach growth (induced rise rates) and on the evacuation percentages (induced normative neighbourhood). Lastly, the influence of the breach growth uncertainty is small in general but can become more significant in case the normative neighbourhood is strongly influenced by the presence of increased surface elevation lines.

Table 4-8: Alert flood safety standards [y^{-1}] for safety standard segment 43-6 by combination of the three considered uncertainty sources of influence on the LIR standards. Each value expresses one combination of the three defined scenarios for each uncertainty source. 25th stands for the 25th percentile scenario, R for reference scenario and 75th for the 75th percentile scenario.

Breach development	Mortality functions			Evacuation
Scenario	75th	R	25th	Scenario
25th	*1793*	*1993*	***2080***	25th
25th	*1312*	*1312*	*1312*	R
25th	*1222*	*1222*	*1222*	75th
R	*1742*	*1742*	*1822*	25th
R	*1284*	***1284***	*1284*	R
R	*1206*	*1206*	*1206*	75th
75th	*1705*	*1705*	*1705*	25th
75th	*1267*	*1267*	*1267*	R
75th	***1190***	*1190*	*1190*	75th

Table 4-9: Alert flood safety standards [y^{-1}] for safety standard segment 43-6 by combination of the three considered uncertainty sources of influence on the SCBA standards. Each value expresses one combination of the three defined scenarios for each uncertainty source. 25th stands for the 25th percentile scenario, R for reference scenario and 75th for the 75th percentile scenario.

Breach development	Damage functions			Investment costs
Scenario	75th	R	25th	Scenario
25th	*4838*	*5822*	***6769***	75th
25th	*4315*	*5193*	*6038*	R
25th	*3895*	*4688*	*5450*	25th
R	*4636*	*5604*	*6528*	75th
R	*4135*	***4999***	*5823*	R
R	*3733*	*4513*	*5256*	25th
75th	*4271*	*5190*	*6057*	75th
75th	*3810*	*4630*	*5403*	R
75th	***3439***	*4179*	*4877*	25th

4.5.2 Combined uncertainty SCBA standards

Table 4-9 provides for each of the 27 unique scenario combinations the resulting SCBA standards for safety standard segment 43-6. First of all, it became clear that the combination reference scenario (combination of the three reference scenarios for the individual uncertainty sources), gives an alert flood safety standard of 1/4999 per year. The strictest and least strict flood safety standards derived from the 27 combinations are respectively 1/6769 per year and 1/3439 per year. The combinations resulting in these standards are logically explained from the individual uncertainty analysis (paragraph 4.4).

Table 4-9 shows that contrary to the LIR standards, the 27 scenario combinations all give unique optimal alert standards. The three uncertainty sources influence the SCBA standards mostly independently from each other. The sole interdependence among the three uncertainty sources is between the breach development and damage functions. For slower breach development, the influence of the damage functions is slightly smaller than for faster breach development. This could be explained by the on average smaller inundation depths for slower breach development. For many damage functions (see appendix A5), the uncertainty spread is smaller for deep floods of 3 or 4m (as maximum damage would be reached already). Slower breach development decreases the maximum inundation depths, which increases the influence of damage function uncertainty. This effect is small but traceable. Compared to the LIR standards in Table 4-8, the overall spread of the SCBA standards is quite large considering the relative widths of the confidence intervals given in Table 4-7 for the individual uncertainty sources. As the uncertainty sources act mostly independent, their influence largely adds up, which gives the larger relative spread in SCBA standards.

Based on the results in Table 4-9, several statements were made: Of the three considered uncertainty sources, the uncertainty in the damage functions is responsible for the largest spread in the SCBA standard, while the uncertainty in the flood defence investment costs is of slightly smaller influence. The breach development uncertainty influence is only small, mainly explained by the role of the spill flow works at Dalem, which stabilise the inundation depths regardless of the breach inflow.

Interdependence between these uncertainty sources is negligible. As a result, the individual uncertainty source influence on the SCBA standards approximately adds up to the strictest and least strict combination SCBA standards, hence the spread in SCBA safety standards is relatively large (approximately a factor 2).

The uncertainty sources shown to be of significant influence on the SCBA flood safety standards in this study were also studied by Gauderis et al. (2011) to analyse uncertainty source influence on the SCBA standards. They showed that especially uncertainty of the inundation pattern (amongst other due to breach development uncertainty) and uncertainty of investment costs are the most important sources of uncertainty for the SCBA standards in dike ring 43, while damage function uncertainty was considered of relatively small influence. The results of this study suggest that uncertainty in damage functions does strongly influence the SCBA standards. Breach development uncertainty is through the influence on the inundation pattern in the study by Gauderis et al. (2011) considered as highly important. It was shown in this study that the influence is quite low due to the influence of the Dalem spill flow works. It must however be noted that Gauderis et al. (2011) studied dike ring 43 in total, instead of only segment 43-6. For other segments of dike ring 43, the uncertainty could be of more influence as the relative influence of the Dalem spill flow works is less prominent for other segments.

4.5.3 Comparison verification and uncertainty analysis standards

In the establishment of the scenarios for the individual uncertainty sources, for four of the five individual uncertainty sources there were reasons to doubt the assumptions made in the verification runs, as the assumptions did not match the uncertainty quantification data or the characteristics of the area. In order to reliably quantify the uncertainty, it was chosen to adapt the settings used in the verification safety standard derivations, without considering this as a separate uncertainty source. In the final step of this research the scenarios for all individual uncertainty sources were combined. This enables comparison with the verification standards, which gives insight in the total effect of the assumptions made in the verification standard derivation versus the assumptions made in the uncertainty analysis in this study.

The verification calculations in this study gave an alert LIR standard for safety standard segment 43-6 of 1/18797 per year. In the combination uncertainty analysis in this study, a realistic spread in LIR standards was found between 1/1190 and 1/2080 per year, containing significantly less strict standards than the verification standard. This shows that besides the uncertainty of the various components in the safety standard derivation, the basic assumptions strongly (and more significantly than the uncertainty) affect the eventual LIR safety standards.

The verification SCBA standard for segment 43-6 was 1/6154 per year. The realistic spread found in the uncertainty analysis gave standards between 1/3439 and 1/6769 per year. These standards do not differ significantly from the verification safety standard. This is partially explained by the fact that the reference assumptions from the verification calculations were not as strongly adapted as for the LIR standards. Furthermore, this is explained by the characteristic that SCBA standards are derived from the total costs and benefits for a safety standard segment. Locally stronger deviations in effects of the individual uncertainty sources are therefore not reflected in the safety standards.

Based on these observations, it is concluded that for segment 43-6 the LIR standards are more sensitive for changes in the derivation process than the SCBA standards, due to the locally varying influences of uncertainty sources. These do affect the LIR standards (which are derived from characteristics on neighbourhood spatial scale) and do not affect the SCBA standards (which are derived from characteristics for the entire flood zone).

When the calculated LIR and SCBA standards are translated into safety standard classes (according to the rules in Table 3-1), it becomes clear that the alert safety standard class for segment 43-6 becomes 2 to 3 classes less strict for the LIR standard and 0 to 1 class less strict for the SCBA standard. In this case, the SCBA standard therefore becomes normative, contrary to the verification standards (Table 4-10). Based on the insights from the uncertainty analysis, it is concluded that the relatively strict LIR safety standard classes currently defined in the Dutch Water Act for this segment are mostly a result from the current conservative assumptions in the LIR standard derivations.

Table 4-10: LIR and SCBA alert safety standards and accompanying class for safety standard segment 43-6

	Verification calculations	**Combination uncertainty analysis**
LIR standard	1/18798	1/1190 – 1/2080
LIR standard class	*1/30000*	*1/1000 – 1/3000*
SCBA standard	1/6154	1/3439 – 1/6769
SCBA standard class	*1/10000*	*1/3000 – 1/10000*

5 Discussion

This chapter first discusses the potential of this study. Afterwards, the limitations of the study approaches are discussed. Next, this chapter elaborates on the possibilities to generalise the case study results to the Dutch flood safety standards in different areas. Lastly, a brief discussion is provided about the possible implications of this study for the current dike improvement tasks in dike ring 43.

5.1 Potential of this study

One of the strong and novel characteristics of this study is the systematic approach in the uncertainty analysis. This study started with deriving a full overview of potential uncertainty sources in all of the main components of the safety standard calculation process. Through the expert elicitations, a ranking of important uncertainty sources was derived in a systematic way. This approach has assured that the most important uncertainty sources were included in the uncertainty analysis of this study.

Earlier studies have never taken a closer look into the individual risk uncertainty and the associated LIR safety standards and have not earlier propagated uncertainty through the actual safety standard derivation process (neither for the LIR nor SCBA standards). Especially to determine the effect of uncertainty sources on the LIR standards, this approach was very useful. It allowed to define spatial characteristics which determine the uncertainty influence. This study has shown that LIR standards are very sensitive to changes in assumptions and uncertainties in the safety standard calculation process, which is strongly determined by distinct spatial characteristics.
The insights into how uncertainty sources influence the safety standards and which spatial characteristics are relevant, can also be used to translate the results for case study dike ring 43 to other areas.

The results from this study also provide insight into how dike design choices or adaptations to the hinterland could potentially influence the flood consequences and optimal safety standards. The implications of dike design choices for flood consequences (and safety standards) are currently not taken into account in dike design. The insights from this study could therefore support decision making for certain dike design alternatives (apply a sand or clay core for example) or support landscape interventions (such as whether to construct or remove lines of increased surface elevation in the hinterland).

Lastly, the results of this study provide incentives for useful further study directions and improvement of the safety standard calculation process. It was shown that some uncertainty sources are of more influence than others and are sometimes not important at all, depending on the spatial characteristics of a dike ring. These insights could help to prioritise further study directions aimed at decreasing safety standard uncertainty.

5.2 Limitations and possibilities to extend this study

An important point of discussion in the approach of this study relates to which and how many uncertainty sources were considered in the uncertainty analysis, and what this tells us about the overall uncertainty of the Dutch flood safety standards; could the overall uncertainty differ significantly from the results gathered in this study in case the study approach would have been different?
The expert elicitations were used to determine which uncertainty sources to include in the uncertainty analysis. Despite that only six experts were consulted, the experts were relatively unified in their opinions about the most important uncertainty sources. It is therefore not likely that the overall judgement about the most prominent uncertainty sources would considerably change in case more experts were consulted. Moreover, if any of the 6 experts is left out, the importance order of the uncertainty sources remains largely the same, indicating that the number of experts is not of strong influence. Consulting more experts would nevertheless provide a stronger support for the derived importance list and it is possible that the uncertainty source ranking would slightly change when additional experts are consulted.

The total realistic spread of the uncertainty in the safety standards given in this study will probably not become significantly larger if additional (less important) uncertainty sources are incorporated. Gauderis et al. (2011) showed that depending on the area, the 4 to 6 most influential uncertainty sources already explained a large majority of the total uncertainty of the SCBA standards. Whether this is the case for the LIR standards as well is difficult to say due to the strong variety of uncertainty influence depending on spatial characteristics. Therefore, for the LIR standards the results of this study could be further supported by investigating whether some of the (on first sight) less important uncertainty sources could still be of significant influence in specific situations. The fact that the uncertainty source ranking is rather gradual suggests that more uncertainty sources could be of less but still significant influence. The uncertainty bandwidths defined in this study must therefore be interpreted as a good estimate of the uncertainty magnitude for the safety standards.

Breach development uncertainty was quantified by distinguishing clay and sand layers, after which standard values for the erosion resistance of clay and sand were used to quantify the breach growth curve uncertainty. The standard quantification values are simplifications of the reality, as there is great variety in type and erosion resistance of clay and sand layers (Verheij, 2003). The Verheij-Van der Knaap equation characteristics show that the erosion resistance variety of clay marginally impacts breach development. Especially the variety in clay/sand ratios influences breach growth. As relatively detailed dike profile data was used in this study for breach development uncertainty quantification, the defined breach development scenarios are quite robust, despite the limitations of the uncertainty quantification method.

For the evacuation uncertainty quantification, a 10% disobedience percentage among the population was assumed, based on the preventive evacuation practices in dike ring 43 during the high river discharges of 1995 (Kolen, 2013). In 1995, the dikes did not breach. It is questionable whether people would disobey evacuation orders as well if a breach has occurred already and flooding is imminent. Evacuation percentages would in that case further increase due to the available acute evacuation time. It therefore depends on the location of the LIR normative neighbourhood whether the LIR standards are sensitive to the assumed disobedience percentage (as shown in an example in Appendix A11 to clarify this effect). The assumed disobedience percentage is an important assumption which should therefore be further investigated (and could for instance be specified with respect to the flood arrival time).

In this study, the investment cost uncertainty was quantified given a basic design philosophy. This design philosophy is however often not yet fixed at the time when safety standards are derived. As a result, the investment cost uncertainty is somewhat larger than presented in this study when this aspect is taken into account (see appendix A10). The confidence interval established in this study for the investment cost uncertainty must therefore be considered as the best possible guess.

Lastly, the interdependence between the LIR standards of the 6 safety standard segments should be discussed (this effect was explained in paragraph 3.1.5). In this study, the breach development uncertainty was only considered for safety standard segment 43-6, while LIR standards in this dike ring are intertwined. The total LIR of the normative neighbourhood for dike ring 43 originates from 4 of the 6 safety standard segments (neighbourhood “Rijswijk”, see appendix A8). The correction factor applied to all LIR standards in dike ring 43 to assure the total LIR stays below the legally allowed value, is derived from the total LIR in this specific neighbourhood (see paragraph 3.1.5). This correction factor will thus only change (and therefore alter the LIR standards derived for segment 43-6 in this study) in case the normative neighbourhoods for the individual segments would change drastically. This is unlikely, as the neighbourhood is often normative by a large margin, regardless of the breach development configurations (see appendix A8). The LIR safety standard bandwidth obtained in this study for segment 43-6 is therefore hardly sensitive for the limited approach used for breach development uncertainty propagation, despite the interdependency of LIR safety standards in dike ring 43. If a similar uncertainty analysis is performed for a different study area, this effect is important to take into consideration.

5.3 Generalisation case study results

This study has focussed on dike ring 43 and specifically safety standard segment 43-6 as case study area to answer the research questions defined in paragraph 1.5. This paragraph discusses to what extent the specific approach and results for the case study can be translated to statements about the uncertainty in the Dutch flood safety standards in other areas in the Netherlands.

The first question is to what extent the uncertainty source importance ranking (Table 4-4) is valid nationwide. This depends amongst others on the size of the dike ring area. Gauderis et al. (2011) showed that for larger dike rings the uncertainty related to the extent of the flooded area, uncertainty in investment costs, mortality functions and evacuation are important sources of uncertainty for the SCBA standards. For small dike rings the uncertainty related to the extent of flooded area (amongst others due to breach development uncertainty) becomes less important. Also, most of the consulted experts argued that due to the large size of dike ring 43, some uncertainty sources were of minor importance as a result of averaging effects. In very small dike rings, for example the building value uncertainty is much more important.

Also, the origin of the flood hazard is an important factor. For flood hazards posed by storm surges, both the flood probability and flood consequences are influenced by different uncertainty sources than for flood hazards posed by high river discharges. Furthermore, the importance of uncertainty sources will differ under different flood hazards, for instance due to the enhanced predictability of river floods and the often longer timespan of river floods compared to floods posed by storm surges.

Dike ring 43 has several distinct characteristics which determine the importance of some uncertainty sources and can differ significantly in other areas. For example, the stretched shape, sloping surface and presence of increased surface elevation lines were mentioned earlier as important factors for the importance of the evacuation scenarios. In areas without these characteristics, the evacuation and mortality uncertainty would be of less influence.

Aspects like these show that the importance ranking of Table 4-4 could very well differ for other areas. The importance order derived in this study is likely similar for the larger dike rings along the Dutch rivers with comparable hinterland characteristics.

Breach development:

It was shown in this study (for safety standard segment 43-6) that especially the error in the originally assumed breach development curve was of great influence on the safety standards, while the 50% confidence interval around the reference curve was rather small. Breach development uncertainty is in principle relevant for all dikes, regardless whether the flood hazard comes from sea or river floods. As becomes clear from Figure 4-5, the uncertainty in dike composition influences the breach growth uncertainty strongest in the first hours after breach initiation. Therefore, also for normally shorter storm-induced floods breach development uncertainty is important.

The conservative breach development scenario found to be of such significant influence in this study, is currently used for all dike rings situated in the province of Gelderland. The flood simulation model and accompanying breach development curve have been used for all flood scenarios in this province. In other provinces, other models were used (Rijkswaterstaat, 2019) and breach development may have been approached in a different way. Therefore, the assumed breach growth scenario might be of smaller influence for different dike rings. In general, the breach development uncertainty based on the Verheij-Van der Knaap equation is largest in case an area is characterised by both sandy and clayey dike compositions. For predominantly clayey dike ring segments, breach development uncertainty is rather small.

The influence of different breach development curves on the LIR flood safety standards is strongly related to the presence of increased surface elevation lines, the assumed representative breach location and the resulting normative neighbourhood. In case normative neighbourhoods are located closer to the breach location and especially when the neighbourhood is surrounded by lines of increased surface elevation, breach development is a more important source of uncertainty. Flood rise rates are in those situations strongest influenced by the breach development, hence the LIR standards as well.

An additional important prerequisite is that the neighbourhood polygon is sufficiently small to not include areas with lower mortality values as well, as in the current LIR standard calculation method, the standards are derived based on the median mortality value in the normative neighbourhood.
Lastly, breach development was shown to be of small influence on the SCBA standards for safety standard segment 43-6, but for other areas the influence will be stronger due to the absence of the spill flow works at Dalem. In the current safety standard calculation approach, the Dalem spill flow works assure that maximum inundation depths remain rather constant regardless of the breach inflow.

Evacuation:
The influence of evacuation uncertainty on the LIR standards was found to depend strongly on the location of the normative neighbourhood. It became clear that for locations situated far from the breach locations, the difference between the verification flood safety standards and the reference standards is largest. The areawide equally assumed evacuation percentage underestimates the available time for evacuation, especially in the areas situated far from the breach location due to the possibility of acute evacuation. Areawide equal evacuation percentages are currently used for all flood prone areas in the Netherlands (Slootjes & van der Most, 2016b).
For areas situated further from the breach location, the uncertainty in evacuation percentage is relatively small (due to the acute evacuation time available) and hence the uncertainty is of little effect on the LIR standards. This effect is especially relevant for the larger dike rings along the rivers, where evacuation percentages can differ significantly due to flood propagation times. In small dike rings the flood arrival time is small, which decreases the importance of acute evacuation, contrary to larger and longer dike rings like dike ring 43 (see Figure 4-8). The evacuation time availability and evacuation percentage relationship (Figure 3-17 & Figure 3-18) do differ significantly over the country depending on the outer water body type (North sea, Rhine, Meuse etc.) (Kolen 2013; Maaskant et al. 2009b). Therefore, the defined general relations between evacuation uncertainty relevance, location of the normative neighbourhood and size of the dike ring apply mainly for the dike rings along the upper Rhine delta, where the time vs. evacuation percentage relation is relatively steep. In areas where this relation is less steep, the evacuation uncertainty will be more prominent as well in areas located further from the breach location.

Mortality:
This study showed that mortality uncertainty influence on the LIR standards strongly depends on whether the flood rise rates in the normative neighbourhood are sufficiently high. In case rise rates are low (< 0,5m/s), both the collapsibility of buildings and the uncertainty of the interpolation mortality functions are of minor importance. For higher rise rates, mortality uncertainty becomes more prominent and gives significant uncertainty bandwidths around the LIR standards. In the Dutch flat landscape, high rise rates can only be found in presence of lines of increased surface elevation and for strong breach inflows. This study showed that implementation of realistic breach development scenarios strongly reduces the importance of mortality function uncertainty, as the mortality uncertainty influence depends on breach development. Mortality uncertainty is therefore likely of minor importance for many other Dutch dike rings as well.

