THE IMPACT OF SPATIALLY DISTRIBUTED EVACUATION FRACTIONS ON FLOOD SAFETY STANDARDS IN THE NETHERLANDS.

MSc thesis report L.L.A Hahn

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Preface

In the world of integrated water management, the pursuit of innovative solutions to enhance the safety and resilience of our communities is very important. This quest led me on a journey of discovery over the past months, in achieving the completion of this master's thesis. This document represents the research I conducted in completing my master journey at the University of Twente, and it has been a privilege to undertake this research, exploring the complex domain of spatially distributed evacuation fractions.

Throughout this journey, I had the honour of working with dedicated individuals whose guidance and support were instrumental in shaping this thesis. I am very grateful to my daily mentors, Sam Westerhof and Ric Huting, from Royal HaskoningDHV. Their commitment to excellence, patience, and guidance were invaluable during this research. Their insights and expertise have left a mark on my academic and professional development.

I also want to extend my appreciation to my academic supervisors, Martijn Booij and Baran Ulak, from the University of Twente. Their guidance, scholarly advice, and encouragement were pivotal in refining the focus and scope of this research.

Furthermore, I would like to express my gratitude to the numerous experts, safety regions, and waterboards who generously shared their knowledge and insights during the course of my research. Their willingness to engage in meaningful discussions and provide valuable data and information were essential in achieving the objectives of this thesis. Their contributions have not only enriched the content of this document but have also expanded my understanding of the complex field of integrated water management.

In closing, I would like to thank all those who have supported me in countless ways, whether through guidance, encouragement, or simply being a sounding board for my ideas. Your belief in my capabilities has helped me in successfully completing this thesis. As I present this work, I hope it contributes to the ongoing dialogue surrounding spatially distributed evacuation fractions and serves as a testament to the collaborative spirit of academia, research, and the pursuit of a safer and more resilient future.

Loek Hahn

[22-11-2023]

Summary

Flood safety is an important concern in the Netherlands, a country characterized by its low-lying terrain, which makes it particularly susceptible to flooding. The nation's flood safety standards are regulated by law, based on three risk measures: individual risk, group risk, and economic risk. These safety standards aim to balance between safeguarding individual lives and optimizing the economic costs of flood protection measures. However, the determination of these standards involves an important component known as the evacuation fraction, which is an estimate of the proportion of the population successfully evacuated in anticipation of a (potential) flood event. There remains a significant research gap concerning the development of evacuation fractions that are spatially explicit and specific to the unique characteristics of dike ring areas. This study aims to bridge this gap by focusing on dike ring 48, using spatial characteristics for this area to the current method of determining evacuation fractions, and by doing so generating spatially distributed evacuation fractions. The objective is to assess how these spatially distributed evacuation fractions affect flood safety, thereby contributing to a more accurate representation of the difficulties involved in safeguarding dike ring areas from floodings.

Research question 1 Investigated how experts review the current evacuation fraction determination method. A qualitative approach was employed, involving interviews with experts in the field of flood risk management, safety regions and waterboard Rijn & IJssel. It was found that experts have opposing opinions regarding the current evacuation fraction methodology consisting of limitations in terms of flexibility, adaptability, and precision. These shortcomings highlighted the room for improvement and how this research could try to fill this gap.

Research question 2 aimed to assess the impact of incorporating flood arrival times into evacuation fraction determination, which was investigated through a combination of data analysis and modelling results. The study utilized inundation data results from a flood inundation model to obtain flood scenario inundation patterns. The results demonstrated that arrival times have a substantial effect on the evacuation fractions that can then be spatially distributed when comparing it to the conservative 56% evacuation fraction. In general, the spatial distribution caused an increase of ~14%. However, at certain locations this increase was much more, resulting in evacuation fractions between 80-100% at different locations.

Research question 3 analysed the effects of spatially distributed evacuation fractions on safety standards. A comparison between the current evacuation fractions and the spatially distributed evacuation fractions was performed by recalculating the dike safety standards with the spatially distributed evacuation fractions from research question 2. The results indicated a substantial shift in safety standards when spatial factors like arrival times are considered. Especially the analysis for the safety standards regarding dike ring section 48_1, the inclusion of spatially distributed evacuation fractions caused the dike section to have a lower flood safety standard.

When discussing the results, it is important to mention that this research is heavily dependent on human behaviour. Human behaviour can be seen as the most important limitation when dealing with evacuation since it is something that is very hard to predict and therefore to make assumptions about. Furthermore, the data gathered from the inundation model Delft-FLS can be seen as another important limitation since this model has since been surpassed within waterboards by the higher resolution D-Hydro model which could have a led to even more substantial effects on the research results. Using this higher resolution model could therefore change the spatially distributed evacuation fractions and thus the assessment of dike ring safety standards.

In conclusion, the research provided an extension to the current methodology with the inclusion of arrival times in determining safety standards. The created spatially distributed evacuation fractions challenge the established safety standards in such a way that certain dike sections would fall into a different safety category when applying arrival times into the safety standard determination. The research therefore recommends policy makers to include arrival times into determining dike safety standards.

Glossary

Concept	Explanation
Flood safety standards	A requirement appointed to a safety standard segment, which defines the maximum allowed annual flood probability to meet the flood risk criteria.
Primary flood defence	To totality of flood defence structures such as dikes and hydraulic structures that together make up the flood defence system of a dike ring against outer water such at the Rhine river branches.
Individual risk	The risk of dying that an individual has at all time regardless of their location withing a dike ring.
Group risk	The risk for large groups of casualties due to a single flood event.
Economic risk	The economic risk expresses the monetary losses directly or indirectly caused by disruption of economic processes and monetised damage to human beings (like casualties and injuries resulting of a flood event).
Dike safety standard	Certain standards that are determined by law in the Dutch water act, which certain norm sections must comply to.
LIR criterion	The Local Individual Risk 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	The Social Cost Benefit Analysis criterion expresses a monetary cost balance between monetised flood consequences and monetised costs required to reduce flood probabilities.
Flood damage	The damage causes by a flood event, expresses in economic damage as well as casualties.
Risk reduction	The reduction of the risk in a certain location due to different alternatives (dike strengthening projects, improving evacuation plans etc.)
Societal benefits	The benefits for the society in case of a dike strengthening project (feeling less vulnerable for example).
policy goal	The objective of a governmental institute for the future (Like improving the safety of certain locations by dike strengthening project).
Preventive evacuation	The evacuation to a safe area outside of the threatened area before a dike breach occurs.
Signal value	A value that once reached, is used to signal the start the preparation phase for a dike strengthening project.

maximum allowable flood probability	The value which determines if a dike section still complies to the set-out dike safety standards. A higher probability value than the maximum allowable flood probability would mean that a dike section does not meet the safety standards any longer.
Dike strengthening project	A project that is meant to strengthen a certain dike section by reducing one (or multiple) of its failure mechanisms (overtopping, piping, macro instability etc.)
Evacuation fraction (EF)	The fraction of residents within a dike ring that can pre-emptively be evacuation before a dike breach.
flood casualties	Deaths due to a flood event.
flood prone areas	Area’s vulnerable to flood events.
Cluster method	The method for evacuation fraction calculations which assumes dike rings with similar characteristics to be part of one “cluster”.
Dike ring	A series of flood defence structures which together form a closed system to protect a certain area of land.
spatial variations	The difference between aspects that differ between locations (like population density, arrival times, geography)
state of the art practices	The practices that are currently being used to determine something
Safety region	A safety region is responsible for disaster management. They are for example responsible for the fire department but also are in charge of evacuation during a flood event.
Waterboard	A policy-layer from the government that only concerns about water related topics. Dike ring 48 is managed and maintained by waterboard Rijn & Ijssel.
Evacuation plan	A plan of execution during certain disasters.
Dike norm section	A certain part of a dike ring for which separate flood safety standards are defined and established by law in the Dutch water Act.
failure probability	The probability of a dike section failing in its purpose (protecting an area from being flooded)
VNK2	(In Dutch: Veiligheid Nederland in Kaart 2) This project analysed the current flood risk in the Netherlands. Using an innovative method, flood loading, probabilities and dike performance probabilities are being linked to the consequences of flooding expressed in terms of economic damage and casualty numbers.
inundation pattern	The pattern in which an area will be flooded over time from a certain dike breach location
Evacuation exit	An exit location from the threatened area.

Normative neighbourhood	The neighbourhood that determines that is most impactful in determining a dike safety standard.
Dike ring cluster	A combination of dike rings that form a dike ring cluster. The dike rings in a certain cluster are assumed to have comparable specifics and are therefore seen as one in determining dike safety standards.
Conditional probabilities	a measure of the probability of an event occurring, given that another event (by assumption, presumption, assertion or evidence) has already occurred.
Public awareness	The process of informing the general public and increasing levels of consciousness about risks and how people can reduce their exposure to disasters
Norm class	A set norm determined by law which a dike section is classified by if it has a flood probability within a certain interval.
NAP	The national reference level for height on land is the Amsterdam Ordnance Datum, or NAP. NAP is approximately the mean water level for Amsterdam in absence of water motion.

1. Introduction

1.1 Background

Flood safety is a critical issue in the Netherlands, a country prone to flooding due to its low-lying geography. As such, flood safety standards have been established by law to regulate flood safety for all primary flood defences in the country (Jonkman et al., 2008). The Dutch Water Act of 2017 (Deltafact, 2023) provides these standards based on three risk measures: individual risk, group risk, and economic risk.

The determination of dike safety standards are based on a combination of two norms; LIR (Local Individual Risk and group risk) norms and SCBA (Social Cost-Benefit Analysis) norms (Pilarczyk, 2006). The most stringent norm between these two criteria is used to establish dike safety standards.

The LIR norms focus on individual risk, ensuring that everyone behind dikes and dunes in the country has at least a basic level of protection with a LIR of 10^{-5} year (Deltafact, 2023) (a one-in-100.000 chance of death due to flooding in a given year). This sets a fundamental safety standard for all areas. On the other hand, the SCBA evaluates the economic costs and benefits of various flood protection measures. It considers factors such as potential flood damage, the costs of risk reduction, and societal benefits. The SCBA helps prioritize investments in flood protection infrastructure based on cost-effectiveness (Kind, 2012).

If the LIR-based norm is more stringent than the SCBA norm in a particular area, it will be used as the dike safety standard. This approach ensures that dike safety standards are established to protect both individual lives and economic assets while optimizing the allocation of resources to achieve the highest level of safety and cost-effectiveness. The norms are based on the policy goal of meeting standards by 2050, with legal values as signal values and maximum allowable flood probabilities (lower boundary in figure 1). The signal values may be briefly exceeded (Slootjes & van der Most, 2016a). When this signal value is reached, the preparation for a dike reinforcement project is initiated (figure 1).

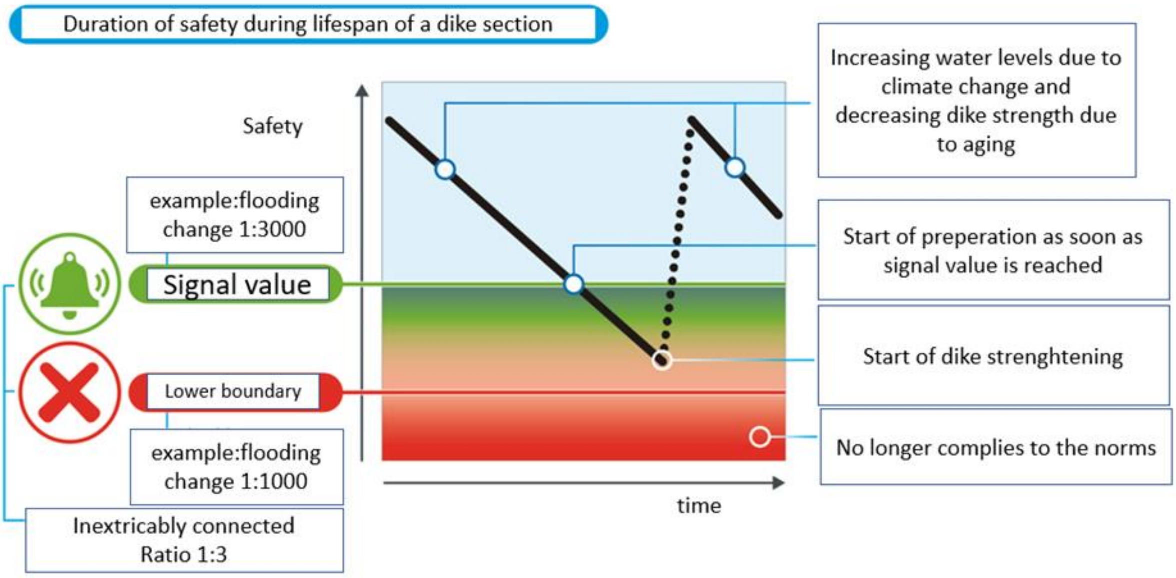

Figure 1. Signal values and lower boundary values contribution to dike strengthening projects. Modified after (Slootjes & Wagenaar, 2016)

One parameter in the calculation of these LIR norms is the evacuation fraction (also used in SCBA but way less impactful), which is an estimate of the population fraction that will have been evacuated before exposure in case of flooding. The evacuation fractions currently used in the flood risk calculations that determine the Dutch flood safety standards are based on range estimates that have been determined for different types of flood-prone areas in the Netherlands (Jonkman et al., 2011). The ranges for these evacuation fractions show the range of uncertainty present in these evacuation fractions. These estimates have several limitations, one of which is that a single evacuation fraction is assumed to be representative for very large dike ring areas, prone to many different flood scenarios (Maaskant, 2009a)(shown in figure 2). As a result, these estimates tend to be rather conservative (Slootjes & van der Most, 2016b). This conservative approach is therefore not a good representation of reality. In particular, areas where the arrival time of a specific flood scenario can be multiple days, a low (potentially too conservative) evacuation fraction is used. These low evacuation fractions at locations with long flooding arrival times are not realistic.

The evacuation fraction has a direct relationship with individual risk, with a ten times higher fraction resulting in ten times lower risk (Maaskant et al., 2009). Additionally, flood casualties are monetized and included in the estimate of the economic risk, making the evacuation fraction influential in this risk measures as well (Jonkman, Vrijling, et al., 2008). Therefore, it can be beneficial to develop well-substantiated and realistic spatially distributed evacuation fractions to quantify spatial flood risks in flood-prone areas.

1.2. State of the art

This section provides a general overview of the state of the art regarding the determination of evacuation fractions, shedding light on the methods employed to calculate these values, with a particular focus on the method used in The Netherlands and how this compares to international methodologies in context of determining dike safety standards.

Current practices in determining evacuation fractions, an important component of emergency response planning, have evolved over time to incorporate various factors influencing the effectiveness of evacuations. These fractions represent the proportion of individuals which can successfully evacuate an area in anticipation of a dike breach or flood event, thereby reducing the risks associated with such disasters.

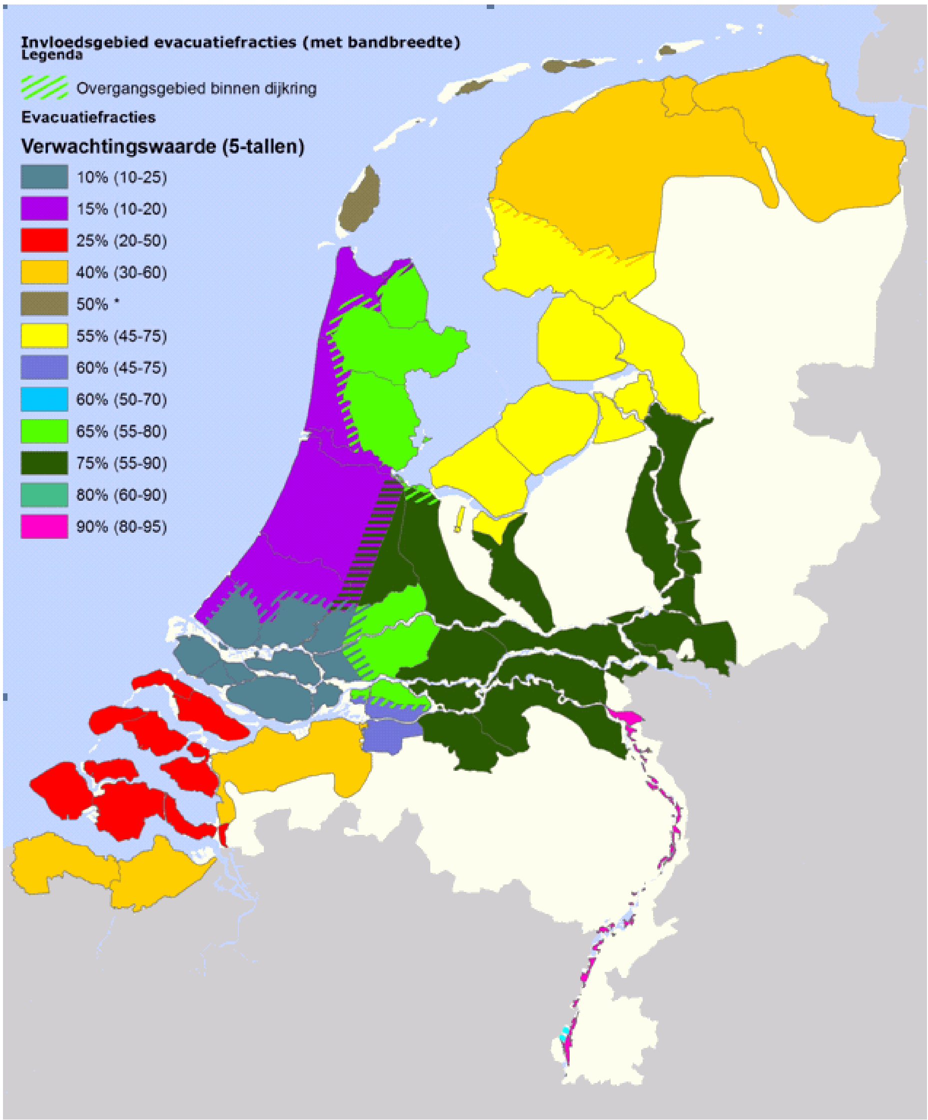

Figure 2. Evacuation fraction ranges used for safety standard calculations (Maaskant, 2009b).

The method currently employed for calculating evacuation fractions in the Netherlands was established in 2009 within the context of the "Water Safety for the 21st Century" (WV21) program. This approach was developed to determine the expected evacuation fraction for each dike ring, the fundamental unit of the Dutch flood defence system. The process involved assessing factors such as threatened areas, non-response rates, self-reliance, and the calculation of person-car equivalents (PAEs) to produce evacuation fractions. In 2013, this method underwent a reassessment by experts, revealing considerable uncertainty surrounding evacuation procedures. As a result, it led to a range of expected evacuation fractions rather than single average values shown in figure 2.

To calculate these evacuation fractions, the current methodology combines insights from two key studies. The first study (Friso et al., 2008),focuses on evacuation fractions per dike ring and accounts for several factors, such as non-response rates and the determination of PAEs. The second study, (Kolen et al., 2008) emphasizes the importance of road capacity in large-scale evacuations during flood threats, advocating for the evacuation of only threatened areas. Notably, these studies have differing assumptions and approaches, such as whether to evacuate the entire dike ring or just the threatened areas and varying non-response factors, which can significantly impact the calculated evacuation fractions. Additionally, this determination process combines conditional probabilities, estimating the likelihood of making an evacuation decision based on the time available for evacuation. These conditional probabilities and the expected evacuation fractions are calculated for each dike ring and its independent evacuation areas.

Dike safety determination methods differ globally. To understand how the Dutch approach differs from other countries, a comparison with Germany, the US and the United Kingdom is made.

Germany's approach to dike safety standards, characterized by precision through advanced hydrodynamic modeling, contrasts with the Dutch methodology. While the Netherlands adopts an integrated approach focused on dike rings, Germany's emphasis on technological implementation and detailed hydrodynamic modeling allows for a detailed understanding of flood scenarios (USSD, 2019). This precision-driven approach in Germany stands out in its detailed consideration of river dynamics, topographical features, and potential breach points. In comparison to the Dutch conditional probability model, Germany's methodology tends to rely more heavily on technological simulations, displaying a distinct emphasis on leveraging advanced technology for flood risk assessment and evacuation planning (Vorogushyn et al., 2012). This difference can for example be important for dike ring areas that overlap between The Netherlands and Germany in understanding the maintenance of a dike ring that spans over two countries with different calculation methodologies. Germany does however see the necessity for international collaboration as stated by (Thieken et al., 2002); “flooding does not stop at national borders and its impact is not confined to specific sectors, risk reduction and disaster response have to be coordinated among various stakeholders and administrative units”. The large flooding event in Germany in 2013 induced a public debate “to shift from flood defence to flood risk management strategies”(Otto et al., 2018). Germany could therefore potentially implement a very similar safety determination methodology as that of the Netherlands in the future.