Damage functions:
The observed influence of damage function uncertainty on the SCBA standards in this study can be more directly translated to other areas in the Netherlands. To calculate SCBA standards, only the total flood damage is considered. Local variations related to the damage function uncertainty or due to variance in land cover are therefore of minor influence for large floods. For larger dike rings and sufficiently large extent of inundated areas, the results of this study would be comparable. Only in case of smaller floods or small dike rings, the variety in land cover can give stronger deviations from the results found in this study.

Investment costs dike improvement:
As explained in this study, flood defence investment cost uncertainty is mostly sensitive to local characteristics and the flood defence design philosophy followed. These can both differ significantly over different areas and are due to the complexity of cost estimations hard to catch in general rules. The influence of the investment cost uncertainty shown in this study will likely be of the same order of magnitude in different areas, but still variable depending on local characteristics.

Lastly, a general characteristic of comparable dike rings and safety standard segments is that LIR standards will always be more uncertain and sensitive to assumptions in the reference scenario than the SCBA standards. LIR standards are derived based on local characteristics which are very sensitive to the underlying assumptions. SCBA standards are based on characteristics for the entire flood zone and are hence less vulnerable to uncertainties or adaptations to the reference assumptions which give locally strong deviations in flood characteristics. The safety standards currently defined for safety standard segments in the Dutch Water Act are therefore more sensitive to assumptions or uncertainty in case the standards originate from the LIR criterion than when they originate from the SCBA criterion.

5.4 Implications for the flood defence improvement task

This study has shown bandwidths for safety standard segment 43-6 of the SCBA flood safety standard and the safety standards required to meet the LIR demand. In light of the dike improvement projects currently in preparation for dike ring 43 and the challenging improvement tasks faced by the responsible waterboard, it is useful to discuss to what extent the results of the uncertainty analysis in this study might influence these dike improvement tasks.

Dike design based on the new flood safety standards is a complicated process, as there are different failure mechanisms which must be dealt with and many different dike designs could be established which all meet the safety standards. For this study, therefore only a first estimate was made of the possible effects of adjusted safety standards on the required crest level for dike sections along safety standard segment 43-6. One case study was evaluated along this segment. Appendix A12 provides the details and calculations for this first estimate.
According to the combination uncertainty analysis results (see Table 4-10), the normative lower limit safety standard class for segment 43-6 is a 1/1000 to 1/3000 class (both classes are present for the derived uncertainty bandwidth). The current normative class given by the Dutch Water Act is a 1/10000 class. The first estimate calculations made in Appendix A12 show that the difference between a 1/10000 and 1/3000 class implies a reduction in required crest level of approximately 0,34m.
This shows that the safety standard uncertainty can potentially have a significant influence on dike design as well, as a reduction in required crest level affects the flood improvement tasks. The current flood probability of safety standard segment 43-6 is estimated at 1/100 annually (Van der Doef et al. 2014), which is much more frequent than the found bandwidth between 1/3439 and 1/6769 annual flood probability for segment 43-6 allows (based on the normative SCBA criterion). With the insights from this study, the magnitude of the necessary flood defence improvement task could therefore be reduced. The results of this study thus show that both the improvement task and the derived dike designs can be influenced.

6 Conclusions & Recommendations

This chapter presents the answers to the research questions and elaborates on the main research goal. Afterwards, several recommendations based on the study results are provided.

6.1 Conclusions

1) *How well can the current flood safety standards for the primary flood defence system be reproduced by application of the documented calculation process for these standards?*

The verification safety standard calculations in this study showed that the SCBA standards are accurately reproducible, while the LIR standards are not. I therefore concluded that the mortality processing steps in the documentation for the LIR safety standard calculation process are currently not clear enough to reproduce the originally derived LIR standards.

2) *Which uncertainty sources in the safety standard calculation process are of most influence on the derived standards?*

The expert estimations of uncertainty influence on the safety standards for dike ring 43 have shown that uncertainties related to the derivation of flood consequences are generally the most prominent uncertainty sources. Furthermore, it was concluded that in both the process to derive the LIR and SCBA standards there are prominent uncertainty sources. The 5 sources of uncertainty which should be considered as most important are breach development, evacuation of people, mortality functions, damage functions and the investment costs for flood defence improvements. Experts argued that both the magnitude of uncertainty and the sensitivity of the safety standards to these sources is significant, hence the influence on the safety standards as well. The obtained uncertainty source ranking is rather gradual. Apart from the identified five most important uncertainty sources, the uncertainty source ranking showed that there are additional relevant uncertainty sources in the safety standard calculation process.

3) *How can the uncertainty of the main sources be quantified and propagated through the calculation process for the safety standards?*

This study used a scenario analysis approach for the uncertainty analysis of the safety standards. Scenarios corresponding to the 50% confidence interval were defined for each of the 5 identified most important uncertainty sources. The reference scenarios used in this study for the uncertainty quantification, were based on adaptations from the verification scenarios for 4 of the 5 uncertainty sources. Those verification scenarios were applied earlier for the safety standards currently defined in the Dutch Water Act. The established reference scenarios correct for earlier proven errors and non-location specific assumptions in the current safety standards. As a result, safety standards derived in this study were based on the best possible estimations of the actual flood risks for case study dike ring 43.

The uncertainty quantification showed that the breach development uncertainty is relatively small, but the established reference scenario does imply a strongly reduced breach size compared to the verification breach growth scenario. The uncertainty of the mortality functions and evacuation of people is spatially variable and was therefore quantified through variations in functions describing the local mortality and evacuation percentages. Especially for the evacuation uncertainty, it was shown that the obtained reference scenario differs strongly from the evacuation scenario in the verification safety standard calculations. For the damage functions, the uncertainty is inundation depth dependent. This uncertainty source was therefore quantified via a beta probability distribution to derive alternative functions corresponding to the 50% confidence interval. Flood defence investment costs were quantified via recent cost estimates for dike improvement projects in dike ring 43.

4) *In what way do individual uncertainty sources influence the LIR and SCBA standards and which spatial characteristics affect the influence?*

The 5 studied uncertainty sources each have a clear influence on the flood safety standards for dike ring 43, but the magnitude of influence is (spatially) variable. It was shown for safety standard segment 43-6, that the slower reference breach development relative to the verification scenario gives less strict SCBA standards and much less strict LIR standards. I therefore concluded that a location specific breach development approach results in safety standards which more closely match the flood risks. The breach development uncertainty surrounding the reference scenario marginally affects the safety standards for the case study. This was explained by the presence of the Dalem spill flow works for the SCBA standards and for the LIR standards by the location of the LIR normative neighbourhood relative to breach location and lines of increased surface elevation.

The influence of the mortality and evacuation uncertainty on the LIR standards deviates over different safety standard segments and is mainly dependent on flood characteristics in the normative neighbourhood. Mortality uncertainty is of stronger influence for higher flood rise rates and evacuation uncertainty is of stronger influence for normative neighbourhoods which are situated closer to the breach location, due to the absence of acute evacuation time.

The influence of damage functions and investment costs is relatively small, mainly because the investment costs and flood damage are considered in the safety standard calculations as total over the entire safety standard segment. Therefore, locally stronger variation of the uncertainty influence does not directly affect the safety standards. Variation of the uncertainty influence over different safety standard segments is fully explained by the land use of the hinterland and by characteristics of the flood defences.

5) *How uncertain are the flood safety standards due to the combined most important uncertainty sources?*

Combination of the 5 uncertainty sources gave plausible intervals of the flood safety standards for segment 43-6. Standards deviate between annual flood probabilities of 1/1190 and 1/2080 for the LIR alert standards and between 1/3439 and 1/6769 for the SCBA alert standards. In comparison to the verification safety standards (respectively 1/18798 and 1/6154 for the LIR and SCBA standards), it was shown that especially the current LIR standards strongly deviate from the standards found in this study. I concluded that this is the result of non-location specific and sometimes obsolete assumptions in the safety standard calculation process. The insights from the uncertainty analysis show that the current flood safety standards in the Dutch Water Act are relatively strict compared to the found reference standards in this study.

The combination uncertainty analysis also revealed that the influence of evacuation and especially mortality uncertainty is strongly related to the breach development scenario. As a result, the contribution of mortality uncertainty is small for the overall LIR standard uncertainty and the overall LIR standard spread is therefore smaller than would be expected based on the individual uncertainty analysis. It was concluded that the uncertainty of the reference LIR standards primarily originates from uncertainty in the evacuation scenarios. The uncertainty sources relevant for the SCBA standards act mostly independent from each other and the spread in SCBA standards is larger than the spread in LIR standards.

The main research objective of this study was expressed as following:

To quantify the uncertainty of the Dutch flood safety standards for the primary flood defences of case study dike ring 43, by performing a scenario analysis.

This study showed that there is a considerable uncertainty bandwidth around both the LIR and SCBA reference standards derived in this study (respectively a factor 1.7 and a factor 2 of the reference standard). For the LIR standards most of the found uncertainty is explained by uncertain evacuation percentages. For the SCBA standards, the uncertainty sources were all shown to affect the safety standards, of which the damage function uncertainty is most important.

I concluded that the influence of uncertainty sources on the LIR standards strongly depends on hinterland characteristics. The presence of lines of increased surface elevation in the hinterland and the location, size and flood rise rates of the LIR normative neighbourhood were shown to affect the influence of the breach development, evacuation and mortality uncertainty. Uncertainty sources relevant for the SCBA standards are less dependent on such specific characteristics of the hinterland.
LIR standards are derived based on the flood characteristics in a small part of the inundation zone (one neighbourhood) where the most extreme conditions are found. The uncertainty sources affect these areas strongest, hence the LIR standards as well. SCBA standards are derived based on properties of the entire inundation zone, which is why averaging effects moderate the uncertainty influence on these standards, especially in larger dike rings such as dike ring 43. Although the LIR standards are generally more prone to uncertainty of the individual sources, interdependence between the uncertainty sources relevant for the LIR standards was shown to limit the influence of mortality uncertainty. Hence, the overall uncertainty of the LIR and SCBA standards is of the same order of magnitude for case study safety standard segment 43-6.

The above-mentioned case study results and conclusions can be partially translated to different dike rings in the Netherlands. The characteristics of the safety standard calculation process imply that LIR standards will always be more susceptible to uncertainty than SCBA standards. The strong deviations from the verification standards found in this study and the influence of individual uncertainty sources are likely similar for comparable Dutch dike rings. For larger dike rings within the Dutch river system, the same basic assumptions were made and they are recognised by similar hinterland characteristics as dike ring 43. These dike rings are therefore characterised by the same uncertainties. The results of this study can be less directly translated to seaside dike rings, as dike ring characteristics, flood hazards and some components of the safety standard derivation process itself differ.

6.2 Recommendations

This section first provides several recommendations for further research related to the safety standard calculation process and this study. Thereafter, based on the insights from this study, several more practical recommendations for policy adjustments are given which could decrease the uncertainty influence in the current approach to determine the flood safety standards.

Recommendations for further study:
First of all, a general recommendation is to transparently document the choices and assumptions in future flood safety studies. It became clear that the safety standard derivation process behind the standards in the Dutch Water Act could only partially be reproduced in this study. For reproducibility and research purposes, it is important to provide good documentation of all made choices and assumptions.

This research has focussed on a specific case study area and studied the influence of the five uncertainty sources considered most important according to a group of experts. Some notes were made on the generalisation of the results of this study and factors which influence the transferability of the results. Further study should seek for a more generalised approach to find the uncertainty of the flood safety standards in other areas, with different types of outer water, flood defences and hinterland characteristics. This could provide more insight into which characteristics determine the influence of uncertainty (sources). It would be especially interesting to conduct a similar study for a coastal dike ring, for which both the dike ring characteristics and safety standard derivation process differ strongest from dike ring 43.
Furthermore, although it is likely that the uncertainty sources considered in this study explain most of the uncertainty in the safety standards, it remains useful to study the influence of additional uncertainty sources, for which the uncertainty source ranking derived in this study is a good base. When considering additional uncertainty sources, one should also critically review the assumptions made in current safety standard derivation method. This study showed that these assumptions might not always be representative for specific situations.

The uncertainty analysis results in this study have pointed out that the five considered uncertainty sources all influence the safety standards. The results can be used to prioritise research aimed at decreasing the uncertainty of the individual components in the safety standard derivation. This could eventually result in more robust safety standards. Research focus should especially be at the breach development process (which has shown to be a decisive factor in the influence of other uncertainty sources and is in itself uncertain due to the current non-location specific approach) and on evacuation scenarios, as this uncertainty source has a highly variable but significant influence on the LIR standards. Furthermore, it is valuable to study evacuation uncertainty influence more in-depth and consider additional uncertain aspects influencing evacuation percentages, such as the disobedience percentage. These aspects were shown in this study to be of significant influence sometimes as well. Efforts to minimise uncertainty in the mortality functions is less useful, as this study has shown that mortality function uncertainty is for many areas likely of small influence on safety standards, in case the currently conservative breach development is approached more location-specific.

Lastly, on a more conceptual level it is suggested to study what the consequences would be for the safety standards if not the flood probabilities are included in the Dutch water Act, but a risk demand such as the maximum allowed LIR value. This would create more space for the development of alternative solutions for dealing with flood risks rather than dike improvement and implement the multi-layer safety approach also in the derivation of the safety standards. As example, it could be studied whether the establishment of a detailed and optimised evacuation plan could achieve the same maximum allowed LIR value as dike improvement projects. This study showed that the LIR standards are highly sensitive to adjustments in the evacuation percentages and smart evacuation planning could provide a good base to make adjustments to the currently conservatively assumed uniform evacuation percentages. Similarly, it could be investigated to what extent safety standards would be influenced when increased surface elevation lines in the landscape are removed or installed. These elements were shown to indirectly influence the flood safety standards, as they strongly affect the flood characteristics. Dike ring 43 could be a suitable case study area to test the implementation of these conceptual changes in the safety standard derivation approach.

This approach would also make it possible to perform a more direct cost-benefit analysis in the design process of these measures, as designers in the design process will both investigate the effects of measures and the associated costs. In the current approach the cost-benefit analysis is more indirect, as the actual dike improvement costs are never weighted with the benefits of improved flood protection. It could for instance be studied to what extent the design of a dike with a sandy or clayey core would influence the safety standards, given the discussed influence of dike design on breach development and investment costs.

Recommendations for policy:

Multiple consulted experts in this study have argued that the current approach of safety standard derivation is not necessarily aimed at localised optimisation of the flood safety standards but rather aimed at following a consistent approach. Only in case the general approach created obvious errors for specific situations, deviations from the default process were installed. This study has shown that for several uncertain aspects, the current general approach still leaves space for significant deviations from the locally optimal safety standards. A more localised approach in the derivation of flood safety standards is therefore recommended, to assure that the safety standards for safety standard segments match the actual flood risk posed and optimise the spending of flood safety improvement budgets.

One clear example is the currently non-location specific breach development scenario implemented. It was shown that this assumption currently gives an overestimation of flood risks for safety standard segment 43-6. Loads of detailed information about dike composition is available already at water boards and other organisations. It is therefore recommended to use dike composition data to derive more locally valid breach development curves to use as base for safety standard derivation.

Especially in areas where dike managers face difficulties to come up with a new dike design (within budget) to meet the new safety standards, it might be worth it to make an additional safety standard calculation iteration in which a more location specific approach is followed. The first estimate made in this study for dike design implications of the found safety standards showed a potentially significant influence on the improvement task. The influence on dike design should be further investigated with more in-depth calculations.

It is also recommended to abandon the use of Delft-FLS as flood simulation model for flood safety standard derivations in the province of Gelderland. With the currently used Delft-FLS model, locally varying breach development curves are time consuming to implement. Furthermore, lines of increased surface elevation are implemented in this model in a rather simplified way. As these local elevation differences sometimes significantly influence flood characteristics and safety standards, it is worth it to improve flood simulation quality with newer and improved flood simulation models. New flood simulation models (with the new D-hydro simulation package) are under development currently for application in Dutch dike rings.

At several moments during this study, it became clear that in the current safety standard derivation approach, often conservative or more extreme assumptions were used. For instance the currently assumed evacuation percentages represent a badly executed evacuation (Slootjes & Van der Most, 2016b) and the assumed representative breach locations were chosen such that they result in the most extreme flood scenario plausible within a dike ring segment (Rijkswaterstaat Waterdienst, 2008). The reasoning behind the current individual risk and economic risk standards demands for average flood scenarios instead of the more extreme situations. Costs and benefits cannot be equally weighted if the flood consequences represent extreme situations. It is therefore recommended for the next revision of the safety standards to develop and use average scenarios or consider multiple plausible scenarios instead of an extreme scenario to derive the optimal safety standards.

Lastly a recommendation for both researchers and policymakers. It is recommended to critically review and study the implications of the use of the current neighbourhood polygons in the LIR standard derivation. It became clear in this study that the definition of neighbourhood polygons currently strongly affects the LIR standards and the influence of uncertainty sources such as breach development. The currently used polygons were not developed for use in flood safety calculations and the neighbourhoods show great variation in both size and population. The LIR is a location specific characteristic and expresses casualty risks. It should therefore be considered to replace the current neighbourhood polygons with polygons of equal size, equal population or a combination of the two. Additional research should seek for a configuration suitable for flood safety standard derivations.

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Appendices

A1 Set-up expert elicitation

This appendix gives a short stepwise overview of the interview set-up which was followed in this study. The experts were all consulted in a private environment and were all consulted individually.

1) Each expert was first asked to comment on their own background and their professional relation with the new flood safety standards, how experienced they are with the subject matter and if they have specific knowledge about parts within the derivation process.
2) The purpose of the study and the purpose of the interview sessions was introduced, along with a small introduction of the case study dike ring 43. The current safety standards for the 6 safety standard segments in dike ring 43 were discussed and the general safety standard calculation process was introduced with a flow diagram of steps, inputs and outputs.
3) Afterwards, the expert was handed over a list with predefined uncertainty sources, in which the uncertainty sources (see Table 3-2) were chronologically ordered according to the step in which the uncertainty source emerges in the safety standard calculation process.
4) For each uncertainty source on the list, the expert was asked to comment about the expected influence on the eventually resulting flood safety standards for the safety standard segments of dike ring 43. The expert was asked for each uncertainty source to award a relative score of expected influence on the standards based on a 5-point grading system, in which a 1 stands for expected small influence and a score of 5 stands for a large expected influence. Experts were allowed to give a score of 0 if they believed that an uncertainty source would have no influence at all. Furthermore, the experts were asked to incorporate in their judgement both the expected magnitude of uncertainty and the influence of the uncertainty source on the standards. In case an expert considered his own knowledge about a specific uncertainty source insufficient to award a score, no score was given.
5) At the end of the interviews, each expert was asked whether he had additional comments on the calculation process of the safety standards, the followed approaches or possibly missed uncertainty sources on the list.

A2 Expert elicitation results

This appendix contains a summary of the interview sessions held with 6 experts. For each of the experts a table with the discussed uncertainties is shown. This table shows the initially awarded (non-scaled) scores for each uncertainty source. Additionally, a small overview of the remarks is given for the uncertainty sources that were discussed more extensively during the interview. If no remarks are shown in the table, the uncertainty source was discussed either very shortly or no additional remarks were made. In case scores for an uncertainty source lack, the expert argued his knowledge of the specific subject was insufficient to give a meaningful judgement about the expected influence of an uncertainty source.

A2.1 Interviewee 1

Personal relation with the topic of (new) flood safety standards:
The interviewee is an experienced professional within the broad topic of flood safety and dike design. He has contributed amongst others to the book “fundamentals of flood protection”, which is a comprehensive book covering flood safety, dike design practice and characteristics in the Netherlands. He has personally not been involved in the derivation of the current flood safety standards, but in his professional carrier has been involved in many flood safety studies. He has a geotechnical and hydraulic background in dike design and is also a visiting lecturer at Delft University of technology, amongst others for the topic of flood safety standards in the Netherlands.