The United States, in determining dike safety standards, uses a policy guided by regional variability and federal guidelines, differing from the more centralized Dutch approach (Ludy &

Kondolf, 2012). While the Netherlands adopts a uniform methodology with a focus on dike rings, the U.S. embraces a decentralized model where each state adapts federal guidelines to suit its unique geographical and climatic challenges (USSD, 2019). This regional autonomy in the U.S. contrasts with the Dutch model's emphasis on a standardized, integrated approach. The difficulty for the United States is in making different regions work together well and have a plan that works across the whole country. This is different from the Netherlands, where they have a more centralized system that is the same across the whole country (Remo et al., n.d.; Tarlock, 2012).

In the United Kingdom (UK), the determination of dike safety standards involves an integrated risk assessment approach, comparative to the Netherlands but with distinctive features (Chan et al., 2022). Similar to the Dutch methodology, the UK emphasizes integrated risk assessment, considering factors like population density, infrastructure vulnerability, and evacuation route availability (USSD, 2019). The UK utilizes sophisticated modeling techniques, including advanced hydrodynamic simulations and geographical information systems, for detailed flood scenario analyses. Climate change projections are integrated to enhance adaptability. A unique feature is the UK's emphasis on adaptive strategies, with regular reviews of evacuation plans, considering emerging threats and technological advancements. This approach reflects a commitment to ongoing improvement and resilience (Austin et al., 2021).

The comparative analysis of Germany, the United States, and the United Kingdom against the Netherlands shows methodological overlaps and differences in dike safety standards determination. Germany's precision through hydrodynamic modeling contrasts with the Dutch conditional probability model, emphasizing technological simulations for flood risk assessment. The U.S., with its regional variability and adaptation of federal guidelines, diverges from the Netherlands' centralized and standardized approach. The United Kingdom, while sharing commonalities with the Dutch methodology in integrated risk assessment, introduces a distinctive feature with its emphasis on adaptive strategies, showcasing ongoing improvement and resilience planning. Understanding these diverse approaches contributes to a nuanced global dialogue on dike safety standards and can give new insights in potential improvements regarding dike safety determination.

1.3. Problem description

Dike ring areas face significant risks from flooding. Evacuation plans and strategies have been developed to ensure the safety of those living in these areas in case of an imminent flood. However, the current evacuation fractions used to determine the safety standards of a dike section are often too conservative and assume a single uniform evacuation fraction for rather large areas, not including the unique characteristics of the location and flood scenario.
Using a single evacuation fraction for large areas is problematic because not all locations and flood scenarios have the same level of risk. For example, an area close to a dike breach has a higher level of risk and requires a different evacuation approach than an area that takes two days for the water to reach. Ignoring these differences and using a one-size-fits-all approach for large dike ring areas can lead to unrealistic evacuation planning, inefficient dike strengthening projects due to the dependency of safety standards on evacuation projections and in general

inefficient use of resources. If these aspects are taken into account, substantial differences in dike safety standards could occur.

While there have been significant efforts to develop evacuation plans and strategies for dike ring areas, there is a gap in the research on the development of spatially explicit evacuation fractions. The current approach assumes a single evacuation fraction for a large area, which leads to conservative estimates (Slootjes & van der Most, 2016). There is a need for more specific and accurate evacuation fractions that consider the spatial variations in flood risk, flood arrival times and population density within dike ring areas. Additionally, there is a lack of research on the potential benefits of using these fractions to establish dike ring norms.

1.4. Research aim

The aim of this research is to develop spatially distributed evacuation fractions for a selected dike ring, and to assess the impact of these fractions on flood safety standards. The research investigated how spatially distributed evacuation fractions in combination with current evacuation plans affect the safety standards regarding flood risk within a selected dike ring area. In short, the research aim is stated as:
"Assess the impact of spatially distributed evacuation fractions on the flood safety standards."

1.5. Research questions

The first research question will investigate how experts review the current method that is used in determining evacuation fractions. This research question will give the researcher a solid baseline in understanding how experts from different organisations think about the current evacuation fraction methodology and why a conservative approach is taken in this determination process.

1. **How do experts review the current evacuation fraction methodology?**

The second research question will investigate how spatial characteristics combined with current evacuation plans can function as an effective addition to the current dike safety determination method. By incorporating spatial characteristics with current evacuation plans, spatially distributed evacuation fractions can be determined.

2. **What are the effects of a spatial distribution on the evacuation fractions used for dike safety determination?**

The third research question will compare the spatially distributed evacuation fraction determined in research question 2 with the current evacuation fraction. This comparison will show how the spatial distribution effects the flood safety standards.

3. **What are the effects of the spatially distributed evacuation fractions on the flood safety standards?**

1.6 Report outline

First an introduction is given about the relevance of evacuation fractions and how they are used regarding flood safety in The Netherlands. A problem description was defined after which a research aim, and research question are determined.

Chapter 2 is added regarding the study area in which this research was conducted together with the current methodology that determines the evacuation fraction.

Chapter 3 describes how the research has been conducted and how this research could be reproduced.

Chapter 4 presents the results which answer the research questions by use of the methods chapter.

Chapter 5 discusses the limitation, research potential, practical implementation, and generalization of this research. This chapter intends to tackle the most important aspects that could raise discussion when reading this report.

Chapter 6 concludes the research and answers the research aim.

Chapter 7 provides potential opportunities for future research as well as opportunities for policy makers.

2. Material

This chapter describes the current methodology in determining evacuation fractions together with the study area in which this research was conducted.

2.1 Study area, dike ring 48

The study area that was used in answering these research questions is dike ring 48. The reason for this choice is the recent research of a previous student (Schippers, 2023) that has done related research to dike safety standards in dike ring 48 (specializing on a different topic than evacuation fractions). Furthermore, Royal HaskoningDHV had already established multiple relevant contact persons regarding safety-regions and the waterboard present in dike ring 48 that could serve to be helpful in my research.

Dike ring 48 is located in the east of the Netherlands east of Arnhem and slightly overlaps with Germany (figure 3). Within the area, waterboard Rijn & IJssel is responsible for the dike ring (Prinsen et al., 2020). Within this dike ring area, safety regions Gelderland-midden and safety region Gelderland Noord-Oost are present. These safety regions are present to ensure the safety for the people living in a certain area. Safety regions are for example responsible for the presence of a fire department in a certain area but also make evacuation plans in case of a disaster like a flood event (relevant for this research).

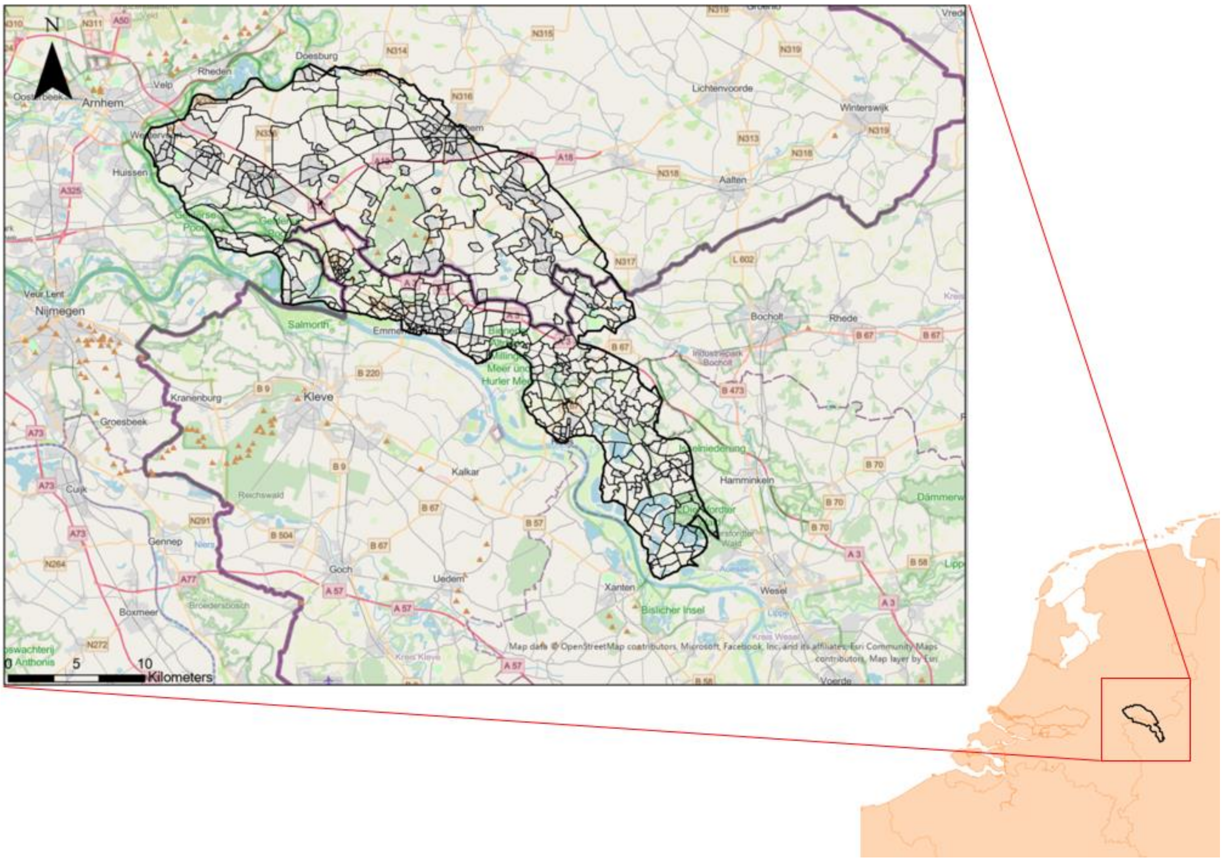

Figure 3. Location of dike ring 48 and all its neighbourhoods

An outline of the key features and characteristics is given below (Kolen et al., 2021; Arends, 2014):

Geographical Extent: Dike ring 48 (as it is called in The Netherlands) has a surface area of 566 km^2, stretching from Wesel-Bieslich in Germany to Lobith, Westervoort, and Doesburg, along the Oude IJssel River, reaching Doetinchem in the Netherlands. There are some elevation differences present in dike ring 48. On average sloping down towards the west with a hill in the middle of the dike ring referred to as “Montferland” shown in figure 4.

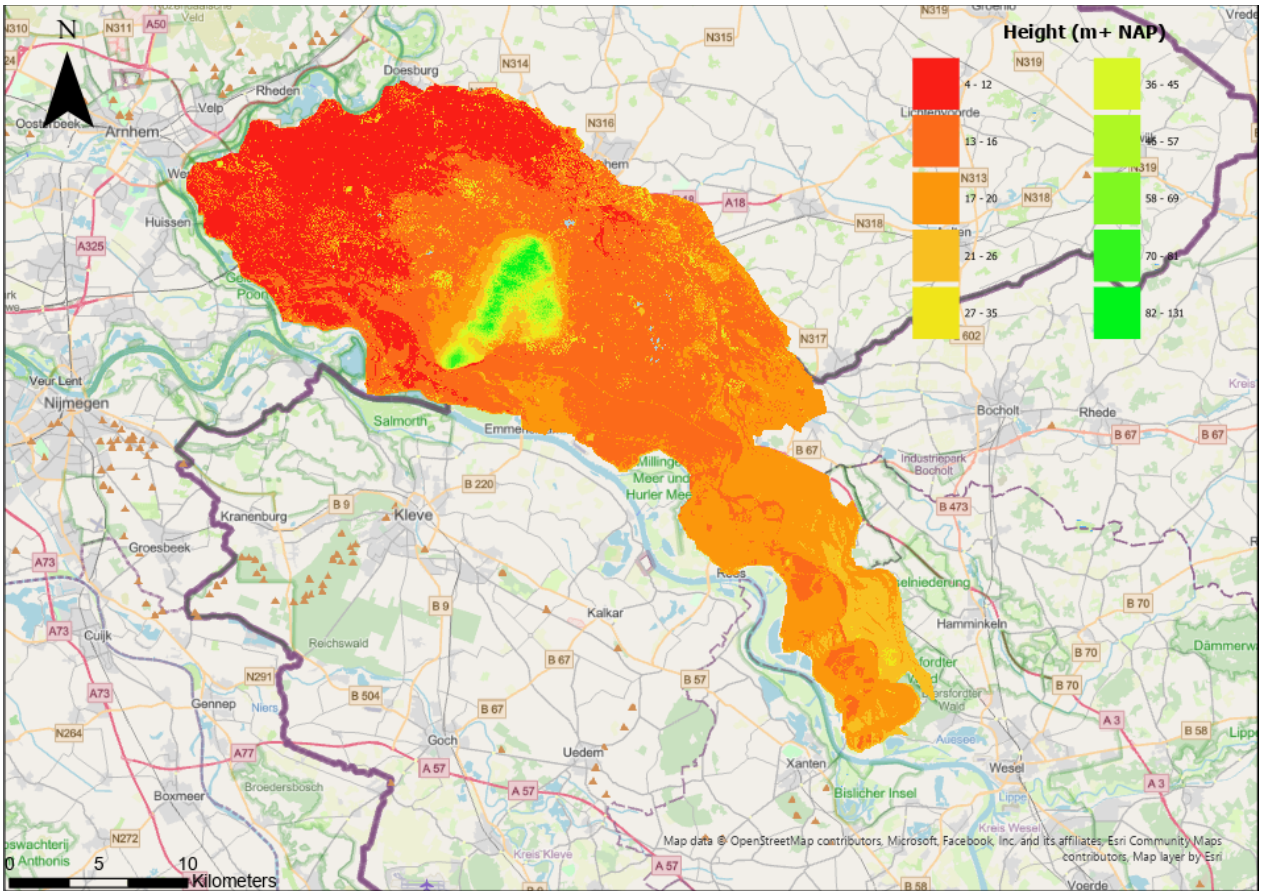

Figure 4. Elevation map of dike ring 48 with respect to NAP.

Hydrological Significance: The primary purpose of Dike Ring 48 is to protect the region from potential flooding originating from multiple water sources, including the Rijn (Rhine) River, the Pannerdensch Kanaal, the IJssel River, and the Oude IJssel River. These flood defences are important in safeguarding the communities.

Protected Population and Infrastructure: Dike Ring 48 serves as a protective barrier for several urban centers, including Rees, Emmerich, Zevenaar, Duiven, and Westervoort. The collective population residing within this area is approximately 240,000, with a predominant 80% residing in the Netherlands (Arends, 2014b). These residents are distributed across around 140 neighbourhoods which play a role in determining flood safety standards.

Normative Sections: For effective flood risk management, Dike Ring 48 is subdivided into three normative sections in the Netherlands: traject 48-1, traject 48-2, and traject 48-3 and 48_0 concerning the German part. Each of these sections has unique criteria for assessing flood risk, complete with target failure probabilities (possibilities for dike breach scenario's) to ensure adequate protection against potential breaches.

Cross-Border Collaboration: It is noteworthy that breaches in Germany, particularly along the north bank of the Rhine River, can also pose a significant threat to Dike Ring 48. Collaborative efforts between the Netherlands and Germany are essential for assessing and managing these transboundary flood risks. This Collaboration has already been initiated by the flood working group known as "Arbeitsgruppe Hochwasser" which tries to coordinate flood protection initiatives in the lower Rhine region.

Water Defence Strength: Dike Ring 48 faces various mechanisms that could lead to the failure of its water defences, including overtopping, overflow, piping, and macro stability. Regular evaluations are conducted to gauge defence strength and ensure compliance with established safety standards (Arends, 2014b).

Evacuation Plans: Evacuation plans are in place within the region to ensure the safety of residents in the event of an impending flood. These plans take into account factors such as available lead time before a breach, identification of weak spots in the defences, and the need to evacuate individuals who may not be self-reliant or lack access to transportation (Van Haaren, 2010). Important to mention is that these plans do not include the arrival time of inundation in a neighbourhood after a dike breach (for which this study aims to provide useful insights).

2.2 Current methodology in determining evacuation fractions

This section will provide an overview regarding the determination method of the currently used evacuation fraction. This method was determined in 2009 in the context of the program water safety for the 21st century (WV21) (van Stokkom et al., 2005) in which each dike ring part in the Netherlands an expected evacuation fraction was determined regarding the percentage of people that could pre-emptively evacuate in advance of a dike breach (Maaskant, 2009b). The evacuation fractions were re-assessed by experts in 2013 which led to an adjusted set of evacuation fractions. In this re-assessment it became clear that there is a-lot of uncertainty regarding evacuation which is why this expert meeting led to a bandwidth of expected evacuation fractions rather than single average values (Riedstra, 2016).

There are quite some literature documents (Table 1) that explain various aspects in the determination process of the evacuation fractions. The documents provided in table 1 specifically focus on studies or reports that address the determination of evacuation fractions for dike ring 48, including existing methodologies, models, or best practices that are currently being used in the field. This literature was used to understand and explain the current methodology in determining the evacuation fractions used for dike ring 48.

Table 1. Sources used for the literature review regarding the determination of evacuation fractions for dike ring 48.

Source	Explanation
(Maaskant et al., 2009)	Report explaining the methodology regarding the state-of-the-art evacuation fractions
(Kolen et al., 2021)	Pilot report exploring the possible improvements regarding pre-emptive evacuation and reduction of casualties.
(Arends, 2014a)	VNK2 flood risk report for dike ring 48
(van den Berg, 2017)	Calculation methodology explanation safety standards dike ring 48
(Kolen et al., 2008)	Report explaining on how to deal with the available road capacity in case of a possible flood (information used in EF calculations).
(Slootjes & van der Most, 2016)	Technical background regarding dike safety standards
(Rijn en IJssel, 2020)	Evacuation plan dike ring 48 (version 2020)

The evacuation fraction has been determined by a methodology that combines two different studies regarding the efficiency of evacuation related to traffic models in combination with conditional probabilities on the effectiveness of an evacuation (Maaskant et al., 2009). The methodology to get to an evacuation fraction will be explained by taking dike ring “Friesland and Groningen” as an example due to missing information on how the evacuation fraction for dike ring 48 has been determined. However, the evacuation fraction (determined by the same methodology) for dike ring 48 will also be presented since this is the evacuation fraction that is relevant for the study area.

2.2.1 Combining two different studies

The current evacuation fraction has been determined by using different studies:

1. “Veiligheid Nederland in Kaart: Modellering en analyse van evacuatie” (Safety for the Netherlands mapped - modellering and analyses of evacuation) (Friso et al., 2008): This study presents evacuation fractions per dike ring and considers various factors such as threatened areas, non-response factor (percentage of people not evacuating), self-reliant individuals, and determination of person-car equivalents (PAEs). The results of this study were used in estimating evacuation fractions in the VNK2 report (a report that analysed the Flood risk in The Netherlands aiming to improve the safety regarding flooding in The Netherlands).

2. “Als het toch dreigt mis te gaan: Invloed van landelijk verkeersmanagement op grootschalige evacuatie bij (dreigende) overstromingen” (If it threatens to go wrong: Influence of road capacity in large scale evacuations during (threat of) floodings) (Kolen et al., 2008): This study focuses on independent evacuation areas and highlights the need to evacuate only the threatened areas within multiple dike rings affected by the threat. It emphasizes the importance of considering road capacity during large-scale evacuations.

The studies by Friso et al. (2008) and Kolen et al. (2008b) have different assumptions and approaches. Friso et al. (2008) considers evacuating the entire dike ring, while Kolen et al. (2008b) focuses on evacuating only the threatened areas. The non-response factors (people that do not comply in case of an evacuation order) also differ, Friso et al. (2008) assumes everyone evacuates, while Kolen et al. (2008b) assumes a 20% non-response rate. These differences can significantly impact the number of people that are expected to evacuate and therefore influence the evacuation fraction. A combination of the results from these studies has determined the current evacuation fraction (ranges).

As mentioned earlier, dike ring 6 is considered because the traffic modelling results for dike ring 48 could not be accessed. However, the modelling information for dike ring 6 is available which is why this dike ring is chosen to show what kind of modelling data is used as input for the determination process of evacuation fractions.

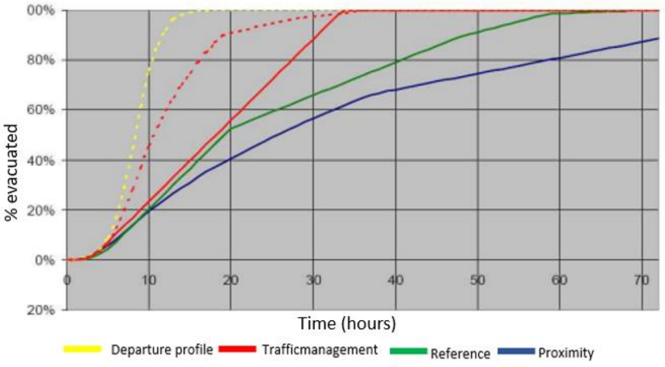

Figure 5. Evacuation curves for dike ring 6 (Cluster: "Friesland & Groningen) (Kolen et al., 2008).