Flood wave & water level development:

Influence on LIR/ SCBA standard?	**Uncertainty source description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Peak discharge representing TL and TL+1D hydraulic conditions	3	Uncertainty within the extrapolation line which results in the discharges for 1/1250 and 1/12500 annual occurrence probabilities has a two-sided effect, as not only the water levels corresponding to these intervals changes, but also the associated decimal height and therefore the costs involved in further dike improvement, which is also involved in the calculation process for the safety standards.
LIR & SCBA	Hydrograph shape representing TL and TL+1D hydraulic conditions	1	This uncertainty source is expected to be overall in dike ring 43 of minor effect on the derived standards, but for the more upstream located breach scenarios of more importance than at the downstream locations, as the time required to fill the hinterland with water is larger for the more upstream locations.
LIR & SCBA	Downstream stage/discharge relation boundary conditions	1	

Flood propagation & Flood characteristics hinterland:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Breach locations for representative flood scenarios		
LIR & SCBA	Moment of breaching	2.5	The interviewee expects that this aspect is relatively important, as the breach inflow discharges and therefore the inundation depths and rise rates are influenced by the moment of breaching. Furthermore, the breach development is also influenced by the moment of breaching.
LIR & SCBA	Breach development width, depth & development time	3	Breach development is uncertain both due to “natural” growth uncertainty, as well as due to possible human (emergency) interventions in case of breached dikes. However, as it is hard to “prove” that human interventions in these extremely rare events are successful, the influence on the flood safety standards is likely not as large for the uncertainty due to human interventions in breach development
LIR & SCBA	Elevation data	0	Likely very small uncertainty in elevation data, and therefore no influence on the safety standards.
LIR & SCBA	Land use data used for roughness estimations	0	The interviewee expects that roughness, grid size, timesteps etc. are all of minor influence on flood simulations like here. These aspects are likely of more influence on for example tsunami simulations, with much faster flow velocities.
LIR & SCBA	Roughness values per land use class	0	
LIR & SCBA	Grid size Delft-FLS	0	
LIR & SCBA	Timesteps Delft-FLS	0	
LIR & SCBA	Correctness Delft-FLS simulation itself		
LIR & SCBA	Derivation flood rise rate based on incremental files		
LIR & SCBA	Stability increased surface elevation lines	2	The interviewee expects that stable versus non stable increased surface elevation lines can have significant influence on the flood pattern, but the current assumption of stability is likely realistic, as the erosive capacity of the slowly rising and propagating floodwater is low. These elements are often very wide, which improves the stability.

LIR & SCBA	Operation Lingewerken & Spill flow works at Dalem	2	These aspects do likely influence the flood pattern, but are not of major influence on the standards, as most of the damage resulting from inundation will already have occurred by the time the spill flow works at Dalem can be opened.
LIR & SCBA	Influence of the positive system effect		
LIR & SCBA	Influence of the negative system effect		

Flood consequences:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Mortality functions		
LIR & SCBA	Evacuation percentages		The interviewee is confused about the fact that the evacuation percentages are included in the LIR calculations, as the LIR expresses the risk to become a casualty due to inundation at a certain location (it is a location-characteristic). This implies that the presence of people has no influence.
SCBA	Population data	0	
SCBA	Correction factor for population growth 2000-2011		
SCBA	land use and asset data	3	Not sure how land use and asset data is calculated, but suspected high influence on the uncertainty of flood safety standards.
SCBA	Damage functions	3	After showing some of the damage functions used in the current safety standard calculation process, the interviewee mentioned that he questions the correctness of some functions. Furthermore, we discussed a study which compared international damage functions. The interviewed expert argued that this uncertain aspect likely has significant influence on the standards.
SCBA	Maximum damage values	1.5	
SCBA	Correction factor for increased economic value 2000-2011	2	
SCBA	Correction factor for unaccounted damage and risk aversion		As the safety standards are already extremely strict, the influence of risk aversion is small.
SCBA	Monetisation values for casualties and victims	2	The interviewee mentions that the monetisation values used in setting flood safety standards are relatively high, compared to the monetised value we award to someone’s life in healthcare for example.

Derivation flood safety standards:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Ratio reference scenarios and extreme flood scenario		
LIR	Neighbourhood-based mortality aggregation		
SCBA	Economic growth scenario 2050	2	
SCBA	Investment costs dike improvements 1 decimal height		
SCBA	Discount rate		For instance decreasing the discount rate would imply that it becomes more attractive to invest earlier and more money in flood protection measures, which results in an increase of the flood safety standards. The 5.5% rate is determined by the Dutch ministry of finance.
LIR & SCBA	Length of the current safety standard segments		
LIR	Neighbourhood-based LIR redistribution over multiple safety standard segments		

Additional remarks:

An additional remark made by the interviewed expert was that the current safety standard calculation procedure can be characterised by a clear technical engineering component on the one hand, but also by a political/administrative component. The standards followed from a mix of these two aspects. As an example, he discussed the way in which over the past decades the peak discharges corresponding to the normative return periods have changed under political pressure, which made him clearly realise that ultimately the protection standard is “just a number”. Alteration of the standard does not necessarily result in a fundamentally different level of safety. As very strict flood safety standards are set up in the Netherlands, the difference between for instance a 1/1000 or 1/30000 class does not give a fundamentally different dike design. Essentially, safety standards of this order of magnitude imply that we do not allow any flood event in these areas.

A2.2 Interviewee 2

Personal relation with the topic of (new) flood safety standards:

The interviewed expert works at Royal HaskoningDHV. His connection with the flood safety and flood safety standard derivation topic amongst other comes via his experience with the Dutch VNK2 flood safety project to determine flood risks in Dutch dike rings. He was also involved closely in the VNK2 study for dike ring 43 specifically. This study used the same flood simulations as considered in the safety standard derivation. The interviewee was also involved in recent German-Dutch flood safety studies, in which the current safety standard derivation process was applied as well. Lastly, the interviewee is also involved in dike imporvement projects, in which designs for primary flood defences are established to meet the newly derived flood safety standards.

Flood wave & water level development:

Influence on LIR/ SCBA Standard?	**Uncertainty source description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Peak discharge representing TL and TL+1D hydraulic conditions	3	In the discussion of this uncertainty source, the interviewee specifically mentioned that uncertainty caused by the inclusion of possible upstream flooding (based on the current situation in Germany) on the return periods of extreme discharge events along dike ring 43 is expected to be of major influence on the derivation of flood safety standards.
LIR & SCBA	Hydrograph shape representing TL and TL+1D hydraulic conditions	2	
LIR & SCBA	Downstream stage/discharge relation boundary conditions	3	

Flood propagation & Flood characteristics hinterland:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Breach locations for representative flood scenarios	1	The interviewed expert mentioned that the dike ring segments and breach locations have been defined based on the resulting flood pattern, which would be similar regardless of the exact breach location. However, the breach location influences the mortalities and individual risk (as directly at the breach location the hydraulic circumstances are more hazardous). At all locations close to the dike therefore the risk is higher than elsewhere. It would be undesirable to base the safety standards specifically on these properties.
LIR & SCBA	Moment of breaching	2	
LIR & SCBA	Breach development width, depth & development time	2	The standard equations used to determine the breach development do contain uncertainty, but it is not likely influencing the safety standards significantly. The breach development equations represent the reality reasonably well and uncertainty herein likely does not influence the eventual standard significantly.
LIR & SCBA	Elevation data	1	
LIR & SCBA	Land use data used for roughness estimations	1	

LIR & SCBA	Roughness values per land use class	1	
LIR & SCBA	Grid size Delft-FLS	3	Grid sizes specifically affect the LIR standards, as mortalities are calculated based on these 100m x 100m grid cells.
LIR & SCBA	Timesteps Delft-FLS	1	
LIR & SCBA	Correctness Delft-FLS simulation itself	2	“Errors” made with the flood simulations, resulting in non-existing damage or casualties have probably been corrected in the derivation process for flood safety standards. It is hard to say if there would be an effect on the safety standard calculation if these errors are not corrected properly. On the one hand these errors could emerge specifically at locations with large inundation depths, however directly at the breach location similar circumstances can be found, so the influence of these errors elsewhere could still be small.
LIR & SCBA	Derivation flood rise rate based on incremental files	2	
LIR & SCBA	Stability increased surface elevation lines	3	The interviewee mentions an example around the village of Kesteren in dike ring 43 where the stability assumption clearly affects the flood pattern and can thus be of influence on the safety standards derived.
LIR & SCBA	Operation Lingewerken & Spill flow works at Dalem	1	These structures function mainly to decrease the flood protect dike ring 16 from flooding via dike ring 43. It is not expected that these elements have a significant effect on the flood safety standards for dike ring 43, as the significant inundation depths which would be reached before these structures can function will have already resulted in most of the damage and casualties.
LIR & SCBA	Influence of the positive system effect	2	
LIR & SCBA	Influence of the negative system effect	2	

Flood consequences:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Mortality functions	3	Mortality is probably overestimated with the current set of mortality functions, especially in the larger dike rings due to the ignorance of evacuation after a breach has occurred. This aspect would reduce the number of casualties in certain areas.

LIR & SCBA	Evacuation percentages	5	Preventive evacuation percentages are uncertain and currently assumed in a very conservative way, especially considering that high river discharges potentially leading to floods can be predicted in advance, which gives time to evacuate. Furthermore, administrators will order evacuation relatively early, as they will want to be on the safe side of the estimate.
SCBA	Population data	1	
SCBA	Correction factor for population growth 2000-2011	1	
SCBA	land use and asset data	2	Uncertainty in land use and asset data as well as in the maximum damage are of most influence in small dike rings or for small flood events. For large-scale floods, inaccuracies are likely averaged out for larger areas like dike ring 43.
SCBA	Damage functions	3	
SCBA	Maximum damage values	2	For large areas like dike ring 43, this aspect is likely of smaller influence as over or underestimations of the damage are averaged in these large areas. In small areas however this aspect could be of significant influence.
SCBA	Correction factor for increased economic value 2000-2011	2	
SCBA	Correction factor for unaccounted damage and risk aversion	3	The interviewee added that it is hard for him to judge about the correction factors, as he is not acquainted with the exact choices that have been made in the derivation of the correction factors.
SCBA	Monetisation values for casualties and victims	2	

Derivation flood safety standards:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Ratio single breach and extreme flood scenario	2	It is realistically thought that in extreme cases, multiple breaches can occur simultaneously.
LIR	Neighbourhood-based mortality aggregation	3	The neighbourhood polygons have had significant effects on the resulting LIR standards calculated for the safety standard segments of dike ring 48. Choices in the translation to neighbourhood mortality values can be considered as quite arbitrary and influence the derived standards.
SCBA	Economic growth scenario 2050	2	

SCBA	Investment costs dike improvements 1 decimal height	4	In principle, a cost-benefit analysis results in an optimal balance between investments and safety standard. This is however not exactly how the problem was framed, as the translation was made to a flood probability-defined standard. After a certain standard has been established, the task to realize a resilient dike design is a separate process, in which the investment costs are determined separately.
SCBA	Discount rate	2	
LIR & SCBA	Length of the current safety standard segments	3	Adjusting the length of safety standard segments has a 2-sided effect. Longer segments have a less strict safety standard. However, in designing a dike for a long segment, the length effect results in the obligation to dimension the dike profile more robust. Ideally, these two opposing effects should compensate, and the definition of segment lengths should not influence the eventual dimensioning of a dike. The interviewee however doubts whether the two effects both cancel each other out. He expects that the length effect in the dimensioning of a dike is weaker effect than the effect in the derivation of flood safety standards.
LIR	Neighbourhood-based LIR redistribution over multiple safety standard segments	4	This aspect will likely have a significant effect on the safety standards if other LIR aggregation and redistribution strategies are applied.

Additional remarks:

The interviewed expert added that the derivation process for flood safety standards and many of the associated uncertainties are politically influenced. Administrative uncertainties are also relevant to further assess in the safety standard calculation process. The safety standard calculation process is influenced by administrative decision making, and technical uncertainties do not cover the administrative aspect in the safety standard calculation and dimensioning of dikes. The administrative uncertainties, such as the question whether a derived standard is acceptable for governmental bodies and stakeholders, are at least as influential on the eventually derived safety standards as the mainly technical uncertainties discussed in the interview.

The political choice was made to apply a general derivation process for flood safety standards to all flood-prone areas in the Netherlands. The question is whether the general methodology has resulted in optimal standards for the distinctive areas like dike ring 43 or whether overall the methodology results in sub-optimal standards if the costs are considered.

A2.3 Interviewee 3

Personal relation with the subject of (new) flood safety standards:
The interviewed expert has been involved in the establishment of several sub-sections of the safety standard calculation process, in an advisory role for Deltares and the Delta safety program (Dutch: “Deltaprogramma veiligheid”). Furthermore, he was involved in the generation of the specific methodology to derive safety standards for the flood defence structures situated in front of secondary flood defence structures (Dutch: “Voorliggende keringen”).

Flood wave & water level development:

Influence on LIR/ SCBA standard?	**Uncertainty source description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Peak discharge representing TL and TL+1D hydraulic conditions	LIR: 1 SCBA: 2	For the LIR standard, this aspect only influences the consequences due to flooding. For the SCBA standard, this aspect influences both the consequences as well as the costs involved in strengthening operations (which is relevant in the SCBA standard derivation). The exact configuration of the discharge vs. return period graph influences the investment costs involved in additional flood safety. Therefore, the possible influence of uncertainty on the flood safety standards is likely higher for the SCBA standard
LIR & SCBA	Hydrograph shape representing TL and TL+1D hydraulic conditions	1	
LIR & SCBA	Downstream stage/discharge relation boundary conditions	1	The effect of implementing alternative hydraulic models is likely relatively small. The current approach considers a worst case scenario in which the extent of the flooded hinterland is considerable. Errors related to the stage/discharge relations will therefore not quickly influence the flood consequences significantly, hence the influence on the safety standards is likely small.

Flood propagation & Flood characteristics hinterland:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Breach locations for representative flood scenarios	1	The expert argued that the breach location especially influences the derived mortality values due to the extreme flood characteristics around the breach location. The breach location itself within the current approach likely has a small influence. The interviewee also argued that the current approach in which several breach locations are considered to determine flood consequences is rather inconsistent with the rest of the safety standard derivation approach. The length effect is incorporated in the flood probability but with the current approach of individual breach locations not consistently in the flood consequence calculation. According to the interviewee, a correction has been applied to the high mortalities around the breach location, to avoid that local very high mortalities around the breach location dominate the LIR standard.
LIR & SCBA	Moment of breaching	1	In the current derivation approach for flood safety standards, the failure criterion overflow/overtopping is solely considered. The 1/1250 flood wave corresponds with the level at which the overflow/overtopping criterion is compromised for the normative return period set in the old safety standards. In reality, a dike might fail earlier or later as well. To solve this issue, a certain fragility curve for failure could be implemented.
LIR & SCBA	Breach development width, depth & development time	2	If other dike characteristics or breach growth equations are used, this would have a clear influence on the derived flood safety standards.
LIR & SCBA	Elevation data	1	This aspect contains hardly any uncertainty and therefore also likely hardly influences the derived standards. However, if increased surface elevation lines in the landscape or small streams are “missed” in the elevation data implemented in the flood simulation, this will have a significant influence on the flood characteristics encountered during a flood event.
LIR & SCBA	Land use data used for roughness estimations	1	The influence of recent developments in land cover which are not present in the used datasets is expected to be small
LIR & SCBA	Roughness values per land use class	1	

LIR & SCBA	Grid size Delft-FLS	1	The local errors which emerge due to the coarse grid sizes do likely not significantly influence the resulting safety standards, as a result of the averaging effect in these large areas. At some locations, the coarse grid cells will result in overestimations of flood consequences, while in other locations consequences will be underestimated. In the end, these effects will probably hardly influence the flood safety standards.
LIR & SCBA	Timesteps Delft-FLS	1	
LIR & SCBA	Correctness Delft-FLS simulation itself	1	
LIR & SCBA	Derivation flood rise rate based on incremental files	1	
LIR & SCBA	Stability increased surface elevation lines	1	This uncertainty source especially influences the single breach scenarios in the derivation of flood safety standards. The difference between fully stable or unstable elevated elements could imply the difference between significant damage and no damage at all for single breach scenarios. As the extreme breach scenario is also incorporated in the derivation of the flood safety standards (with more than one breach location), the effect of uncertainty due to stable or instable elevated elements in single breach scenarios will likely be small. At locations where the failure of secondary flood defences can have significant influence for the flood consequences, conditional failure probabilities are incorporated already.
LIR & SCBA	Operation Lingewerken & Spill flow works at Dalem	1.5	
LIR & SCBA	Influence of the positive system effect	2	This is an aspect which has likely a significant influence. Upstream flooding (in Germany for example) influences the flood probabilities downstream, and in the current approach results in an overestimation of flood probabilities downstream. However, it would be hard to incorporate upstream flooding in a consistent way, as upstream flooding can occur at different inundation depths for different failure mechanisms. Furthermore, if the positive system effect is incorporated, this does not imply less strict standards should be set in dike ring 43, as the required investments to decrease the flood probability will become smaller, which makes it economically more attractive to set a stricter safety standard.

			If the river system would be considered as a whole in setting up the safety standards, the effects on the safety standards and overall costs could be significant.
LIR & SCBA	Influence of the negative system effect		The negative system effect is incorporated in the safety standard calculation methodology for dike ring 43.

Flood consequences:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Mortality functions	1.5	The mortality functions are a significant source of uncertainty for the derived flood safety standards if the plausible difference to the reality is concerned. However, the derivation of the used mortality functions was done in a correct way considering the data that was available, so on short term it is likely not plausible to decrease the uncertainty involved in the mortality functions.
LIR & SCBA	Evacuation percentages	1.5	The effect of additionally incorporating escape behaviour after a dike has breached, is likely of influence on the presence of people in this dike ring. The expected effects on the safety standards is probably limited.
SCBA	Population data	1	
SCBA	Correction factor for population growth 2000-2011	1	
SCBA	land use and asset data	1	
SCBA	Damage functions	2	Uncertainty in the flood damage is likely largely resulting from the uncertainty of indirect damage categories. What is the impact on the Dutch economy of flood events? To what extent will direct flood damage result in positive or negative economic effects outside of the flooded area? Will economic activity move abroad?
SCBA	Maximum damage values	1	
SCBA	Correction factor for increased economic value 2000-2011	1	
SCBA	Correction factor for unaccounted damage and risk aversion	2	
SCBA	Monetisation values for casualties and victims	1	

Derivation flood safety standards:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Ratio reference scenarios and extreme flood scenario	1	
LIR	Neighbourhood-based mortality aggregation		Neighbourhood based mortality aggregation was applied to decrease the effect of small-scale errors and oddities. Furthermore, without this step and to be able to base the safety standards on smaller spatial units, the requirements for the level of detail, data requirements and degree of certainty of the calculations would become enormous. These requirements cannot be met currently.
SCBA	Economic growth scenario 2050	1	
SCBA	Investment costs dike improvements 1 decimal height	1.5	The interviewee mentioned that calculations made with KOSWAT for flood defence strengthening projects often appear to be very inaccurate. KOSWAT has been used in the derivation process for the flood safety standards as well.
SCBA	Discount rate	1.5	
LIR & SCBA	Length of the current safety standard segments	1	The length of the safety standard segments should not be of influence, but in the current approach it does due to simplifications and assumptions in the approach.
LIR	Neighbourhood-based LIR redistribution over multiple safety standard segments	2	Relevant for this aspect, the interviewee also added that currently, after the LIR standards have been determined based on the equal scaling procedure, there are also safety standard segments for which the SCBA standard later appears to be stricter than the requirement derived from the individual risk analysis. This means that the individual risk therefore decreases again with the stricter SCBA standard. No correction has taken place for this effect.