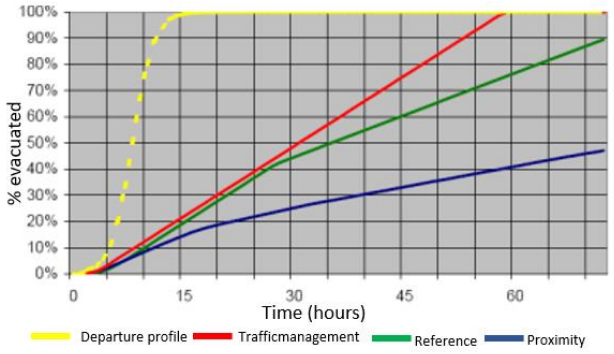

Figure 6. Evacuation curves for dike ring 6 (Cluster: "Friesland & Groningen) (Friso et al., 2008).

Table 2. Dike ring 6 evacuation percentages for different available times and different types of execution (Kolen et al., 2008).

Time for high-water	Available time for evacuation	Evacuation percentage (%)		
		Proximity	Reference	Traffic management
1 day	0 days	0	0	0
2 days	1 day	50	58	70
3 days	2 days	72	90	100
4 days	3 days	88	100	100

Table 3. Dike ring 6 evacuation percentages for different available times and different types of execution (Friso et al., 2008).

Time for high-water	Available time for evacuation	Evacuation percentage (%)		
		Proximity	Reference	Traffic management
1 day	0 days	0	0	0
2 days	1 day	21	37	38
3 days	2 days	36	65	83
4 days	3 days	47	90	100

Figures 5 and 6 show dotted and bold lines. The bold lines show static calculations (excluding details from the road network) and use single input values for average vehicle speeds and traffic flow rates. The dotted lines show dynamic calculations which do include details from the road network. Not for all evacuation area's dynamic calculations are available which is why it was decided to only use the static calculations for evacuation fraction determination (Maaskant et al., 2009). Another important aspect to mention is that both studies assume that for coastal area's (dike ring 6, example case), 24 hours in advance of a dike breach it is not possible to evacuate (due to weather conditions) which is why the evacuation results show 0% evacuation for a "1 day time to high-water". For river areas (dike ring 48) this is not the case since floods are coming from the river that are often not paired with extreme weather that may disrupt the potential to evacuate (see table 4).

The three different traffic scenarios that are considered in both studies are:

- Reference: It is assumed that the evacuees are evenly distributed across the defined exits of the respective area.
- Proximity: It is assumed that each evacuee leaves the respective area through the nearest exit, regardless of the capacity of that exit. This strategy prioritizes minimizing vehicle kilometers and only allows for converging traffic flows, without any crossing traffic flows.
- Traffic management: In this strategy, evacuees are distributed over the exits in proportion to their capacity. Given this utilization, vehicle kilometers are minimized. This strategy does not involve crossing traffic flows and predominantly has converging traffic flows.

The method to calculate evacuation fractions is a combination of the two studies mentioned above. It looks at the results of both studies for each available number of days. For each available time, the six available evacuation percentages (proximity, reference, and traffic management from both studies) are ranked from minimum to maximum. The average of the two maximum percentages is taken as the upper limit, the average of the two minimum percentages as the lower limit, and the average of the four middle percentages as the average evacuation percentage.

Maaskant (2009) uses this method to determine which evacuation percentages are considered for different time steps regarding all dike ring clusters in the Netherlands. By using this method (but then with the traffic model evacuation data for dike ring 48) the average evacuation percentages for dike ring 48 have been calculated. Dike ring 48 is part of dike ring cluster "rivers Rhine" which resulted in the average evacuation fractions shown in table 4:

Table 4. Evacuation percentages for dike ring 48 regarding a combination of (Friso et al., 2008; Kolen et al., 2008).

Available time for evacuation (days)	minimum evacuation percentage (%)	Average evacuation percentage (%)	Maximum evacuation percentage (%)
1 day	66	85	96
2 days	90	98	100
3 days	94	99	100
4 days	100	100	100

2.2.2 Conditional probabilities

In combination with the method described in section 2.2.1, conditional probabilities regarding the likelihood for an evacuation decision were estimated for the different independent evacuation areas (all the areas with similar characteristics regarding flooding, also known as a “dike ring cluster”) during an expert meeting. The conditional probabilities for an evacuation decision in dike ring 48 are shown in table 5 (Maaskant et al., 2009).

Table 5. Conditional probability for dike ring 48 that a decision is taken to evacuate regarding different available time periods for the execution of an evacuation (0 being the chance of an unexpected flood) (Maaskant et al., 2009b).

Available time for evacuation (days)	Conditional probability
4	0
3	0.2
2	0.5
1	0.2
0	0.1

Next to this, conditional probabilities for the performance of execution of the evacuation are assigned to the minimum, average, and maximum evacuation fractions. A normal distribution allocation was chosen, meaning that the average fraction is considered more likely than the minimum and maximum fractions, and the minimum and maximum fractions are equally likely. During the expert meeting, a distribution of conditional probabilities of 0.2 for the maximum, 0.6 for the average, and 0.2 for the minimum was chosen. The same conditional probabilities for execution were used for each available time period.

2.2.3 Combined result evacuation fraction

With the estimates of conditional probabilities and average evacuation fractions per available time, expected values of the evacuation fraction can be calculated for each area. This is done by use of “evacuation trees”. In figure 7, the evacuation tree for dike ring cluster “rivers Rhine” is presented which is used to determine the evacuation fraction for dike ring 48. This tree includes the available time for evacuation in combination with the level of execution (how well an evacuation is executed) and their conditional probabilities.

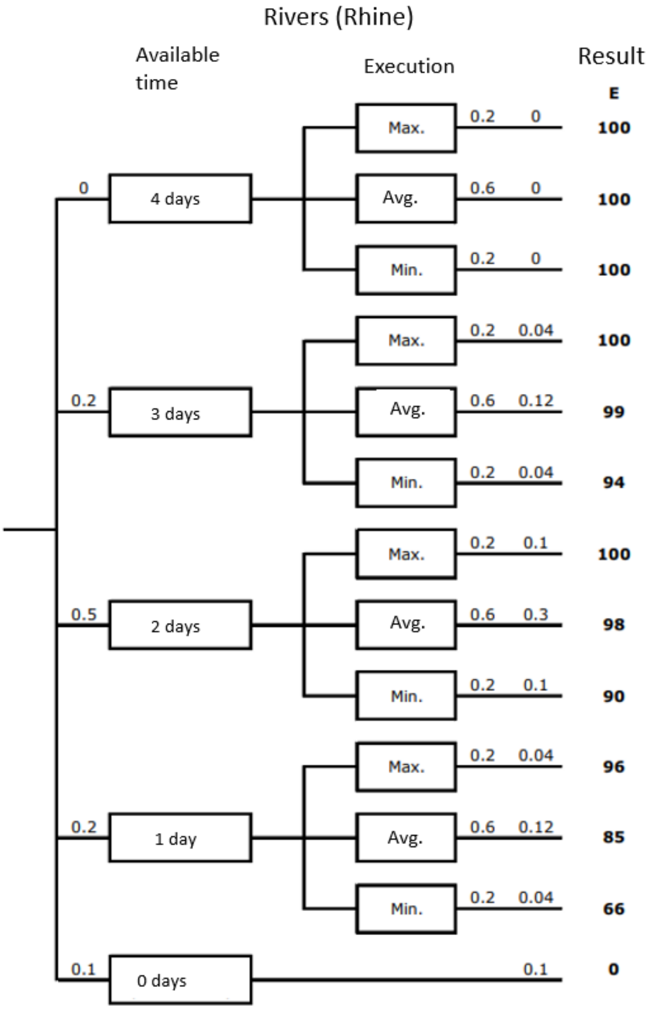

Figure 7. Evacuation tree dike ring cluster rivers (Rhine) (Maaskant et al., 2009).

By using this evacuation tree one can calculate the expected evacuation fraction considering multiple available time periods in which an evacuation decision is taken in advance of a (threatening) flood, the matter of execution and the conditional probabilities over all these aspects. For dike ring 48 this results in an expected evacuation fraction of ~85% (appendix A 1.2). By taking the conservative approach of minimal execution of evacuation this results in an expected evacuation fraction of ~76% (Appendix A 1.3). This is the expected evacuation fraction considering the current method. However, another conservative assumption was taken by policy makers which assumed that there is a 20% non-response factor which resulted in a lower limit of the evacuation fraction bandwidth of 56% for dike ring 48 (shown in figure 2).

3. Methods

In this method chapter the steps are explained that have been executed to answer the proposed research questions.

3.1. RQ 1; How do experts review the current evacuation fraction methodology?

The first research question intends to explore how experts review the current method that is used to determine the evacuation fractions that are used in LIR calculations to determine dike safety standards and what aspects play a key role in the determination process of the currently used evacuation fractions.

Multiple interviews were conducted with experts from different institutions. Three different views regarding the currently used evacuation fractions were gathered. In determining evacuation fractions, waterboards, safety regions and experts (which advise both instituted) have played a role in determining the current evacuation fractions. To gather these different views the following people (and their expertise) have been interviewed:

Table 6. Interviewed people regarding evacuation fractions.

Person	expertise
Kasper van Zuilekom	Traffic expert and creator of the evacuation calculator.
Marco van Ravenstein	Policy advisor flooding for safety region Gelderland-Midden.
Jan Bruggink	Policy advisor risk management for safety region Gelderland Noord-Oost.
Kees Jan Leuvenink	Policy advisor water safety at waterboard Rijn & Ijssel.
Bas Kolen	Author of multiple evacuation fraction determination documents.

To get different views on aspects related to evacuation fractions and this research, the following topics regarding evacuation fractions were covered in each interview making each interview semi-structured regarding the following topics:

- Role in the determination process of the currently used evacuation fraction.
- View on the determination process for evacuation fractions.
- Reason for using conservative evacuation fractions in safety standard determination.
- Potential issues in creating spatially distributed evacuation fractions.
- View on my proposed research.

After collecting information regarding the current evacuation fractions from the literature review as discussed in the material section and the interviews, the findings were analysed and synthesized. This involved combining the information from the literature review and the interviews to create an overview regarding the view from the waterboard, safety region and experts. The interviews were summarized in a table format covering the three different views on evacuation fractions.

Based on the interviews, conclusions were drawn about how experts review current practices and the factors that determine the evacuation fraction for dike ring 48.

3.2 RQ 2; What are the effects of a spatial distribution on the evacuation fractions used for dike safety determination?

The second research question aims to obtain spatially distributed evacuation fractions by incorporating spatial characteristics and flood arrival times. By the incorporation of spatial characteristics, arrival times and existing evacuation plans, the (possible) change of evacuation fractions were assessed. The method for answering research question 2 is schematized in figure 8.

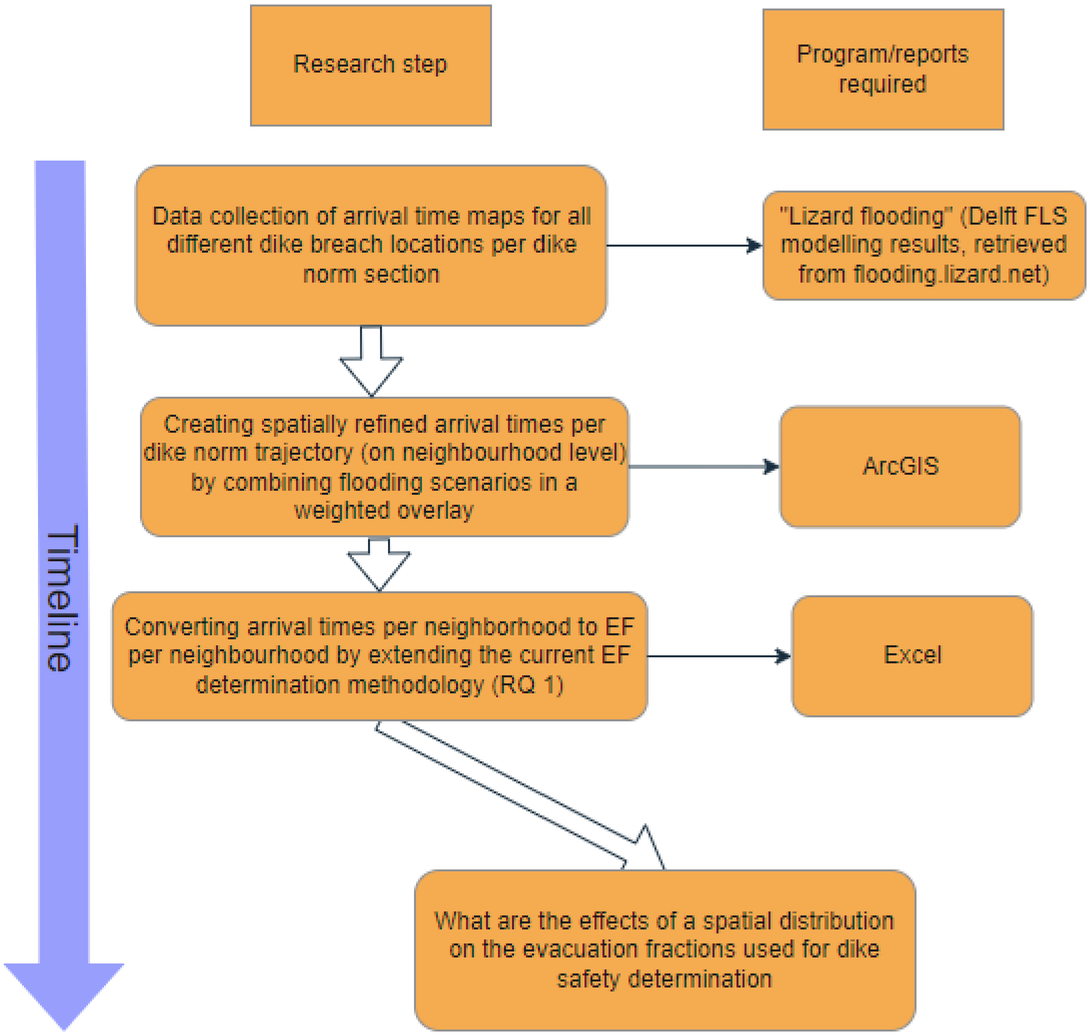

Figure 8. Steps for research question 2.

3.2.1 Data collection of arrival time maps for different breach locations per dike norm section

The first step in this research question is to gather the required spatial data and arrival times for all flood scenarios within dike ring 48. This data was retrieved from “Lizard Flooding” using an account provided by waterboard Rijn & IJssel. Lizard Flooding used the flood inundation model “Delft FLS” (Hesselink et al., 2003) to determine flood patterns for each norm section of dike ring 48. Multiple dike breach locations have been determined that are representative for a certain section of the dike (figure 9). Only these locations have been modeled since every dike breach within a certain dike section will result in a similar inundation pattern as has been modeled with the specified breach location.

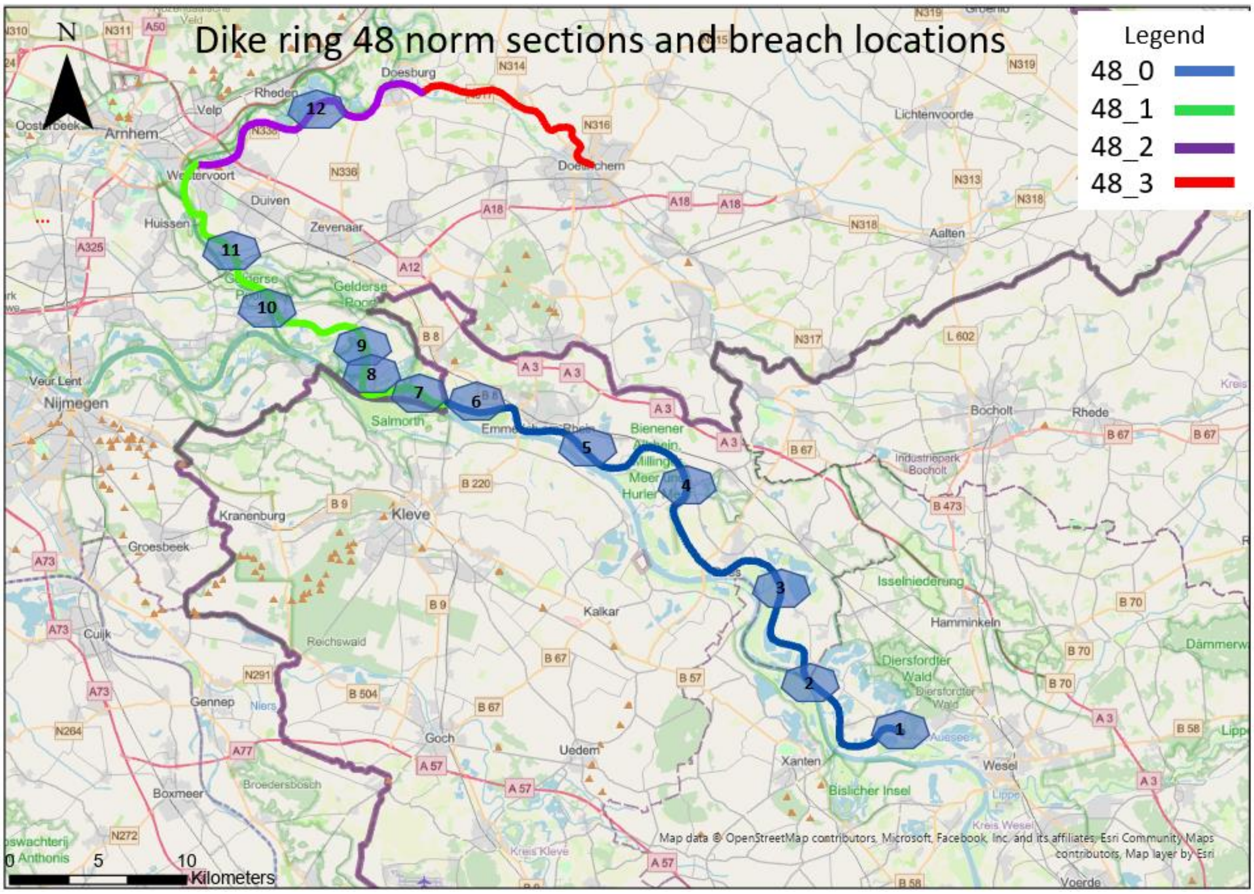

Figure 9 . Norm sections and their breach locations that are used in calculating flood patterns for dike ring 48.

3.2.2 Deriving spatially distributed arrival times per dike norm section

The collected arrival time maps for each breach location were imported in ArcGIS. Within ArcGIS combined maps were made for each norm section. If there were multiple breach locations present within a norm section, a weighted overlay was made in ArcGIS that combined the arrival times from the different breach locations within a norm section (individual flood patterns shown in appendix B) by their conditional chance of occurring. These conditional probabilities were determined by the length of a dike ring part divided by the length of the total norm section (see table 7). This methodology is in line with how current safety standards are determined.

Table 7. Conditional probability for different breach locations (van den Berg, 2017)

Norm section	Breach location	Dike ring part number (figure 9)	Length dike ring part (km)	Cond. probability
48_0	Bislich	1	8,6	0,187
	Haffen-Mehr	2	6,7	0,145
	Kreisstrasse	3	9,2	0,201
	Deichstation	4	8,3	0,180
	Gebaude_am_Deich	5	3,5	0,075
	Emmerich_am_Rhein	6	9,7	0,212
48_1	Spijk	7	5,1	0,198
	Gravenwaardse_dam	8	2,9	0,112
	Herwen	9	6,8	0,264
	Kandiagemaal	10	2,9	0,113
	Loo	11	8,1	0,313
48_2	Giesbeek	12	14,9	1,000
48_3	Breach 48-3	13	13,1	1,000

After having created four maps in ArcGIS for all norm sections of dike ring 48, the maps were overlayed on a neighbourhood map layer which resulted in an arrival time per neighbourhood per flooding scenario from a certain norm section. This weighted overlay from arrival time maps in combination with the spatial variation of neighbourhoods resulted in spatially distributed arrival times per neighbourhood for all four norm sections.

3.2.3 Converting arrival times per neighborhood to evacuation fraction per neighborhood by extending the current determination methodology

With these arrival times per neighbourhood, new evacuation fraction values were determined per neighbourhood. This was done by extending the existing evacuation tree (figure 7) that is used in the determination of the currently used evacuation fraction. The evacuation tree was extended by adding the available time (the arrival time of a flood) for each neighbourhood, schematized in appendix B. With this “extra” available time, the evacuation fraction for each neighbourhood was recalculated by using the evacuation curves from the traffic model results in the river Rhine area as shown in figure 10 (Kolen et al., 2008).