Additional remarks:
An additional remark the expert made clear is that there are a number of inconsistencies in the derivation methodology for the new flood safety standards as a whole. For example, it is currently assumed that the strength and flood probability of flood defences are correlated over the length, while for the flood consequence side, flood scenarios with breaches at specific locations are incorporated according to the ratios between the lengths of the dike ring segments. To generate a consistent approach, it could be argued to incorporate multiple breach scenarios with individual probabilities of occurrence (as the dikes are in reality not equally strong everywhere), which together sum up to 1, or alternatively assume equal strength over the entire safety standard segment and assume that failure occurs everywhere simultaneously. The effects of solving this methodological inconsistency on the derived safety standards could be very large according to the expert.

Another point the expert stressed to, was the relation between the goal of the safety standard calculation methodology and the characteristics of the methodology, with the involved models, assumptions and choices. The context in which people want to take decisions influences the characteristics of the methodology to base the decisions on. For instance within the desired context, the ignorance of the full system effect in the derivation of the flood safety standards can therefore be considered as a deliberate choice rather than an error or uncertainty. Incorporation of the system effect would significantly complicate the derivation process and would as well influence the derivation of the hydraulic boundary conditions. Although not accurately representing reality, neglecting the full system effect is therefore a deliberate choice. Furthermore, the expert also stressed to the fact that the Dutch approach to derive flood safety standards is very rule-based. There is a desire to base the safety standards on clear sets of models and methods. If the models and methods however give odd results or have undesired characteristics, it was tried to correct the model behaviour, by incorporating additional smaller scale processes within the model simplifications, to derive acceptable outputs. This behaviour in the calculation methodology for the flood safety standards is also a result of the broader Dutch negotiation and coalition culture and the desire to arrive at safety standards which are acceptable to all stakeholders and policy makers.

A2.4 Interviewee 4

Personal relation with the subject of (new) flood safety standards:
Interviewee 3 has been involved in the development of the new safety standard calculation process via his position at Rijkswaterstaat. Rijkswaterstaat was via the Dutch ministry of infrastructure and the environment the formal client for the generation of the new methodology to derive flood safety standards, for which private parties like Deltares and HKV were involved to cooperate. The expert's own background lies mainly in the topics of external safety and personal risk assessment. Within the generation of the new safety standard calculation process, he was therefore mostly involved in the individual flood risk assessment, group risk assessment and the derivation of the associated LIR standards and group risk standards.

Flood wave & water level development:

Influence on LIR/ SCBA standard?	**Uncertainty source description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Peak discharge representing TL and TL+1D hydraulic conditions	2	The peak discharge uncertainty is likely not very influential for the flood safety standards. The difference in flood consequences between the scenarios with 1/1250 and 1/12500 peak discharges lies in the order of magnitude of 35%. Given this order of magnitude, uncertainty of the exact peak discharges corresponding to these annual occurrence probabilities will likely not have a large influence on the safety standards.
LIR & SCBA	Hydrograph shape representing TL and TL+1D hydraulic conditions	2	Uncertainty in breach inflow volumes, caused for example by the uncertainty in hydrograph shape do not significantly influence the consequences and hence not significantly influence the standards either.
LIR & SCBA	Downstream stage/discharge relation boundary conditions	1	

Flood propagation & Flood characteristics hinterland:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Breach locations for representative flood scenarios	0	According to the interviewee, the breach location within a dike ring segment does not influence the flood safety standards, as the dike ring segments have been defined such that the resulting flood pattern does not vary for different breach locations. During the conversation about this uncertainty source, we also discussed the possible effect that a different breach location could lead to increased numbers of casualties, as the breach zone with high flow velocities is characterised by higher mortalities. This effect is by the interviewee however believed to be very small, as the breach zone with high mortalities is often very small.
LIR & SCBA	Moment of breaching	2	The interviewed expert mentioned the fact that breaches can occur due to different failure mechanisms, with varying likely breach initiation moments. Piping is for dike ring 43 often an important failure mechanism, a mechanism which takes time to develop and can result in breaching after peak discharges have passed. This can influence the breach inflow volumes.
LIR & SCBA	Breach development width, depth & development time	3	This uncertainty source is according to the interviewee the most important uncertainty source in the derivation of the flood pattern. Breach development highly determines the breach inflow volume and hence the flood pattern and associated consequences. The interviewee also mentioned that currently there are many new developments and research is conducted within the breach development process, which might give different breach development patterns than considered in the current Delft-FLS simulations.
LIR & SCBA	Elevation data	0	
LIR & SCBA	Land use data used for roughness estimations	1	For large dike rings like dike ring 43, these aspects have very small influence on the flood safety standards.
LIR & SCBA	Roughness values per land use class	1	

LIR & SCBA	Grid size Delft-FLS	0	For large dike rings such as dike ring 43, the inaccuracies due to coarse grid sizes are of little influence. Local under- or over estimations of flood characteristics due to the coarse grid will for large dike rings largely average out and hence not influence the standards. For small dike rings like in the province of Limburg, this uncertainty might be more prominent.
LIR & SCBA	Timesteps Delft-FLS	0	For the SCBA standard, timesteps are not of importance as the maximum inundation depths are incorporated in the flood consequence calculations. For the LIR standard, there might be a small influence as the flood rise rates can be influenced by timesteps used in the flood simulations. This effect will likely be very small.
LIR & SCBA	Correctness Delft-FLS simulation itself	0	Errors in flood simulations resulting in wrong mortality values, are filtered out of the derivation process for the flood safety standards, by incorporating median mortality values in neighbourhood polygons instead of values per grid cell, which prevents that small errors directly influence the standards.
LIR & SCBA	Derivation flood rise rate based on incremental files	1	The rise rate is influenced by the configuration of the incremental inundation depth classes. As mortalities are calculated based on a few distinguished rise rate classes, this issue could influence the mortality as well. However, to prevent that the rise rate calculation method significantly influences the mortality values, additional interpolated mortality functions were used, to prevent that the inaccurate rise rates can result in very inaccurate mortality values.
LIR & SCBA	Stability increased surface elevation lines	1	For the LIR standards, the stability of linear elements is not of importance, as independent of the stability, initially water will always pile up behind increased surface elevation lines, hence rise rates will not be influenced. The possible difference in damage caused by lower maximum inundation depths when linear elements fail earlier will also be of minor importance. Inundation depths (and damage) will decrease in front of the increased surface elevation line, but as a result of earlier failure will increase downstream, which results in increased damage downstream.
LIR & SCBA	Operation Lingewerken & Spill flow works at Dalem	2	

LIR & SCBA	Influence of the positive system effect	1	The two upstream breach locations considered for the extreme flood scenario in dike ring 43 correspond to a plausible situation that could occur in reality under extreme circumstances. Therefore, the associated uncertainty and influence on the safety standards is low.
LIR & SCBA	Influence of the negative system effect		

Flood consequences:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Mortality functions	3	The current mortality functions are uncertain for the considered flood scenarios. Evacuation after a breach has occurred upstream (escape behaviour) is incorporated implicitly in the used mortality functions, which are based on the mortality data from the floods the southwest if the Netherlands in 1953. For large dike rings like dike ring 43, explicitly differentiating between locations within a dike ring based on varying arrival times of flood water could result in local differences in casualty numbers. Differences between the 1953 and modern-day stability of buildings and the associated effects on mortality are highly uncertain as well. Modern houses likely remain stable under flood circumstances, in contrast to the buildings in 1953, which is also a subject of study currently. The interviewed expert also mentioned the fact that currently the mortality functions are defined from 0m inundation depth, which implies that casualties can occur already at marginal depths, which in reality is not very likely.
LIR & SCBA	Evacuation percentages	2.5	The considered preventive evacuation scenarios are very conservative. In the VNK2-studies, less conservative evacuation scenarios of 75% were used. This uncertainty source mainly influences the LIR standards, as monetised casualties and victims often make up a relatively small fraction of the total monetised flood damage. If decent evacuation scenarios are developed in the future, even higher evacuation percentages become realistic.
SCBA	Population data	0	

SCBA	Correction factor for population growth 2000-2011	1	Local deviations from the 5% assumed population growth in the Netherlands likely have a small influence on the SCBA standard, as the monetised casualties and victims make up a smaller fraction of the total monetised damage.
SCBA	land use and asset data	1	For extensive floods as is plausible for dike ring 43, the influence of neglected development in land use cover in recent years will hardly influence the safety standards.
SCBA	Damage functions	2	The depth damage functions used in HIS-SSM have been updated recently according to several new insights, especially concerning indirect flood damage effects. Furthermore, Rijkswaterstaat has evaluated the possible consequences of replacing the old with new damage functions in the safety standard calculations. They found that the flood damage on average increases 20% in the Netherlands. Consequentially, approximately 1 out of 6 safety standard segments in the Netherlands would receive a different safety standard in case the new damage functions would be applied.
SCBA	Maximum damage values	1	The maximum damage values have also been updated in the new damage calculation model SSM-2017. The flood safety standards are not very sensitive for this uncertainty source.
SCBA	Correction factor for increased economic value 2000-2011	0	The calculations for the flood safety standards have been executed after 2011, so the correction based on economic growth relies on measured growth, which implies that there is no uncertainty in this parameter.
SCBA	Correction factor for unaccounted damage and risk aversion		
SCBA	Monetisation values for casualties and victims	1.5	On average 30% of the total calculated monetised damage consists of monetised immaterial damage. Therefore, the uncertainty in the monetisation values is not of significant influence on the derived SCBA standards. The interviewee added that within traffic and infrastructure policy planning, the same ministry of infrastructure and the environment uses a different monetisation value (2.2 million euro's) for casualties.

Derivation flood safety standards:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Ratio reference scenarios and extreme flood scenario		The interviewee is not acquainted with the underlying reasoning which resulted in the 60/40 ratio between the single breach and extreme scenarios.
LIR	Neighbourhood-based mortality aggregation		During the conversation, the interviewee agreed that strictly the use of neighbourhood polygons makes the current LIR standard not an individual risk-based standard as the name suggests, but rather a neighbourhood-based risk standard. However, the reasoning behind using neighbourhood polygons is according to the interviewee justified by for instance small-scale errors resulting from the flood simulations, as it prevents that such errors directly influence the flood safety standards. A mortality value per hectare would therefore introduce more uncertainty. As the standard is set based on the neighbourhood with the highest mortality value, the procedure is still robust, although the procedure can result in ignorance of small-scale extreme mortality values.
SCBA	Economic growth scenario 2050	4	The future economic growth is an uncertain parameter and linearly influences the economic damage. It is therefore of considerable influence on the resulting SCBA standard.
SCBA	Investment costs dike improvements 1 decimal height	1.5	Uncertainty in investment costs is an important parameter, as it directly influences the SCBA standard. For dike ring 43, the uncertainty in the investment costs is likely not as significant as in other areas with for example more urbanised dikes.
SCBA	Discount rate	3.5	During the interview, we discussed the presence of a risk component in the discount rate. According to some experts, the risk component in the discount rate is too high to incorporate in calculations for feasibility of investments in flood defences, as the lifespan of these structures is very long.
LIR & SCBA	Length of the current safety standard segments		

LIR	Neighbourhood-based LIR redistribution over multiple safety standard segments	1	This aspect has been incorporated in the derivation of the flood safety standard, but has been a tailor-made process based on common sense and analysis of the economically efficient LIR annotation to different safety standard segments.

Additional remarks:
At several moments during the conversation, the interviewee also clearly stressed to the political/administrative component within the new derivation process for flood safety standards. With Rijkswaterstaat as governmental body, creating support for the derivation process and the derived standards was important. This has resulted for example in slight deviations from the rationally optimal safety standards at some locations, or in alterations of the calculation process itself.
At the end of the interview, the interviewed expert added that additional uncertainty sources which might be of importance in the derivation process for the new flood safety standards are climate change effects and land subsidence in the coming decades. These effects are especially of influence on the dike rings closer to the Dutch coast, but might also influence the safety standards for example for dike ring 43.

A2.5 Interviewee 5

Personal relation with the safety standard derivation subject:
The Interviewee has been involved in the derivation of the new methodology to establish flood safety standards via his position at Deltares. In the role of project manager, he coordinated the various inputs for the cost-benefit analyses and risk analyses in the safety standard derivation process, as well as the definition of the new safety standard segments and safety standard classes. He has also been involved in the documentation of the procedures to calculate the new safety standards.

Flood wave & water level development:

Influence on LIR/ SCBA standard?	**Uncertainty source description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Peak discharge representing TL and TL+1D hydraulic conditions	1.5	The 1/1250 and 1/12500 scenarios were considered to study the consequences of a reference extreme scenario and a slightly more extreme scenario, to approximate the foreseen extent of flood consequences. This method contains some uncertainty, as one tries to approximate flood consequences based on solely two cases. Considering this, more cases would make the result more accurate. Climate change was not considered in detail in the implemented hydrographs. The eventually calculated safety standards are likely relatively insensitive for uncertainty in the used peak discharges.

LIR & SCBA	Hydrograph shape representing TL and TL+1D hydraulic conditions	1.5	Expected to be of small influence on the safety standards. This aspect is of more influence on the LIR standard than on the SCBA standard, as this dike ring eventually fills up with flood water (the rate at which this happens influences especially the individual risk rather than the economic damage)
LIR & SCBA	Downstream stage/discharge relation boundary conditions		

Flood propagation & Flood characteristics hinterland:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Breach locations for representative flood scenarios	2.5	
LIR & SCBA	Moment of breaching	1.5	The moment of breaching might differ among different locations in the Netherlands (for example due to different local dike characteristics). The safety standard calculation process has been defined on a national scale. The choice was made to follow a consistent approach everywhere rather than optimising the likely moment of breaching for different areas. More generally for the entire calculation process for the safety standards, always a consistent approach was chosen unless there were evident reasons to divert from a consistent approach. For the safety standards, the uncertainty in the moment of breaching is expected to be of relatively small influence.
LIR & SCBA	Breach development width, depth & development time		It is hard to estimate to what extent this uncertainty is of influence on the flood safety standards. The interviewee mentioned that the Verheij-Van der Knaap breach growth function was used, in which he believes only clay and sand dikes were distinguished. There are many other configurations possible, which could influence the flood safety standards. This aspect was not discussed extensively during the establishment of the safety standard calculation methodology and again a consistent approach was chosen rather than a locally optimised approach
LIR & SCBA	Elevation data	1	

LIR & SCBA	Land use data used for roughness estimations	1	The roughness mainly influences the propagation rate through the hinterland and will hardly influence the eventual flood pattern.
LIR & SCBA	Roughness values per land use class	1	
LIR & SCBA	Grid size Delft-FLS		For large and relatively flat areas like dike ring 43, the effect of inaccuracies due to the chosen grid size are likely of minor influence on the derived standards. Around the breach location, inaccuracies caused by the coarse grid might be of more influence, especially on the LIR standard (as flood characteristics directly influence the mortality fractions). Due to averaging effects, local inaccuracies due to grid sizes are of small influence on the overall results.
LIR & SCBA	Timesteps Delft-FLS		
LIR & SCBA	Correctness Delft-FLS simulation itself		The flood simulations used for the safety standard calculations have been reused from earlier projects like VNK2 and have not been reassessed in detail.
LIR & SCBA	Derivation flood rise rate based on incremental files	1.5	As dike ring 43 is a large dike ring in which flood water spreads out, rise rates will be slow in general and the associated mortality function for slow rise rates will often be representative. Uncertainty due to the use of aggregated rise rates will therefore likely be of relatively small influence on the standards.
LIR & SCBA	Stability increased surface elevation lines		
LIR & SCBA	Operation Lingewerken & Spill flow works at Dalem		
LIR & SCBA	Influence of the positive system effect		
LIR & SCBA	Influence of the negative system effect		

Flood consequences:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Mortality functions	2.5	The originally developed mortality functions by Bas Jonkman have been used. However, as these functions originally only distinguished between two rise rates classes, the decision was made to add some additional interpolated mortality functions to the original functions, to prevent that slightly different rise rates would result in unrealistically different mortality values. Escape behaviour by residents when areas are already being flooded is incorporated in the mortality functions, based on the mortality data incorporated in the derivation of the mortality functions by Bas Jonkman from historical floods. People will not wait until they slowly drown. Hence, when rise rates are low people have more possibilities to flee than for high rise rates. To what extent the modern-day situation is still represented accurately by those functions is questionable.
LIR & SCBA	Evacuation percentages		The currently used evacuation percentages are conservative. The choice for these conservative percentages is explained by the fact that responsible organisations for preventive evacuation might consider these percentages as an obligatory goal in case of a flood event. Therefore, the used percentage is kept relatively low.
SCBA	Population data		
SCBA	Correction factor for population growth 2000-2011		
SCBA	land use and asset data		
SCBA	Damage functions		
SCBA	Maximum damage values		
SCBA	Correction factor for increased economic value 2000-2011	1	This uncertainty is likely small and of minor influence.
SCBA	Correction factor for unaccounted damage and risk aversion		

SCBA	Monetisation values for casualties and victims	2	Some people argue that a monetisation value of 6,7 million euros for casualties is high, also when this value is compared to for example traffic-related casualty monetisation values. On average, the economic damage appointed to monetised casualties and flood victims is less than 30%, which implies that uncertainty in these monetisation values will not significantly influence the SCBA standard.

Derivation flood safety standards:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Ratio reference scenarios and extreme flood scenario		
LIR	Neighbourhood-based mortality aggregation		
SCBA	Economic growth scenario 2050	2	In some cases, adjusting growth scenarios will result in a different safety standard-class, but overall the influence is expected to be small. There has been a study covering the so-called delta scenarios and the differentiation of expected growth over regions within the Netherlands.
SCBA	Investment costs dike improvements 1 decimal height	3	This is an important uncertainty source. Investment costs have been derived based on the KOSWAT instrument.
SCBA	Discount rate		The expert network for flood safety (ENW) discussed this item and found that the used discount rates are too high for this application. However, as the ministry always uses this percentage, the value had to be used in this application as well.
LIR & SCBA	Length of the current safety standard segments		
LIR	Neighbourhood-based LIR redistribution over multiple safety standard segments	1.5	The interviewee argues that the influence of the method to redistribute the LIR over the safety standard segments is likely of small influence and only in distinct cases of more significant influence. This aspect has been discussed extensively during the establishment of the derivation process for the new flood safety standards.

Additional remarks:
The interviewed expert stressed to the fact that the flood simulations made for the VNK2-project were an important foundation to base the definition of the current safety standard segments on (the division of dike rings in a number of segments). The results from the many individual flood simulations for each dike ring clarify at which locations breaches result in different flood consequences and therefore clarify which areas should be designated as a separate segment in the derivation of standards.

Furthermore, a somewhat arbitrary criterion based on equal length of safety standard segments was used to define the segments, to assure that equal standards will eventually correspond to approximately equal dike dimensions. The chosen configuration of safety standard segments is one of the more important sources of uncertainty in the safety standard calculation process. Other choices could have been made here. The segment configurations have been discussed with water boards as well and were settled at some point when everyone could agree to the configuration.

During the interview, we also discussed the followed approach to base the standards mainly on dike heights and the associated overflow/overtopping failure mechanisms, while in reality other failure mechanisms like piping might be relevant for dike ring 43. The interviewee mentioned that during the period in which the new safety standard calculation methodology was discussed and developed, this aspect was discussed and in a way also incorporated in the estimated costs required to decrease the flood probability with a factor 10. With hindsight, the level of detail in which this aspect was considered might be insufficient. This is also a point of much discussion, as some people argue that flood risks appointed to piping are overestimated, for example due to the existing mitigation options and uncertain actual piping probability, due to the heterogeneity of ground layers for example.

During the interview, the safety standard class definitions according to the 1-3-10 systematics were discussed as well. The interviewee mentioned that there has been discussion about the chosen systematics. The calculated safety standards were grouped into safety standard classes as a robustness measure. The interviewee agreed that the current classification methodology is sometimes quite rough and if for example a calculated safety standard is close to the boundary of a safety standard class, the current methodology essentially adds an uncertainty margin at only one side of the calculated value. During the discussions concerning the new safety standard calculation process, other ideas for safety standard classes were introduced as well, such as a 1-10-100 system.

A2.6 Interviewee 6

Personal relation with the subject of (new) flood safety standards:

The interviewed expert was involved in the generation of the new derivation methodology for flood safety standards. By the time when the decision was made to calculate the SCBA flood safety standards based on the simplified method he became involved in the derivation process. He has made calculations for the new flood safety standards with the HIS-SSM consequence models and the derivation equations afterwards. The expert was not involved in the flood simulations relevant for the derivation of the safety standards but is aware of the used VNK2 flood simulations that were used. The expert’s role in the establishment of the safety standard calculation process was more on the background and he was not directly involved in the expert network for flood safety and the discussions which led to the new derivation process. As modeller, his input was regularly discussed in the expert network. The main expertise of the interviewee is the flood consequence side of the new safety standard calculation process.

Flood wave & water level development:

Influence on LIR/ SCBA standard?	**Uncertainty source description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Peak discharge representing TL and TL+1D hydraulic conditions	3	There is some uncertainty associated with the statistical data used in the derivation of the peak discharges. The interviewee also mentioned that the use of 1/1250 and 1/12500 flood scenarios might not be representative, when much stricter protection standards are derived afterwards.

LIR & SCBA	Hydrograph shape representing TL and TL+1D hydraulic conditions	4	New insights in hydrograph shapes (based on the GRADE project) result in narrower hydrographs for the Rhine and are likely of significant influence on the derived standards.
LIR & SCBA	Downstream stage/discharge relation boundary conditions	3	

Flood propagation & Flood characteristics hinterland:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Breach locations for representative flood scenarios	2	Uncertainty associated with breach locations is of more importance for dike rings with many small compartment dikes, like in Zealand, where deviating breach locations within a dike ring segment can result in different flood patterns. For dike ring 43, the associated uncertainty is likely of less influence. The people who established the breach locations in light of the VNK2 flood safety program have carefully made their decisions. Hence, the influence of this aspect is likely small.
LIR & SCBA	Moment of breaching	4	
LIR & SCBA	Breach development width, depth & development time	4	Breach development is highly uncertain and especially of influence on the LIR standard. For slower breach development, less water will flow in and influence the rise rates.
LIR & SCBA	Elevation data	2	
LIR & SCBA	Land use data used for roughness estimations	1	This aspect mainly influences the propagation velocity and therefore as well the rise rates, but is likely not of significant influence on the flood safety standards.
LIR & SCBA	Roughness values per land use class	2	This aspect is likely of small influence on the flood safety standards. Roughness values are highly uncertain and influence the rise rates and flow velocities, but variation likely does not significantly influence the flood pattern and derived standard.
LIR & SCBA	Grid size Delft-FLS	2	Grid sizes are for the large dike rings like dike ring 43 not of significant influence, as the under or overestimations of flood consequences are relatively small compared to the total flood consequences for large dike rings.
LIR & SCBA	Timesteps Delft-FLS	2	

LIR & SCBA	Correctness Delft-FLS simulation itself	1	Small scale errors like due to wrong definitions of borders between areas inside or outside a dike ring have a likely small influence on the SCBA standard, as the under or overestimations of flood consequences are small relative to the total consequences. For the LIR standard, these errors will not have influence either, as the neighbourhood median is used in the safety standard calculation, which cancels out these errors.
LIR & SCBA	Derivation flood rise rate based on incremental files	4	The derivation of flood rise rates based on incremental inundation depths is directly related to the mortality functions. The mortality functions consider the rise rate over the first 1.5m inundation depth, so the rise rate is also calculated over this first 1.5m. The associated uncertainty in this calculation consists of two components: firstly, the exact configuration of the inundation depth classes, have a limited influence on the derived safety standards, but secondly the procedure to calculate the rise rate is of significant influence on the standards. A different definition of the rise rate (not over the first 1.5m) could influence the mortality values and therefore the safety standards significantly.
LIR & SCBA	Stability increased surface elevation lines	2	Uncertainty within this aspect lies both in the correctness of the schematisation of the elements (like proper inclusion of tunnels etc.) and in the stability of the elements. However, for dike ring 43 this aspect is not very important, as the spatial flood extent is hardly dependent on these elements. They might influence the rise rates (and therefore the LIR standard), however the influence for dike ring 43 is likely small.
LIR & SCBA	Operation Lingewerken & Spill flow works at Dalem	4	The functioning of these elements influences the inundation depths in dike ring 43. This could influence both the SCBA standard as well as the LIR standard. As rise rates are calculated over the first 1.5m inundation depth, functioning or non-functioning of these emergency measures could significantly influence the LIR standards in some cases. Altered inundation depths can also influence the SCBA standards via the damage functions, but this effect is likely smaller according to the expert.
LIR & SCBA	Influence of the positive system effect	2	
LIR & SCBA	Influence of the negative system effect	3	

Flood consequences:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Mortality functions	5	The mortality functions are highly uncertain and are of influence on the derived standards. The conditions for which the mortality functions were defined do not represent modern-day conditions, as for example warning possibilities are improved and the stability of buildings has significantly improved and will likely not collapse (which is how many people lost their lives in the floods from which the mortality data was used to derive the mortality functions. Furthermore, especially for dike ring 43, the issue of flood arrival time and influence on the mortality is a major source of uncertainty. As proper data is not available, these functions are not updated and corrected for these many of these aspects. Furthermore the mortality is a highly non-linear concept which makes it hard to give accurate estimations.
LIR & SCBA	Evacuation percentages	4	The currently used evacuation scenarios are likely too conservative. The reason for the conservative estimates lies in the influence of parties which would be responsible for evacuation in case of a foreseen flood events. The expert argued that the perception of the evacuation percentages in the safety standard calculation process by some parties has been a factor in the current low foreseen percentages.
SCBA	Population data	1	
SCBA	Correction factor for population growth 2000-2011	1	The correction factor for increased population data introduces errors on smaller scale, but for large dike rings like dike ring 43, the under and overestimated population numbers average out largely and do not significantly influence the standards.
SCBA	land use and asset data	1	

SCBA	Damage functions	4	The conditions and data for which the current damage functions have been defined are according to the interviewed expert likely no longer representative and the shape could be updated. Implicitly, the current shape of some damage functions represents a probability of collapse and poorly represents the modern-day damage which flood water would cause for lower inundation depths. However as recent data availability is poor, the defined functions are not updated.
SCBA	Maximum damage values	2	Interesting issue mentioned by the interviewee is how to define the maximum damage, as market value or reconstruction value, considering the difference in value of similar property in different areas of the country. The newly developed flood consequence model from 2017 has solved this issue.
SCBA	Correction factor for increased economic value 2000-2011	3	This correction factor consists of both the inflation and economic growth. The inflation rates contain no uncertainty, but the economic growth does, as it is unknown whether economic growth over this period can be appointed fully to damageable property or not.
SCBA	Correction factor for unaccounted damage and risk aversion	4	The correction value for unaccounted economic effects of flood events is highly uncertain and highly non-linear, but also very difficult to determine with more certainty.
SCBA	Monetisation values for casualties and victims	2	On average only a few percent of the total damage as used in the SCBA standard calculation results from casualties, so uncertainty in the monetisation value for casualties has a minor influence.

Derivation flood safety standards:

Influence on LIR/ SCBA standard?	**Uncertainty description**	**Expected influence:** Scale of 1 (small) to 5 (large)	**Remarks:**
LIR & SCBA	Ratio reference scenarios and extreme flood scenario	3	The assumptions based upon which the ratio between reference and extreme flood scenario has been defined are uncertain and could influence the ratio between the flood scenarios. In other countries, the followed assumptions differ and this can have significant influence on the derived safety standards.

LIR	Neighbourhood-based mortality aggregation	4	A side effect which might introduce uncertainty in the LIR standard may be the procedure to only incorporate the flooded grid cells to determine the median mortality value for a neighbourhood. If very few cells within a neighbourhood are flooded, this might result in barely flooded neighbourhoods to become normative due to the currently followed procedure.
SCBA	Economic growth scenario 2050	3	The economic growth scenario has recently been set at 1,5% annually instead of 1,9%.
SCBA	Investment costs dike improvements 1 decimal height	4	This uncertainty source is one of the most prominent uncertainty sources and directly influences the SCBA standard. The degree of uncertainty is however hard to determine.
SCBA	Discount rate	3	The discount rate has been set at 4,5% recently. The discount rate and economic growth scenario are positively correlated but have an opposite effect on the SCBA standard. Stronger economic growth results in stricter standards, while increased discount rates result in less strict standards.
LIR & SCBA	Length of the current safety standard segments	3	
LIR	Neighbourhood-based LIR redistribution over multiple safety standard segments	5	The uncertainty of the safety standards associated with the method of redistributing the LIR over multiple safety standard segments is of significant influence. Multiple legally valid safety standard configurations are possible, but the question could be asked to what extent different configurations of LIR redistribution are ethically defendable. The average calculated safety standard of all segments within a certain safety standard class is approximately equal to the class value itself. If for example cost optimisation is applied or when the safety standards are set such that most segments end up in a different safety standard class, this characteristic will disappear, and one can ask whether this is “fair” or not.

Additional remarks:

Additionally, the expert also mentioned a possible inconsistency in the safety standard calculation methodology. The safety standards are derived based on water levels and associated flood scenarios, while the safety standards are defined as a flood probability (which is not solely depending on water levels). The current reasoning is that the failure probability associated with dike characteristics is not incorporated, as the dike will be designed afterwards.

The expert also mentioned that for the LIR standard derivations, the normative neighbourhood based on the flood characteristics were often critically reviewed. If high mortalities in a neighbourhood could not be “logically” explained, sometimes undocumented deviations from the standard derivation of the LIR standard were made.

Additionally, the expert mentioned that the assumptions based upon which it was decided that the simplified method to calculate the flood safety standards can be used, can contain uncertainty as well. Furthermore, the applicability and correctness of the simplified method differs among safety standard segments, which for some segments results in uncertainty of the safety standards as well.

During the interview we also discussed a more ethical question relevant in the flood safety standard calculation methodology. The mortality for flood simulations may be dominated by especially elderly people, as the physical condition differs among people. The question could be asked whether as a society we are willing to invest 6.7 million euros for each individual or that we could invest less for elderly people.

Lastly, the expert stressed to the political influence on the derivation process of the new flood safety standards. During the establishment of the new flood safety standards there has been coordination with governmental organisations like water boards regularly. In some cases, coordination with these organisations led to adjustments of the flood safety standard calculation process when convincing reasons made it plausible and justifiable to make adjustments to the process.

A3 Dike composition data safety standard segment 43-6

A3.1 Dike composition data dike ring segment Haaften

Below several examples are shown of the dike composition data available for dike ring segment Haaften. These cross sections originate from the last major dike reconstruction works in the 1990’s (Waterschap Rivierenland, 2014).

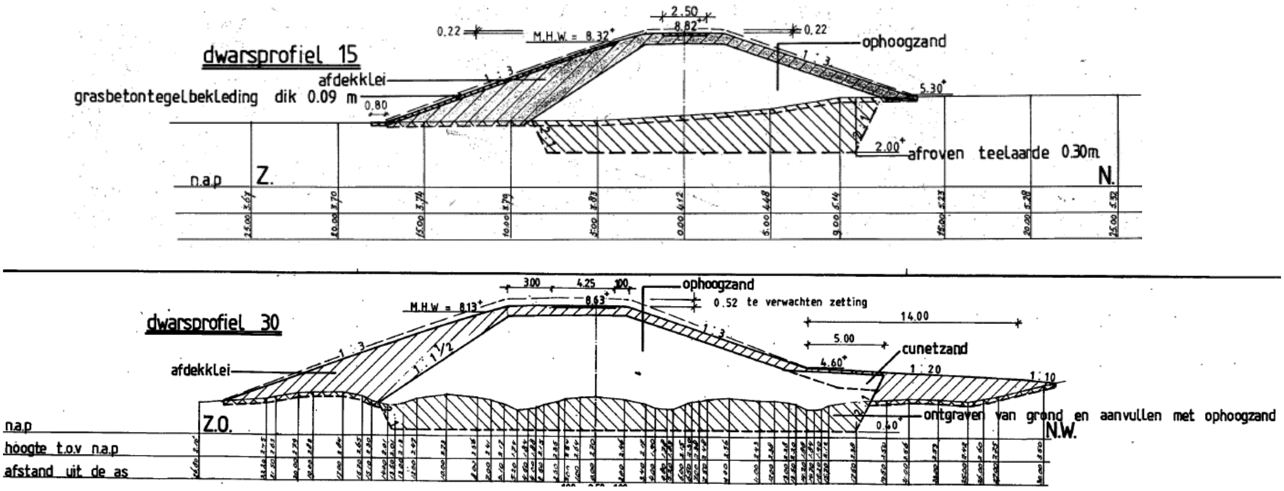

Figure A3-1: Examples of cross sections consisting of sandy material mostly

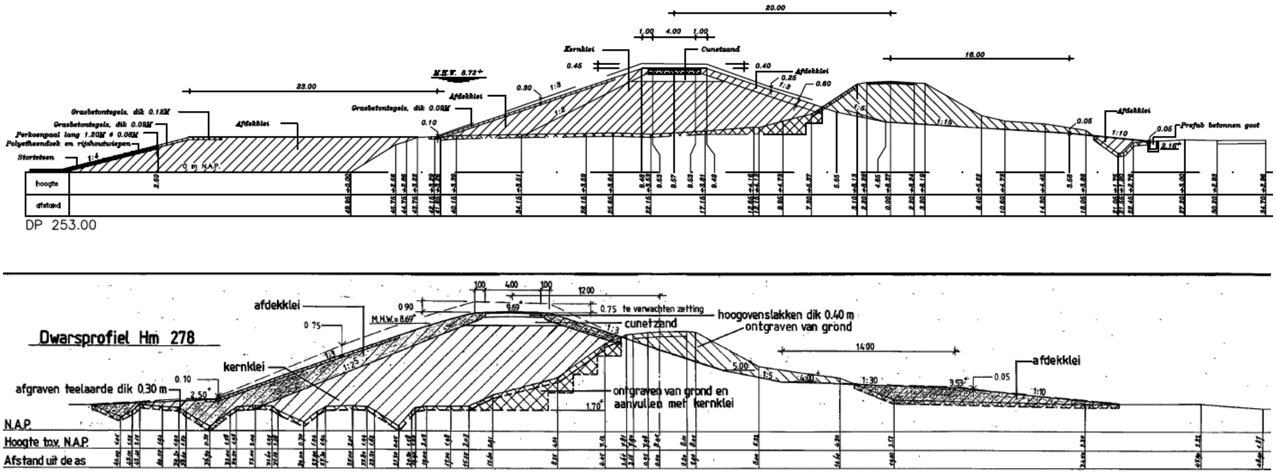

Figure A3-2: Examples of cross sections consisting of clayey material mostly

A3.2 Dike composition data dike ring segment Tiel-West

This section shows the dike composition data used in this study to quantify the uncertainty of breach development in dike ring segment Tiel-West. The data originates from the Dutch Dinoloket soil database (TNO, 2019). The data originates from core drill samples of the inner dike material. The data distinguishes between sandy and clayey material.

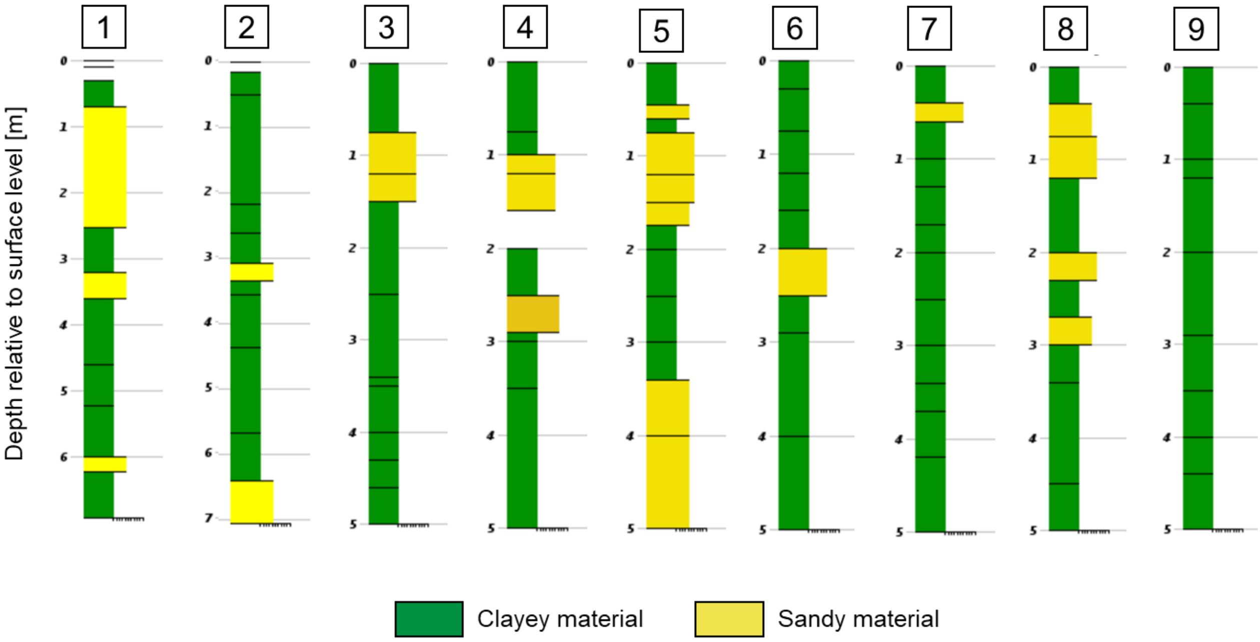

Figure A3-3: Core drill data for dike ring section Tiel-West (TNO, 2019)

Table A3-2: Coordinates and surface level at the location of the core drill samples

Sample number:	Coordinates of sample [RD]	Surface level elevation, relative to sealevel [m+NAP]
1	146400,426850	8.78
2	148500,426675	9.24
3	150764,426542	10.63
4	151112,426387	10.65
5	154346,427019	11.08
6	156231,428801	11.30
7	156611,429599	11.41
8	157127,431600	11.79
9	157560,431957	11.72

A4 Damage functions verification scenario

This appendix shows the 11 unique damage functions used to calculate the economic damage for the verification calculations in this study. The functions are described in Kok et al. (2005)