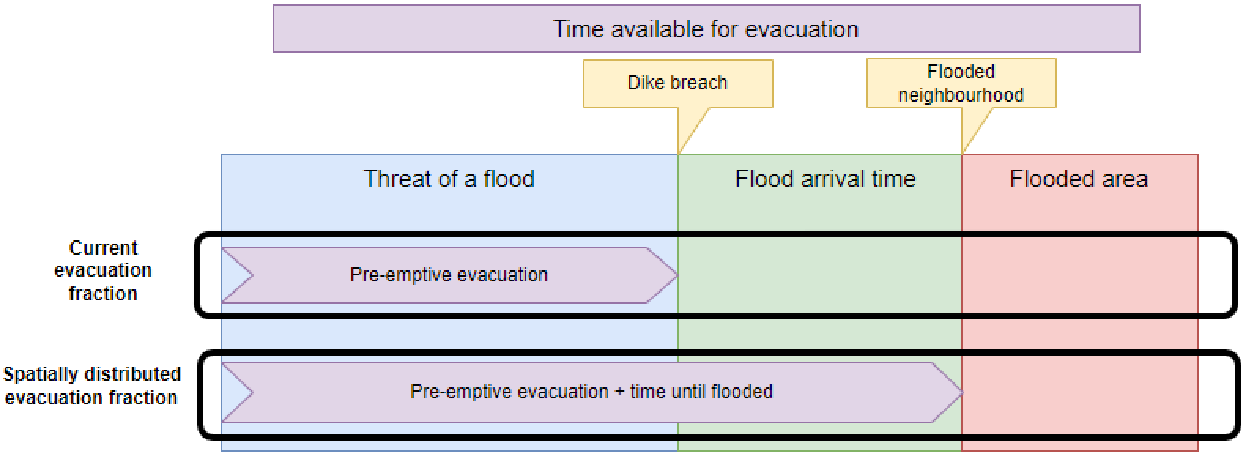

Figure 10. Schematized difference in available time for evacuation between the current method and the proposed method by using spatially distributed evacuation fractions.

The curve “trafficmanagement_dynamic” (appendix B) was used as input for the percentage expected evacuated values between 0-24 hours in the river Rhine area. The reason to use this curve as a baseline for an interpolation for the first 24 hours (see appendix B) is because this is the traffic scenario that is thought to be most realistic (Holterman et al., 2009). As can be seen in figure 7 in the evacuation tree for dike ring 48 any time between 0- 24 hours, 0% evacuation occurs. By including arrival times per neighbourhood in combination with these traffic model results, any time in the interval of 0- 24 hours was analysed and as an extension added to the existing evacuation tree to create spatially distributed evacuation fractions (visualised in appendix C).

For the period of 24 hours from the time of a dike breach occurring, for each time step (with 2-hour intervals) evacuation fraction percentage values were connected to the available time (arrival time of a flood event). By this method the “gap” in the current methodology which does not consider evacuation possibilities for the first 24 hours was filled (shown in appendix B).

The newly defined evacuation fractions per neighbourhood determined by the incorporation of arrival time maps were inserted in a norm calculation sheet in excel as individual evacuation fractions per neighbourhood. Each neighbourhood was now given its individual spatially distributed evacuation fraction (instead of using the lower boundary of 56% for each neighbourhood).

3.3. RQ 3; What are the effects of the spatially distributed evacuation fractions on the flood safety standards?

This research question aims to assess the effects of spatially distributed evacuation fractions on flood safety standards within dike ring 48. The primary objective is to compare the newly developed spatially distributed evacuation fractions, which incorporate arrival times, with the existing evacuation fractions used in the region. This comparison allowed for the re-evaluation of norm section safety standards to determine the impact of the spatially distributed fractions on flood safety standards.

The existing safety standards that correspond with the current evacuation fractions (excluding spatial characteristics) can be found in (Slootjes & Wagenaar, 2016). These safety standards can however be recalculated with the newly developed spatially distributed evacuation fractions determined in research question 2 using a safety standard calculation sheet in excel.

The normative neighbourhood (essential in determining dike section safety standards) was recalculated in excel with the new evacuation fractions according to the LIR safety standards.

The next step in the analysis involved a direct comparison of the existing evacuation fractions with the spatially distributed evacuation fractions and how they change certain safety standard values per dike section considering the LIR norm of 10^{-5}.

The results of the comparison between old and new safety standards were interpreted to understand the effects of the spatially distributed evacuation fractions on flood safety standards. This interpretation considered how the new evacuation fractions could cause certain norm sections in dike ring 48 to fall into a different safety standard category determined by law (Table 8).

Table 8. Safety standard categories (flooding chance) for dike safety standards (Slootjes & Wagenaar, 2016).

Flooding chance category (1/year)	Interval
1/300	> 1/550
1/1.000	1/550 – 1/1.700
1/3.000	1/1.700 – 1/5.500
1/10.000	1/5.500 – 1/17.000
1/30.000	1/17.000 – 1/55.000
1/100.000	1/55.000 – 1/170.000

4. Results.

4.1. RQ 1; How do experts review the current evacuation fraction methodology?

Table 9 gives an overview regarding the key differences/agreements between the safety region, water board and experts that came out of the interviews and how they complement/contradict one another. The interview summaries can be found in the appendix A.

Table 9. Interview summaries.

	Kasper van Zuilekom	Marco van Ravenstein	Jan Bruggink	Kees Jan Leuvenink	Bas Kolen
Role in the determination process of the currently used evacuation fraction.	Helped creating the "evacuation calculator" which is a program that was used to calculate different traffic scenario's (the traffic model results that are used in determining average evacuation percentages).	No active role in the determination process. Safety region is the executing party in case of organising an evacuation	No active role in the determination process. Safety region is the executing party in case of organising an evacuation	Waterboard Rijn & Ijssel played an advisory role in the likelihood of a flood event in the dike area 48	One of the authors of the document used regarding traffic model results, one of the experts in present in the held expert meetings and author of the document in which the determination process is explained
View on the determination process for evacuation fractions.	The determination process can be seen as a political game in which different parties have different views. However, the different parties rely on one another. For that reason, A conservative approach is understandable.	Thinks that the conservative approach in the determination process is smart due to the uncertainty of human behaviour.	No idea regarding the determination process and how this was calculated.	Understands the conservative approach. However, expects when the threat of a flood really gets real, an area will be evacuated even further in advance than expected.	The Evacuation fraction is calculated regarding a bandwidth. However, policy makers often use the lower (most pessimistic) boundary in this bandwidth which counteracts the whole idea behind the bandwidth purpose.
Reason for using conservative evacuation fractions in safety standard determination.	Gives a ballpark value. However, since this value is calculated rather conservatively one can question how realistic certain evacuation fraction values are. For most area's I assume higher evacuation fractions.	Evacuation fractions could be more detailed. Including new inundation (higher) resolution grid maps could update these fractions. However, does not expect large differences	-	Evacuation fractions can be updated (or validated) regarding the new flooding maps made by the D-Hydro model which is the waterboard currently working on.	Still relevant. Thinks there might be some slight changes due to the increase of people, transport possibilities and communication methods. However, this will not make significant changes regarding safety standard calculations
Potential issues in creating spatially distributed evacuation fractions.	It is not realistic that everyone evacuates by car. Which is assumed in these traffic models. For areas in which safety is close by it is realistic that (in case of emergency) a-lot of people for by Bike/foot.	Human behaviour is for the safety region the number 1 worry.	Doubts to what extend you can predict the evacuation fraction. How people will behave is hard to predict, especially in the Netherlands where large evacuation due to floods do not happen	Careful that we shouldn't not make decisions on a couple percentage difference EF, there are too many uncertainties for that.	Does not think that by including arrival times there is a-lot to gain (maybe a 10% difference). The biggest improvement could be made by implementing smart evacuation strategies (vertical evacuation).
View on my proposed research.	Suggests the use of a criteria in which for example inundation depths can change evacuation fraction values next to arrival times. Some places are not critically inundated after one can question if these areas should affect the overall EF (stretching the EF definition)	Agrees with the compartmentation approach of dike ring 48 and calculate the EF for each compartment. However, worries that people will take the same decision at the same time (human behaviour worry).	Mentioned that for any actions the safety region wants clear and short documentation regarding evacuation, as fast, as clear, and as pure as possible in actions.	There is a-lot to gain by creating spatially distributed EF. Especially which areas should be evacuated first regarding different flooding scenario's.	The biggest impact when including arrival times regarding the EF is when you look at floods coming from Germany. The arrival time regarding these scenario's will be significantly large to affect the EF

4.1.1 Answer on RQ 1

In answering research question 1 **"How do experts review the current evacuation fraction methodology?*"***, interviews with experts showed that there are different opinions in the way these norms are calculated and how different evacuation fractions could result in lower dike trajectory norms. The main concern of safety regions is human behaviour in case of a flooding event. The waterboard however, states that their advice to the safety regions is always given as a range of possibilities, which can be argued to be redundant since only the absolute worst-case scenario is to be considered by policy makers. Multiple experts mentioned different solutions in the way evacuation fractions can be improved but also express their doubts in the way these potentially lower flood safety standards will ever be accepted due to the unwillingness of accountability. All parties did however mention their doubts regarding the generalization (using a single evacuation fraction for a rather large area) applied to multiple different dike rings within the "cluster method" in determining evacuation fractions and how this could be improved by looking at dike rings individually. Including arrival times and accessing dike ring 48 individually could therefore result in more accurate new findings regarding spatial evacuation fractions for dike ring 48. And by doing so, instead of generalizing multiple dike rings with similar characteristics with a single evacuation fraction (as is done currently), to create higher resolution evacuation fractions by including flood arrival times.

4.2. RQ 2; What are the effects of a spatial distribution on the evacuation fractions used for dike safety determination?

4.2.1. Creating spatially distributed evacuation fractions

To create spatially distributed evacuation fractions, a spatial distribution is made for the neighbourhoods present in dike ring 48. This was done by analysing the arrival time of a flood regarding multiple flooding scenarios for each dike ring section. The methodology explained in section 2.2 resulted in 4 spatially distributed arrival time per neighbourhood maps for the combined flood scenarios within the 4 dike sections.

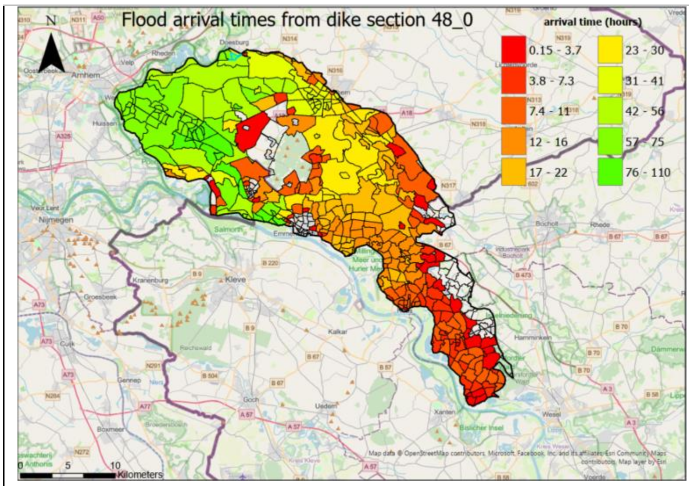

Figure 11. Flood arrival time per neighbourhood for dike section 48_0.