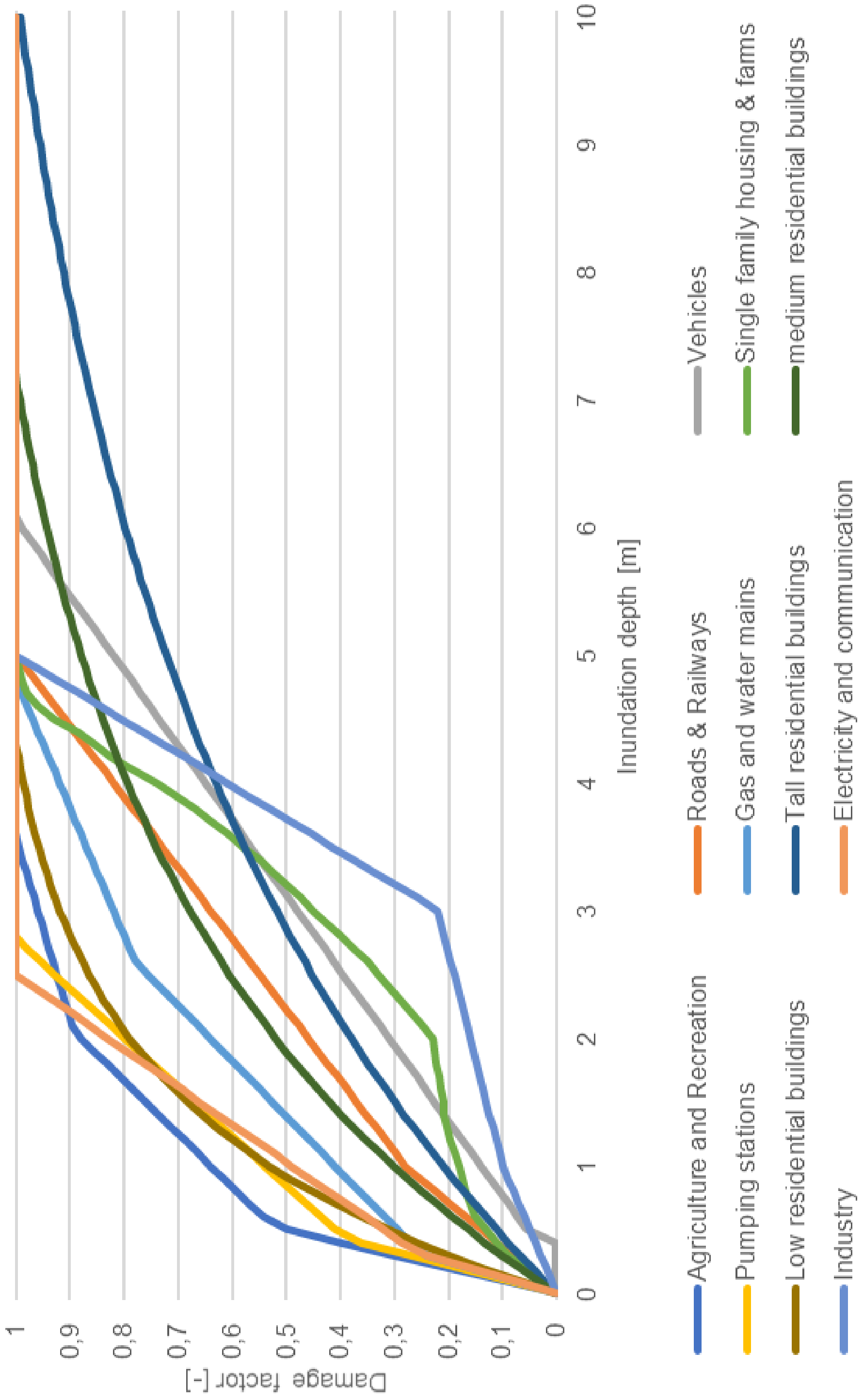

Figure A4-1: Overview of the 11 unique damage functions distinguished by Kok et al. (2005)

A5 Damage functions uncertainty analysis

This appendix shows for each of the distinguished reference damage functions the uncertainty as 50% confidence interval, quantified according to the procedure described in paragraph 3.3.5.

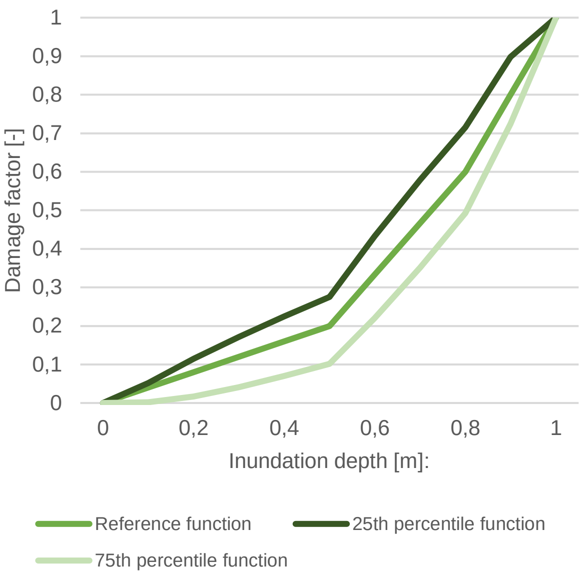

Figure A5-1: Uncertainty for function “Vehicles”

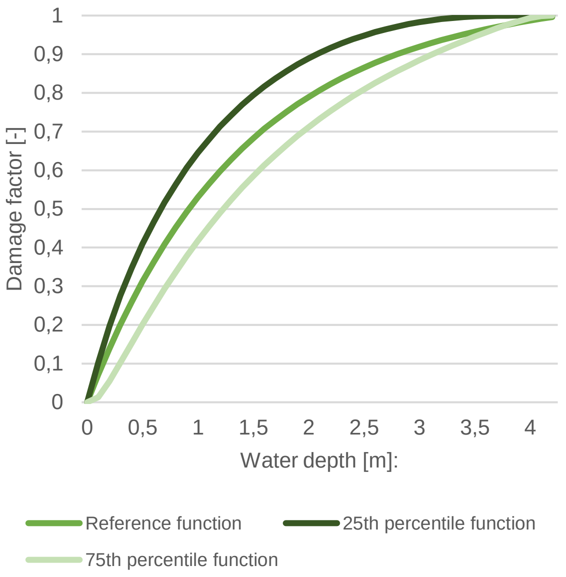

Figure A5-2: Uncertainty for function “Low residential buildings”

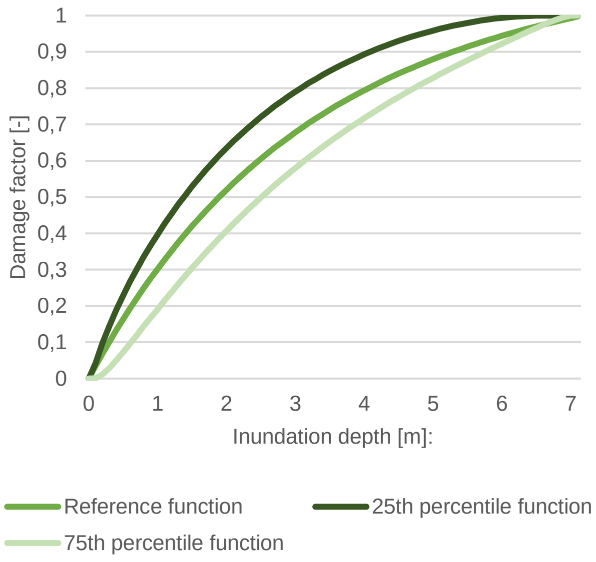

Figure A5-3: Uncertainty for function "Average residential buildings"

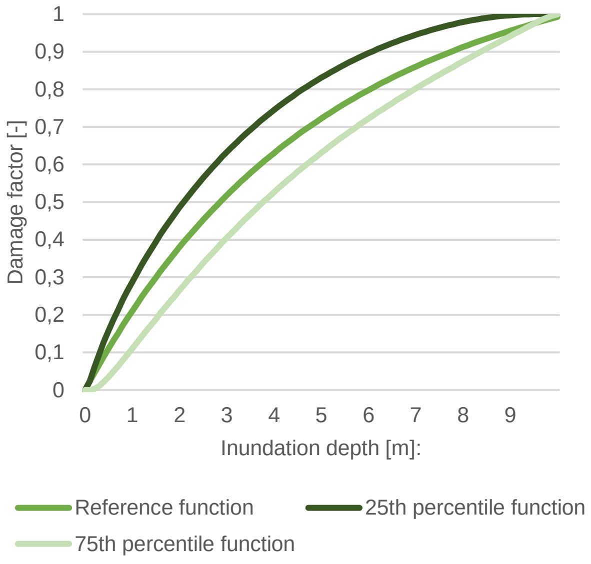

Figure A5-4: Uncertainty for function "High residential buildings”

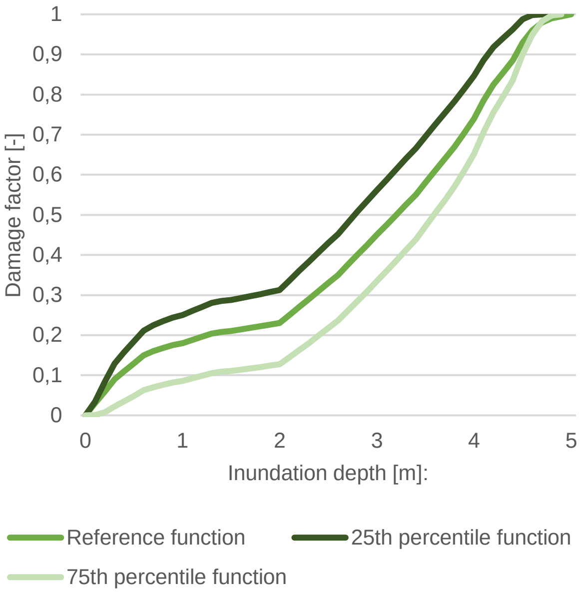

Figure A5-5: Uncertainty for function "Single family- and farm houses"

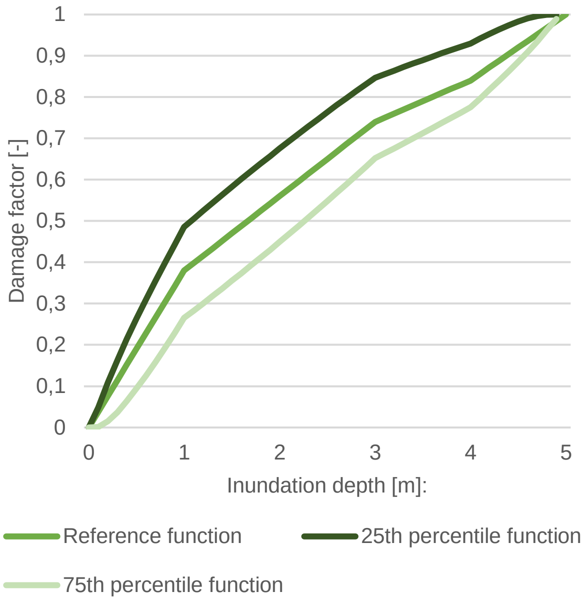

Figure A5-6: Uncertainty for function "industry"

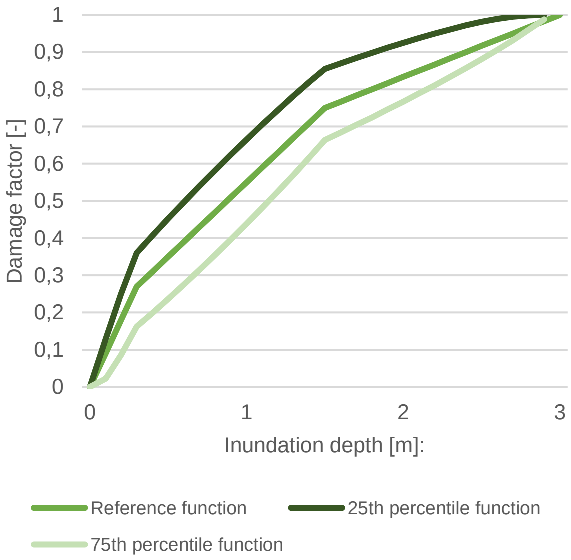

Figure A5-7: Uncertainty for function "Commercial areas"

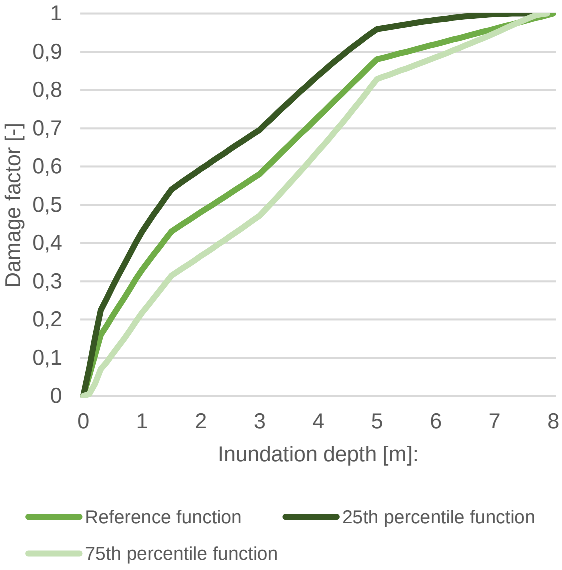

Figure A5-8: Uncertainty for function "offices"

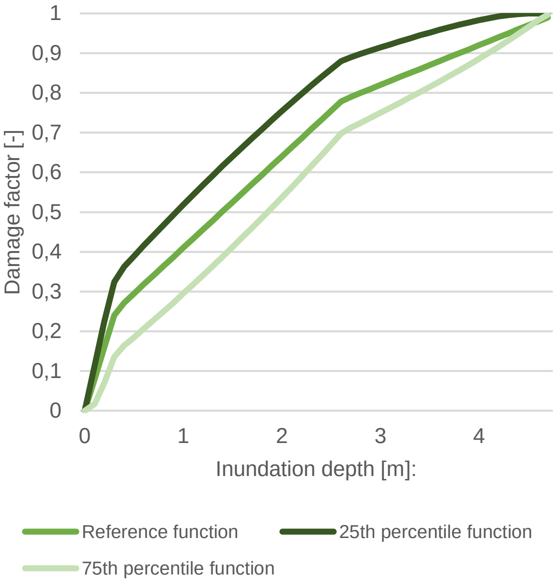

Figure A5-9: *Uncertainty for function "Gas and water mains"*

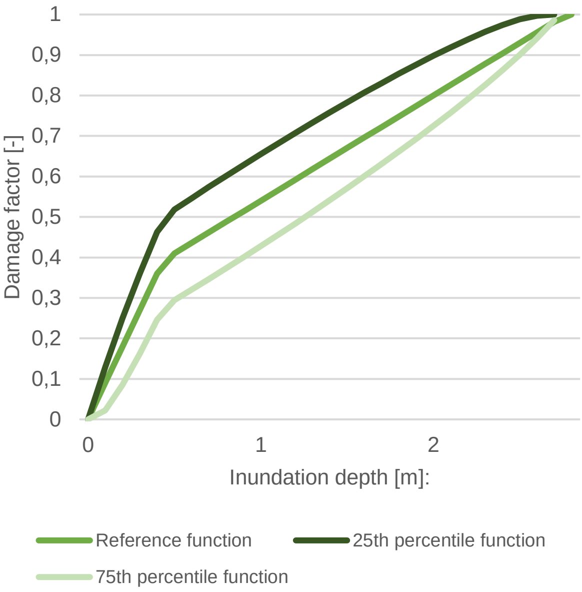

Figure A5-10: *Uncertainty for function "pumping stations"*

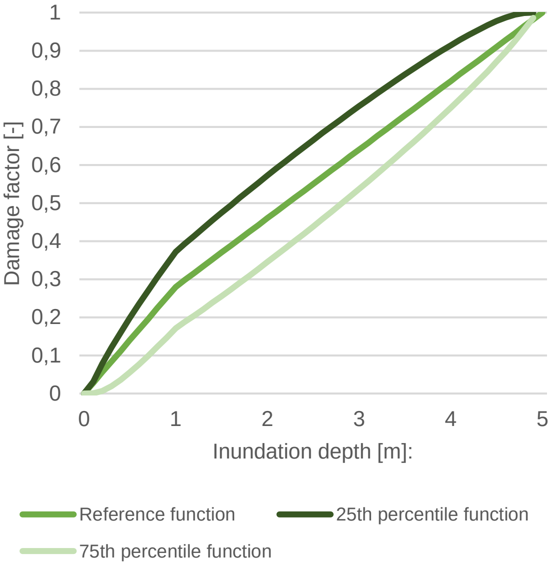

Figure A5-11: *Uncertainty for function "Roads and railways"*

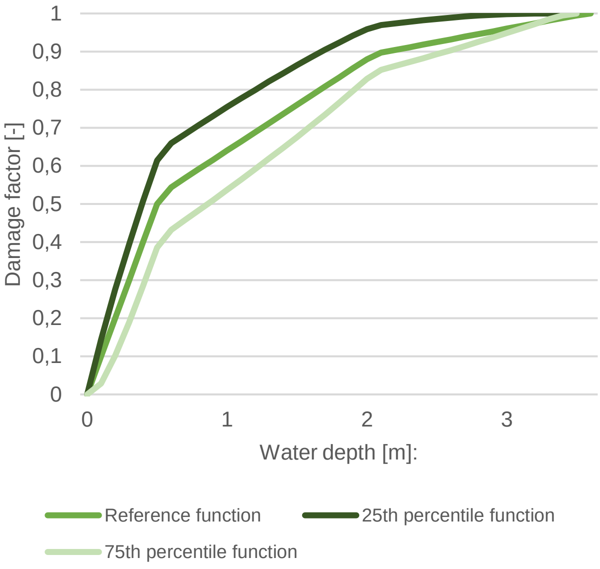

Figure A5-12: *Uncertainty for function "Agriculture and recreation"*

A6 Breach growth uncertainty; time-averaged head difference

In this study, the average head difference over the breach was kept at a constant 2.8m regardless of the breach location or the breach development scenario. This is a simplification, as the time-averaged head difference is in reality dependent on the location of the breach and the accompanying local river stage, elevation of the hinterland and other characteristics of the hinterland which determine how quick the inland inundation levels increase. This simplification was also made in the original safety standard calculations. Due to the significant time-consumption of the flood simulation model, it was not feasible to determine location-specific head differences. Furthermore, the time-averaged head difference is dependent on the breach growth itself, which implies that multiple iterations would be required for each different scenario for dike composition to determine the actual time-averaged head differences. This appendix gives a short analysis of the validity of this assumption and describes how the results of this study would change if this assumption was not followed.

Figure A6-1 shows the measured head difference over the breach for 6 uncertainty analysis flood simulations made in this study. It becomes clear that the head difference varies for the two breach locations of safety standard segment 43-6, as well as for the hydraulic conditions at these locations. Head differences at Tiel diminish relatively quickly after breach initiation, as the area directly behind this breach location behaves like a small bath-tub, resulting in rapidly rising inundation levels (also discussed in paragraph 4.4.1).
The assumed time-averaged head difference of 2.8m for both locations was compared to the observations in Figure A6-1. For the flood scenarios at Tiel-West, 2,8m is a very reasonable assumption as time-averaged head difference. At Haaften, the found head differences are around 2,1m.

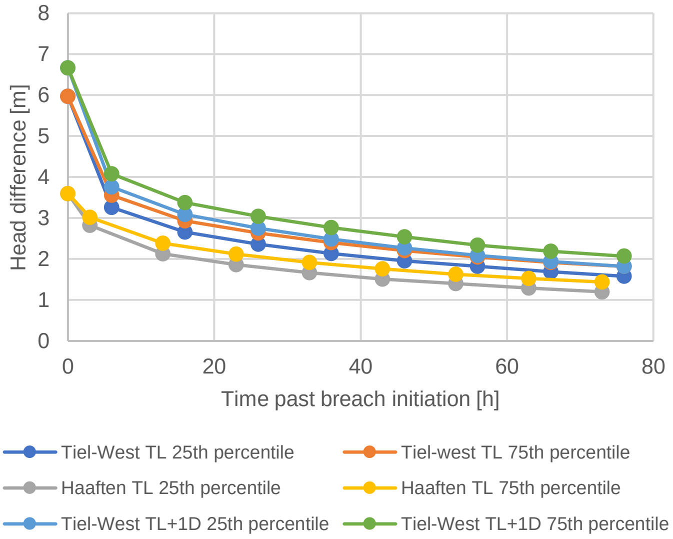

Figure A6-1: Head difference development over the breach during the breach development time for TL-hydraulic conditions (Haaften and Tiel-West) and TL+1D hydraulic conditions (Tiel-West)

Table A6-1: Average head level difference for 6 flood scenarios in the uncertainty analysis in safety standard segment 43-6:

Flood scenario	Average head difference [m]
Tiel-West TL 25th percentile	2,60
Tiel-West TL 75th percentile	2,83
Tiel-West TL+1D 25th percentile	2,99
Tiel-West TL+1D 75th percentile	3,23
Haaften TL 25th percentile	1,94
Haaften TL 75th percentile	2,16

So, it can be concluded that 2.8m is an overestimated average head level difference for Haaften and a reasonable estimate for Tiel-West. In case the flood simulations for Haaften would have been updated with a lower value for H, this would have led to a slower breach development (approximately 30% slower than for H=2.8m) and therefore less breach inflow. Would this have led to significant changes in the uncertainty analysis results? Likely not. Flood damage would not significantly decrease as a result of the bath-tub characteristics of dike ring 43 (the area fills up until the spill flow works at Dalem can discharge water into the Waal). Therefore, the SCBA standards would marginally decrease, even more considering that the total flood damage is weighted from both the Tiel-West and Haaften flood scenarios.

The LIR standards are derived based on both the Tiel-West and Haaften flood scenarios as well. As the normative neighbourhood for safety standard segment 43-6 is situated for almost all uncertainty analysis scenarios in an area which is also flooded from breach location Haaften, the LIR standards derived in the breach development uncertainty analysis would become slightly less strict.

In the combination uncertainty analysis, the strictest safety standard was derived based on a neighbourhood which is not flooded from breach location Haaften. The LIR standard is in that case not influenced by the decreased breach width at Haaften. The realistic bandwidth derived for the LIR and SCBA safety standards in this study is thus not influenced by the overestimated breach development widths at Haaften.

A7 Example flood characteristics Delft-FLS

The figures in this appendix give an example of the flood characteristics data as derived from the Delft-FLS flood simulations, for a flood scenario at breach location Bemmel for TL hydraulic conditions.

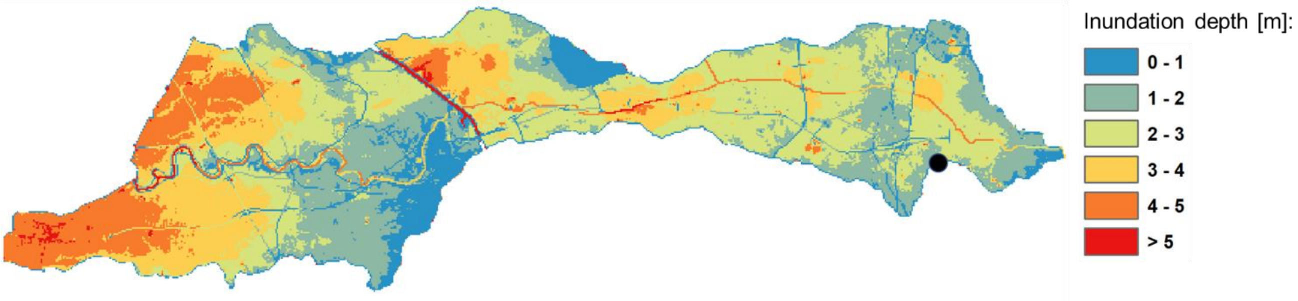

Figure A7-1: Maximum inundation depth dike ring 43 for a flood scenario at Bemmel (black dot) for TL hydraulic conditions

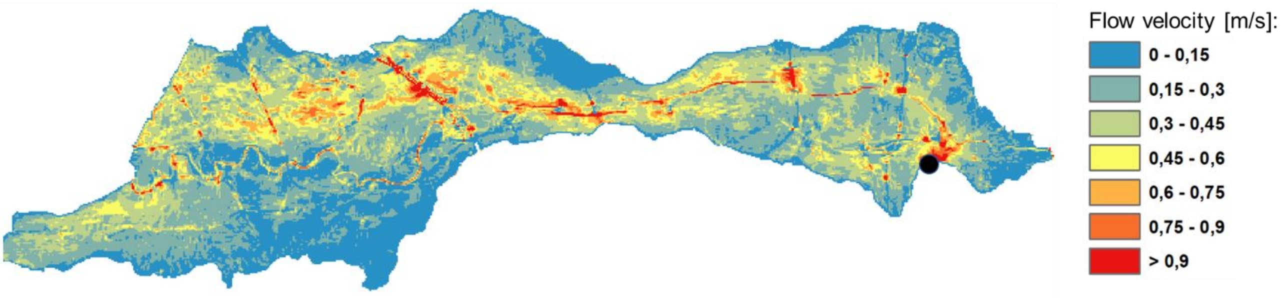

Figure A7-2: Maximum flow velocities dike ring 43 for a flood scenario at Bemmel (black dot) for TL hydraulic conditions

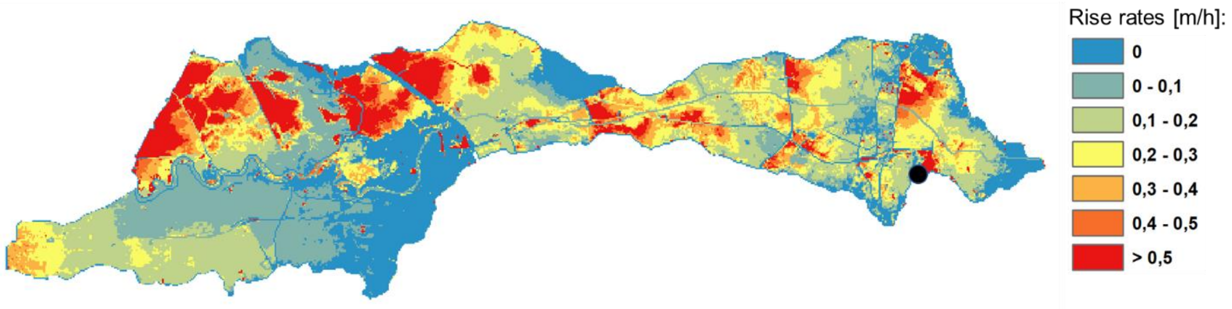

Figure A7-3: Rise rates ober the first 1,5m inundation depth for a flood scenario at Bemmel (black dot) for TL hydraulic conditions

A8 Neighbourhood mortality maps verification safety standards

This appendix shows for each safety standard segment in dike ring 43 a map of the median mortality values for the neighbourhoods in dike ring 43, along with the normative neighbourhood based upon which the verification LIR standards have been set. In each figure, the respective safety standard segment is highlighted in green and the accompanying breach locations are shown as an asterisk.

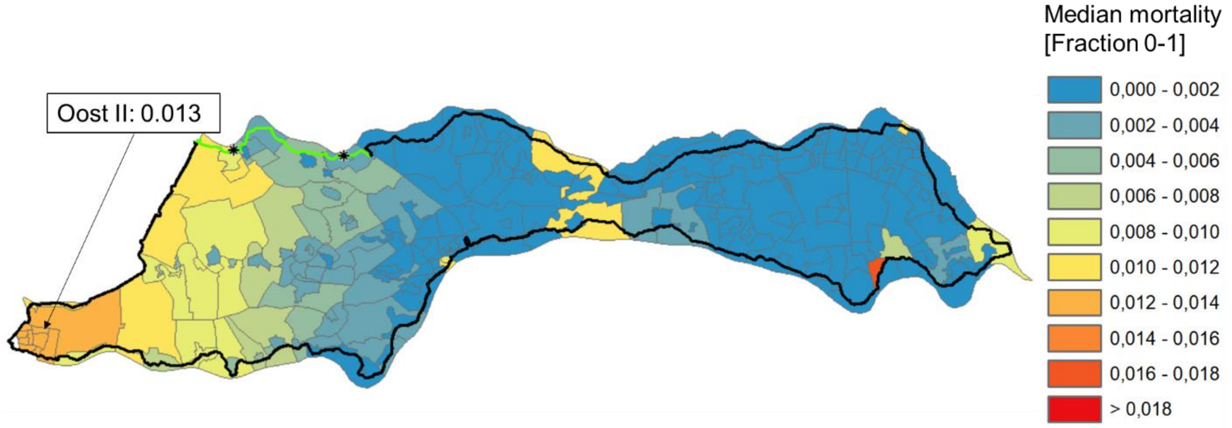

Figure A8-1: Median mortality per neighbourhood safety standard segment 43-1

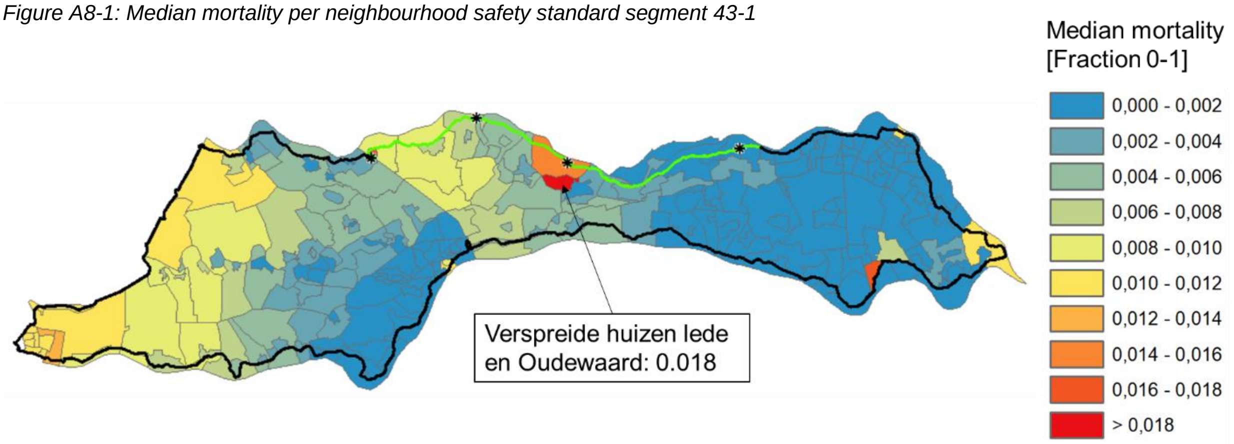

Figure A8-2: Median mortality per neighbourhood safety standard segment 43-2

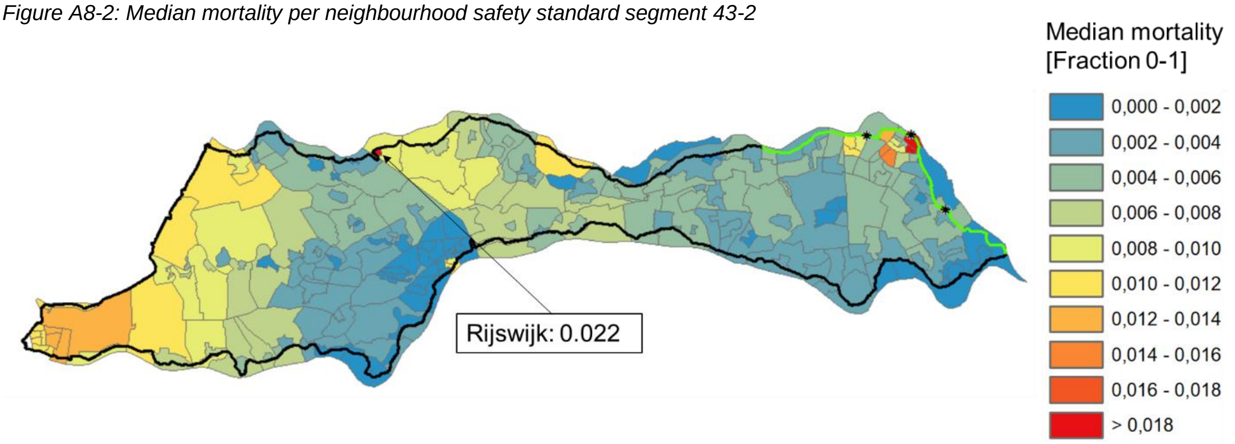

Figure A8-3: Median mortality per neighbourhood safety standard segment 43-3

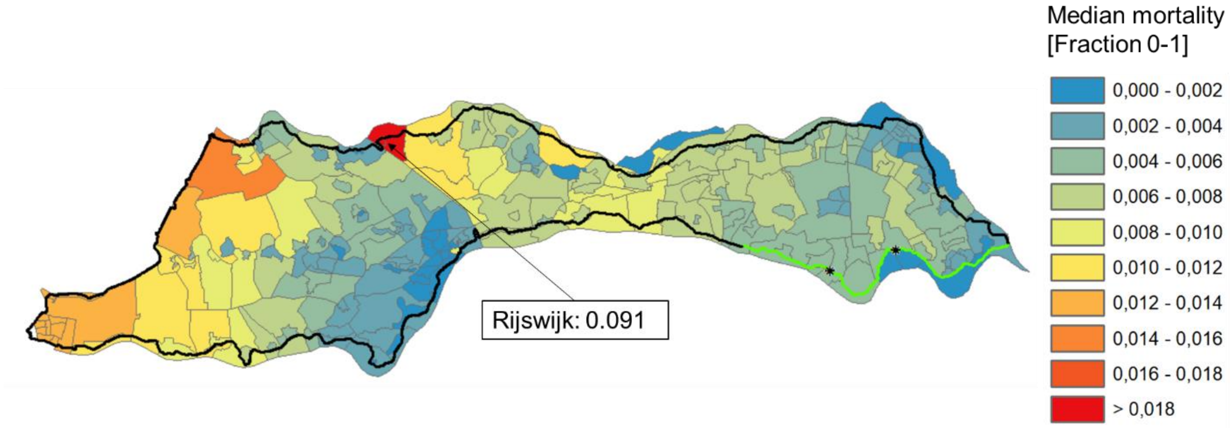

Figure A8-4: Median mortality per neighbourhood safety standard segment 43-4

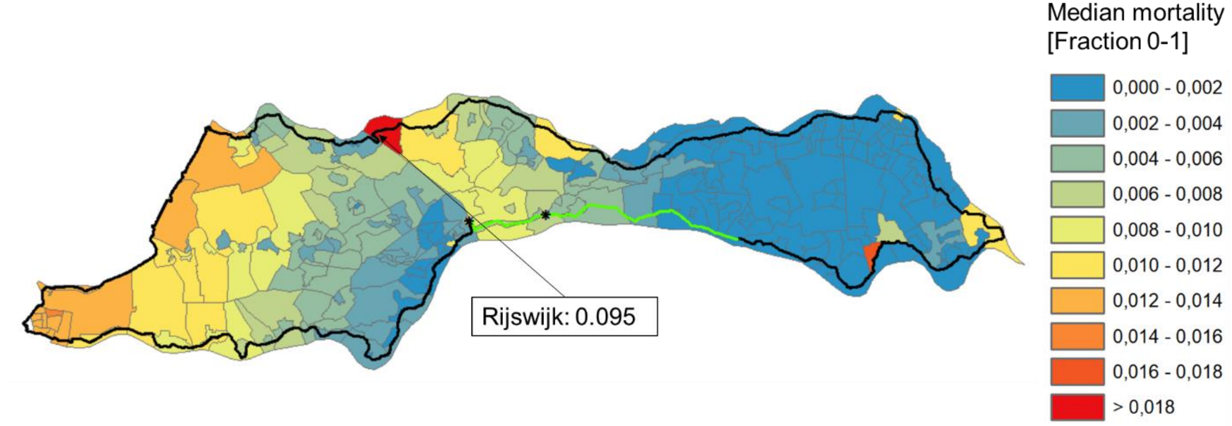

Figure A8-5: Median mortality per neighbourhood safety standard segment 43-5

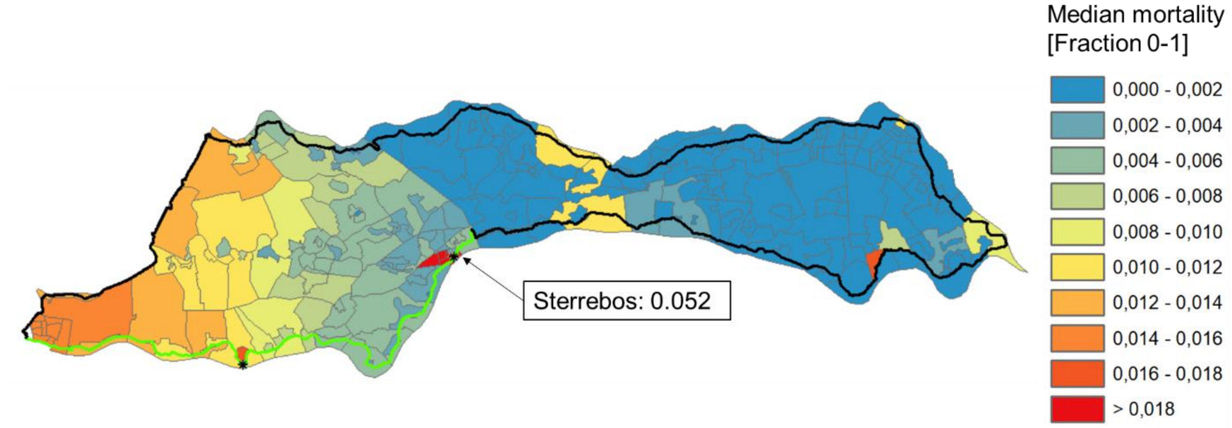

Figure A8-6: Median mortality per neighbourhood safety standard segment 43-6

A9 Evacuation uncertainty: flood arrival times

This appendix shows for each of the 6 safety standard segments of dike ring 43 the flood arrival time in each neighbourhood (as the minimum value observed in the considered flood scenarios for each segment). Furthermore, in each figure the neighbourhoods normative to the LIR standard of the segments are pointed out. For each evacuation uncertainty analysis scenario, the normative neighbourhood and flood arrival time in this neighbourhood is shown. The blue box represents the verification scenario, while the green boxes represent the 25th percentile (dark green), reference (middle green) and 75th percentile scenario (light green).

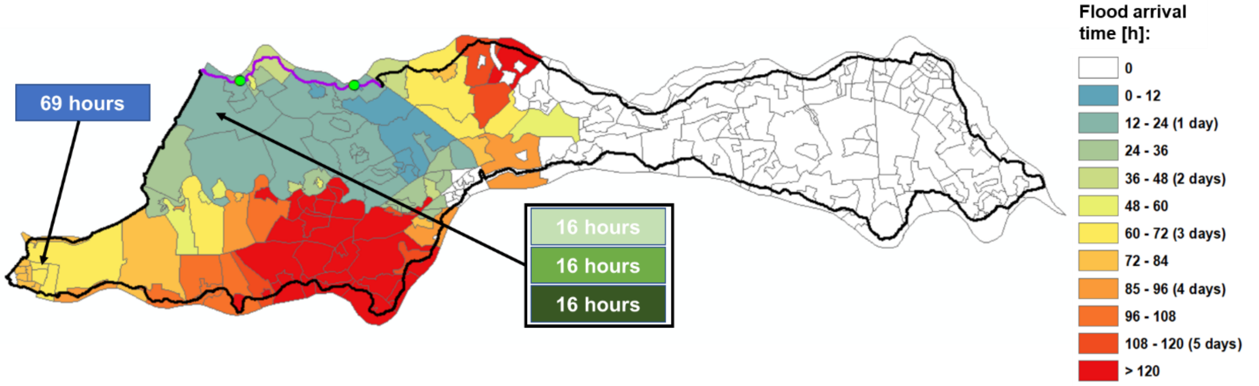

Figure A9-1: Flood arrival times and LIR normative neighbourhoods for the evacuation scenarios in the individual uncertainty analysis for safety standard segment 43-1

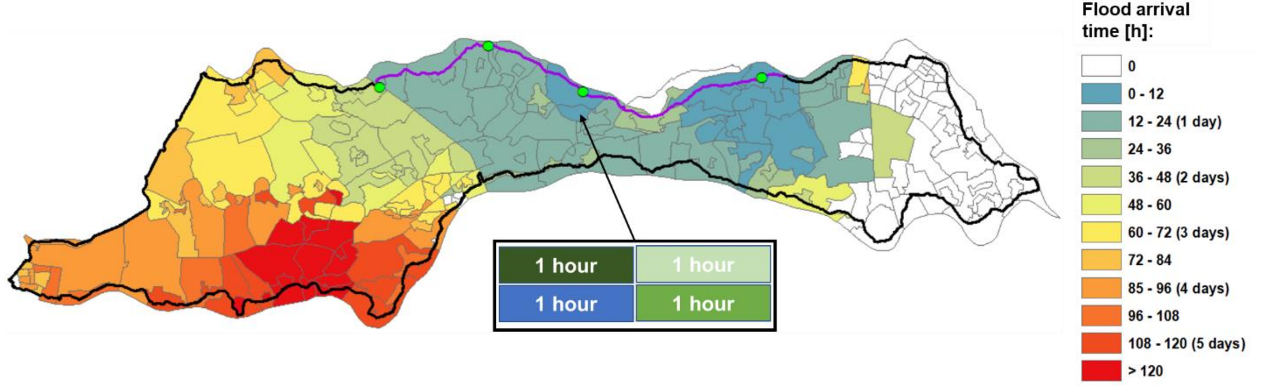

Figure A9-2: Flood arrival times and LIR normative neighbourhoods for the evacuation scenarios in the individual uncertainty analysis for safety standard segment 43-2

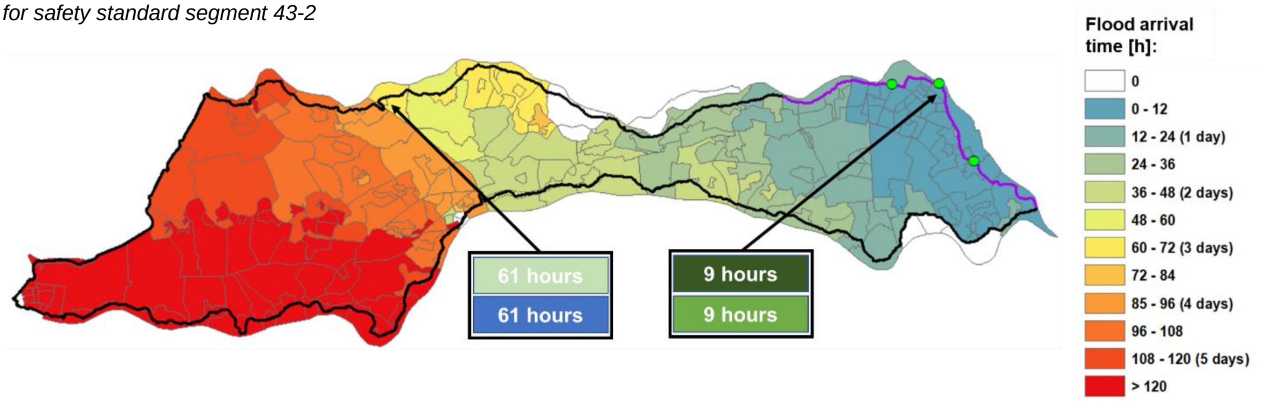

Figure A9-3: Flood arrival times and LIR normative neighbourhoods for the evacuation scenarios in the individual uncertainty analysis for safety standard segment 43-3

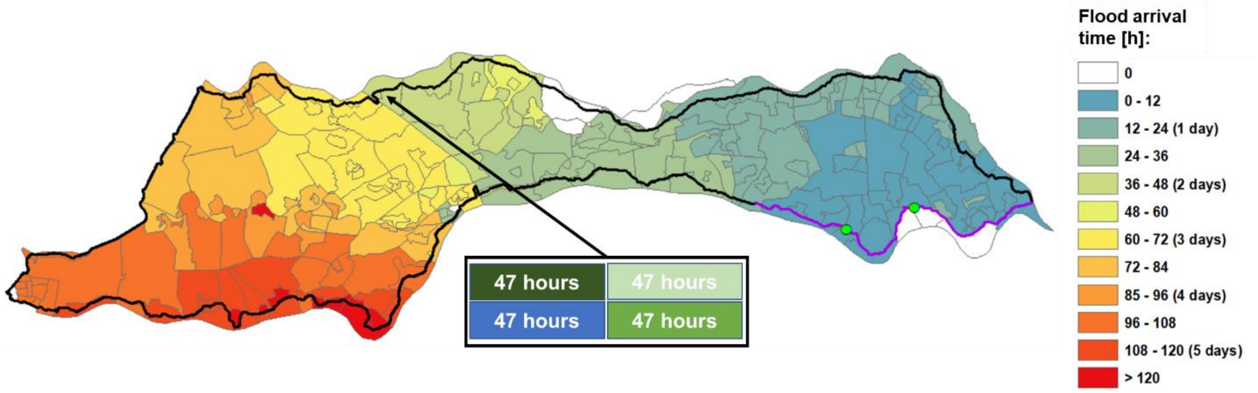

Figure A9-4: Flood arrival times and LIR normative neighbourhoods for the evacuation scenarios in the individual uncertainty analysis for safety standard segment 43-4

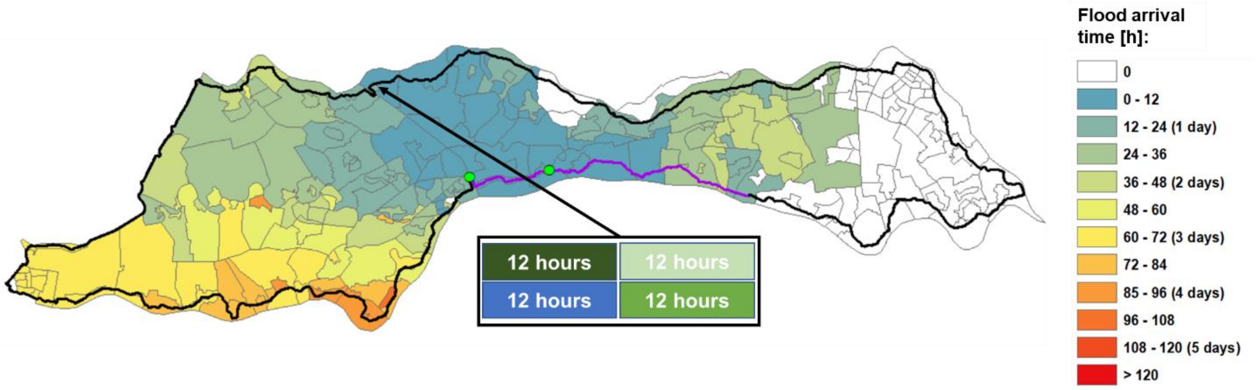

Figure A9-5: Flood arrival times and LIR normative neighbourhoods for the evacuation scenarios in the individual uncertainty analysis for safety standard segment 43-5

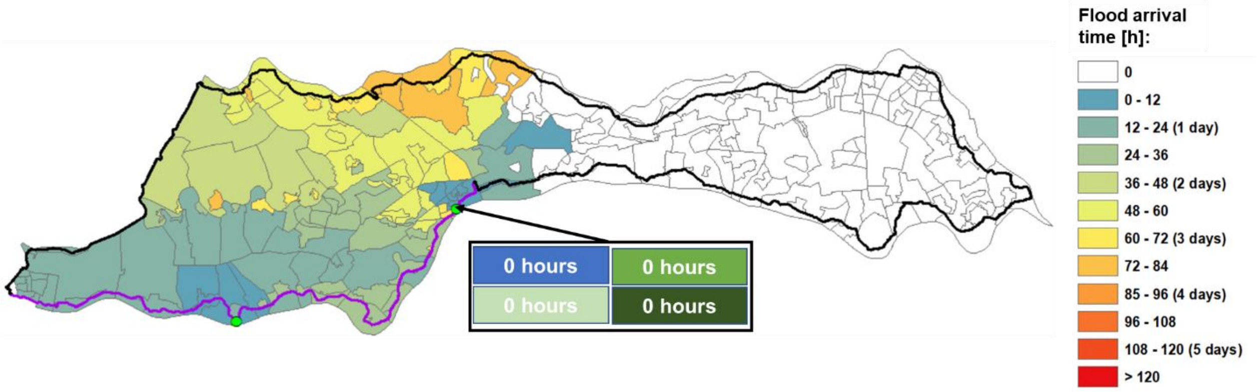

Figure A9-6: Flood arrival times and LIR normative neighbourhoods for the evacuation scenarios in the individual uncertainty analysis for safety standard segment 43-6

A10 Uncertainty investment costs for flood defence improvement

This appendix gives some additional background to the cost estimations used in the verification safety standard derivation and in the uncertainty quantification approach used in this study.

Differences cost estimations verification safety standard derivations and cost estimations for the current dike improvement projects:
The absolute cost estimates made for the current dike improvement projects have a different purpose and can therefore not be used as more accurate cost-estimate in the uncertainty analysis as adaptation of the verification scenario for the dike improvement costs. The most important differences are summed up below:

- Cost estimates verification safety standards: Express the costs required to withstand hydraulic conditions with a 1/12500 annual occurrence probability, from a non-existing reference situation in which the dikes can withstand hydraulic conditions with a 1/1250 annual occurrence probability
- Cost estimates current improvement projects: Express the costs to meet the “new” flood probability-based flood safety standards, based on the currently present flood defences. The degree of improvement is therefore higher in these cost estimations
- The allowed overflow/overtopping discharge differs between the two cost estimates, resulting in a different improvement task.

The approximation equation used to derive the SCBA standards (equation 2 in paragraph 3.1.3) is valid for cost estimations for dike improvement of one decimal height (Slootjes & van der Most, 2016b). As the current cost estimates are not made for one decimal height of improvement, these absolute cost estimates cannot be directly used in the SCBA standard derivations.

Uncertainty in cost estimations for flood defence improvement:
The investment costs for improvement of flood defences is uncertain due to many different aspects. Some important aspects according to the cost estimators at Royal HaskoningDHV include:

- Can the material found in the “old” dike be reused in the new design or not?
- Logistics, where will materials come from?
- Presence of pipes, cables and unexploded ordnance
- Compensation for depreciation of private property and expropriation
- Uncertainty in the raw material costs
- The magnitude of hydraulic effects of the dike design, which requires compensation measures
- Risks encountered during construction (required time, procedures etc.)

Cost experts at Royal HaskoningDHV make probabilistic cost estimations for dike improvement projects, taking into account the above-mentioned uncertainty sources via probability distributions. The uncertainty quantification followed in this study incorporates these aspects. These are all uncertainty sources relevant in dike improvement projects in general, regardless of the specific design. The magnitude of importance of these aspects differs among different projects, depending amongst others on the site specifications and the dike design. This is an important explanation why for instance the variation coefficient for the cost estimates differs significantly for segments 43-4 and 43-6, as the respective designs differ significantly, making some uncertainty sources more or less prominent in these projects.

This difference points to an additional source of uncertainty, which is in the uncertainty quantification in this study not incorporated: the design uncertainty. The basic design strategy for which the cost estimates are made that were used in the (verification) safety standard calculations in this study originate from an automated hierarchy of plausible measures (Dutch: “verdringingsreeks”). This hierarchy prefers the least expensive dike improvement strategy (also see De Grave & Baarse (2011)). The dike design affects both the absolute investment costs as well as the magnitude of importance of the above-mentioned uncertainties and therefore the variation coefficient. Table A10-1 shows the cost estimate data for the three dike improvement projects considered in this study, as made by the probabilistic cost estimations at Royal HaskoningDHV.

The basic dike designs for the projects currently in preparation for safety standard segments 43-4 and 43-6 have already been decided on. For segment 43-5 however, there are currently still three possible basic design alternatives, for which a decision is yet to be made. This example shows that the total uncertainty in flood defence investment costs is (depending on the project phase) larger than the uncertainty expressed by the variation coefficients in Table A10-1. As time progresses, the total uncertainty slowly decreases because the design is slowly further crystallised, and the role of the uncertainty sources summed up above decreases slowly. In this study, the variation coefficients based on the most recent dike designs were used to quantify the uncertainty. The summed up uncertain aspects above are included in these variation coefficients, however not the design uncertainty. On the time when safety standards are derived, the total investment cost uncertainty therefore is somewhat larger than represented in the variation coefficients shown in Table A10-1.

Table A10-1: Investment costs per km for three safety standard segments. The second column gives the costs as they were used in the verification calculations. The third column gives the cost estimates made by cost estimators at Royal HaskoningDHV for three dike improvement projects within these three safety standard segments, along with the variation coefficients for these probabilistic estimations in the fourth column. The project phase in which these cost estimates were made is shown as well in the sixth column. For segment 43-5, two additional cost estimates are given for alternative dike designs. The bold numbers were used in the uncertainty quantification in this study.

** NOTE: The three absolute cost-estimates cannot be compared directly, as they do not express the same magnitude of decreasing flood probability.*

Safety standard segment	Investment costs per km flood defence		Variation coefficient	Project phase
	Verification safety standard calculations*	Recent estimates dike improvement projects*		
43-4 (Wolferen-Sprok)	**€ 6.051.000,-**	€ 10.335.000,-	**0,22**	Preferred alternative elaboration
43-5 (Neder-Betuwe)	**€ 8.042.000,-**	€ 13.477.000,- *(dike design: improvements landside)*	**0,24**	Initiation phase
43-5 (Neder-Betuwe)		€ 12.354.000,- *(dike design: improvements within current dike profile)*	0,23	Initiation phase
43-5 (Neder-Betuwe)		€ 14.953.000,- *(dike design: improvements riverside)*	0,25	Initiation phase
43-6 (Gorinchem-Waardenburg)	**€ 6.086.000,-**	€ 19.786.000,-	**0,16**	Preferred alternative elaboration

A11 Evacuation: Alternative disobedience percentages

This appendix gives an example of the sensitivity of the safety standard calculation process to the disobedience percentage among people who should evacuate. In case the neighbourhood dominating the LIR standard of a safety standard segment, is situated far away from the breach location, the LIR standards are highly sensitive to the disobedience percentage. An example for safety standard segment 43-4 shows this effect.

The figure below shows the difference in mortality for a situation with 10% disobedience and 1% disobedience for post-breach evacuation. It becomes clear that for areas further away from the breach location, the mortality approaches zero (as virtually everybody is evacuated), while closer to the breach the mortality hardly drops due to the short flood arrival times. Because the LIR normative neighbourhood for this safety standard segment is dominant by a large margin for this segment, the disobedience percentage directly affects the LIR standards. As a result, the LIR standards in this segment would become 10 times less strict. This effect is much less important in case the LIR standard is not strongly dominated by one neighbourhood far away from the breach location.

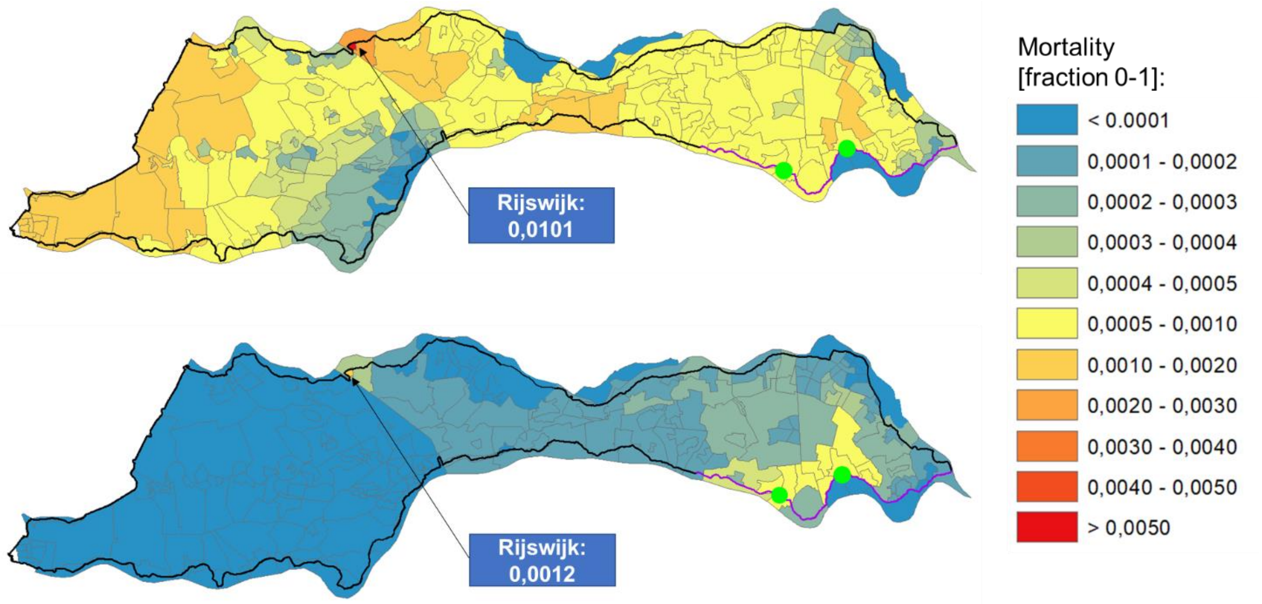

Figure A11-1: Top: median mortality per neighbourhood for safety standard segment 43-4, as derived in the individual uncertainty analysis for the reference evacuation scenario with a 10% disobedience percentage. Bottom: median mortality per neighbourhood for safety standard segment 43-4, as derived in the individual uncertainty analysis for the reference evacuation scenario, but for a 1% disobedience percentage. The LIR normative neighbourhood (Rijswijk) does not change for the two situations.

A12 Dike design implications for a different safety standard class

This appendix gives an example of a first estimate calculation to see how the derived safety standards in this study might influence dike design.

The regular dike design approach based on the new safety standards uses a standard failure probability budget, which is used to assign failure probabilities to different failure mechanisms in the design process (see RWS-WVL & Kennisplatform Risicobenadering (2015)). In the end a design is derived for which the combined failure probability of all failure mechanisms does not exceed the total flood probability that was set by the safety standards. The allowed annual failure probability on cross-sectional scale was derived based on the following equation (RWS-WVL & Kennisplatform Risicobenadering, 2017):

$$P_{cross\ section} = \frac{P_{max} * \omega}{N} \qquad (\mathbf{9})$$

<u>*In which:*</u>

$P_{cross\ section}$ = *Annual failure probability on cross-sectional level for failure mechanism "Overflow and wave overtopping"* [y^{-1}]
P_{max} = *Lower limit flood probability class of the safety standard segment* [y^{-1}] *= 1/10000 in the current flood safety standards, maximum 1/3000 based on the bandwidths derived in this study*
ω = *Failure probability space for failure mechanism "overflow and wave overtopping" [-] = 0,24*
N = Lengt-effect factor [-] = 1 for safety standard segment 43-6 for the "overflow and overtopping" failure mechanism.

Based on this equation for dike design, the annual failure probability due to overflow/overtopping is set at 1/41667 for the current legal flood safety standards and 1/12500 for the found safety standard class in this study.

These failure probabilities were translated into required crest levels of the flood defences of safety standard segment 43-6. For this quick-scan, one location was considered: a dike section along the Waal at the village of Heeselt (see Figure A12-1). The required crest levels were determined with the Hydra-NL hydraulic model (Duits, 2018). This model can determine required crest levels for the overflow/overtopping criterion of flood defences based on probabilistic analysis of river discharges and wave conditions. Hydra-NL is widely used for dike design in the Netherlands. Under the assumption of a default 1:3 outer slope of the dike, for an overtopping criterion of 10l/m/s and under the present-day hydraulic conditions (2015), the following required crest levels were found for this dike along the Waal:

- 1/41667 annual failure probability: 10,37 m+NAP
- 1/12500 annual failure probability: 10,03 m+NAP

Figure A12-1: Location of the dike section considered in the quick-scan