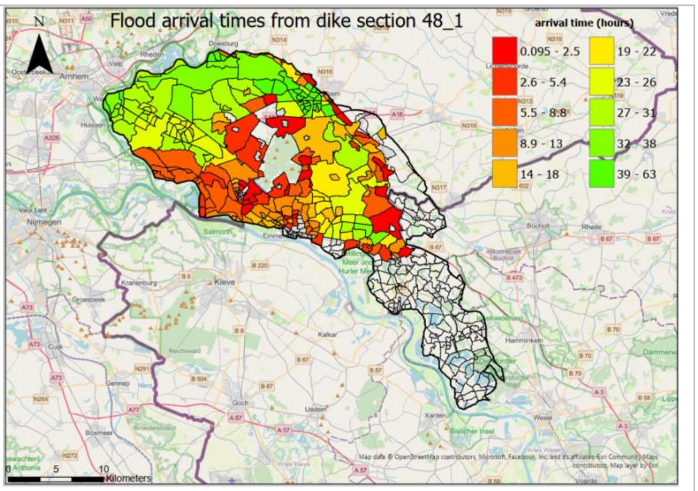

Figure 12. Flood arrival time per neighbourhood for dike section 48_1.

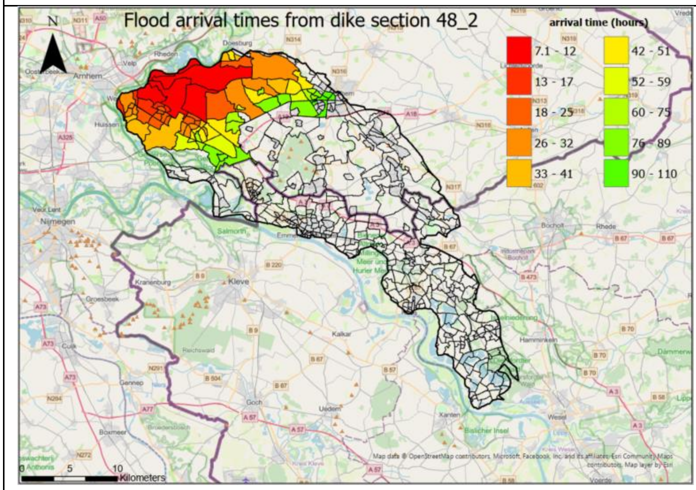

Figure 13. Flood arrival time per neighbourhood for dike section 48_2.

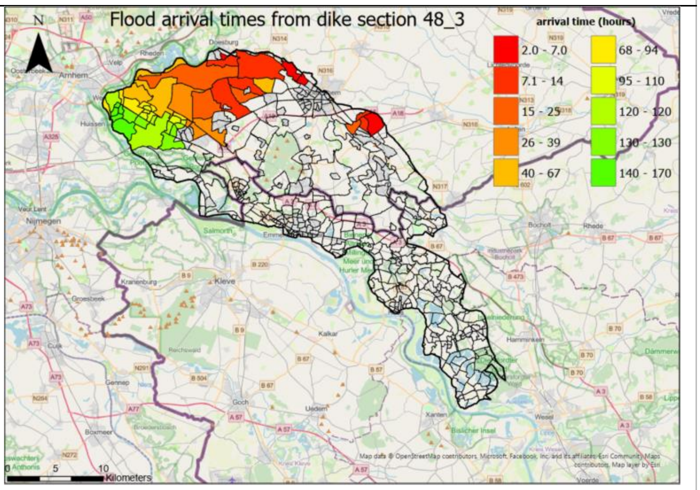

Figure 14. Flood arrival time per neighbourhood for dike section 48_3

The arrival time maps (figures 11-14) are then used to determine an arrival time value per neighbourhood for the four different dike sections. By use of the method explained in section 2.2 the evacuation fraction of every neighbourhood was recalculated. Which resulted in an average expected EF of 90%. Considering the same pessimistic assumptions as used in the current methodology (-20% due to non-response factor) the EF is expected to be 70% which means an increase of +14% on average compared to the existing methodology. This value is however an average for the weighted overlay of each norm section. However, by incorporation of arrival times, each neighbourhood can be given an individual EF. This also means that neighbourhoods that will not be affected by a certain dike breach are given a 100% EF since these neighbourhoods will not be inundated regarding a certain scenario.

The integration of spatially distributed evacuation fractions, informed by detailed arrival time analysis, stands as an important advancement in assessing safety standards within dike ring norm sections. These distributed fractions, determined by examination of flood scenarios and neighbourhood-specific conditions, yield variations in safety standards across the four different dike sections. By incorporating neighbourhoods and their vulnerability to certain flood scenarios, these new standards can not only offer more precise insights into evacuation planning but also underscore the necessity for a nuanced and adaptable approach to dike safety. The data presented here clearly demonstrates the potential for a more accurate representation of risk, making it possible to optimize resources and enhance preparedness for certain communities in the flood-prone areas.

4.2.2. Answer on RQ 2

In conclusion, the investigation into the effects of spatially distributed evacuation fractions within dike ring 48 has presented insights into dike safety determination. The shift from a uniform evacuation fraction to a spatially distributed approach, informed by detailed analyses of arrival times and flood scenarios, shows a significant difference from the traditional methodology. Unlike the previous one-size-fits-all evacuation fraction of 56%, the spatially distributed fractions demonstrate notable variations across neighbourhoods in the dike ring. Depending on the location of a potential dike breach, a neighbourhoods' evacuation fraction can now differ, reflecting the unique spatial characteristics and vulnerability profiles of each area. The recalculated average expected evacuation fraction of 90%, an increase of +14% compared to the existing methodology, shows the effectiveness of this spatially distributed approach in providing a more accurate representation of risk.

4.3. RQ 3; What are the effects of the spatially distributed evacuation fractions on the flood safety standards?

4.3.1. Comparison between the currently used evacuation fractions and newly defined spatially distributed evacuation fractions regarding dike safety standards

In this section the effects of the recalculated signal values and lower boundary LIR values are analysed. In this analysis the spatially distributed evacuation fractions from the previous research question are used to analyse how these spatially distributed evacuation fractions could induce differences in the dike safety standards for the dike sections in dike ring 48.

The four norm sections (see figure 9) in dike ring 48 are determined due to the most stringent norm between the LIR norm and the SCBA norm. Whatever appeared to be the most stringent norm between the LIR norm and SCBA norm determines in which safety category a certain dike section would have to meet the safety standards for. The norm sections within dike ring 48 that have been determined either by SCBA or LIR norm are shown in appendix (F) (Slootjes & Wagenaar, 2016).

By using the individual spatially distributed EF for each neighbourhood, new signal values and lower boundary LIR values regarding safety standards can be calculated for each norm section. This resulted in differences compared to the used signal values for dike safety standard calculations. The results and comparison with currently used signal values and lower boundary LIR values (calculated with 56% EF for each neighbourhood) are given in table 10 and table 11. If it is assumed that that there will be a 20% non-response factor (as is done in the current determination methodology), the signal values and lower boundary LIR values change significantly as can be seen in table 10 and 11. For comparison purposes the signal values and lower boundary LIR values have also been calculated for the old methodology without the 20% non-response assumption.

Table 10. Signal values calculated with evacuation fractions per neighbourhood by including arrival times. Four scenario's are considerened, the current methodology including a 20% non-response faction (row 2) and excluding the 20% non-response factor (row 3), and the new methodology that uses the spatially distributed evacuation fractions including the 20% non-response factor (row 4) and exclusing the 20% non-response factor (row 5).

	Signal value norm section 48_0	**Signal value norm section 48_1**	**Signal value norm section 48_2**	**Signal value norm section 48_3**
Old method (56% EF - 20% due to non-response assumption)	1/8525	1/22584	1/1698	1/856
Old method (expected EF 76% excluding arrival time)	1/4598	1/12179	1/940	1/463
New method Expected EF (EF -20% due to non-response assumption)	1/6070	1/15609	1/1102	1/450
New method Expected EF (including arrival times per neighbourhood)	1/1738	1/4277	1/276	1/111

Table 11. Lower boundary LIR values with evacuation fractions per neighbourhood by including arrival times. Four scenarios are considered, the current methodology including a 20% non-response faction (row 2) and excluding the 20% non-response factor (row 3), and the new methodology that uses the spatially distributed evacuation fractions including the 20% non-response factor (row 4) and excluding the 20% non-response factor (row 5).

	Lower boundary LIR values section 48_0	**Lower boundary LIR values 48_1**	**Lower boundary LIR values section 48_2**	**Lower boundary LIR values section 48_3**
Old method (56% EF - 20% due to non-response assumption)	1/4214	1/11165	1/862	1/425
Old method (expected EF 76% excluding arrival time)	1/2298	1/6090	1/470	1/231
New method Expected EF (EF -20% due to non-response assumption)	1/3166	1/8143	1/575	1/225
New method (expected EF including arrival times per neighbourhood)	1/869	1/2138	1/138	1/55

If the spatially distributed evacuations fraction would be used for norm calculations this would result in lower safety standards. For norm section 48_1 (in which the LIR norm was the most stringent) the LIR norms would be substantially lower as presented in table 13. It has to be stated that the assumption of a 20% non-response factor makes an enormous difference in the calculation of the LIR.

Table 13. Difference in norm class determination by using spatially distributed evacuation fractions. Row 2 showing the scenario in which the 20% non-response factor is excluded, row 3 includes the 20% non-response factor. Columns 4 and 5 show if the method used would cause a shift in norm class compared to the current method and norm class.

Method	Signal value 48_1	Lower boundary LIR value 48_1	Corresponding signal value safety standard class (1/year), (+/- norm class compared to current safety class)	Corresponding lower boundary LIR value safety standard class (1/year), (+/- norm class compared to current safety class)
Using the expected evacuation fraction method	1/4277	1/2138	1/3000	1/3000 **(-1 norm class)**
Using the expected evacuation fraction method -20% non-response factor	1/15609	1/8143	1/10.000	1/10.000 **(-1 norm class)**

As shown in table 13, for the section in which the LIR is most stringent (48_1), the spatially distributed evacuation fractions would cause the safety standards of norm section 48_1 to be decreased by one norm class. This would mean that the LIR norm would fall into the same norm class as the SCBA norm for this dike section, meaning that both norms are normative in determining the safety standard for this dike section. For the other norm sections the LIR value also substantially differ and therefore also fall into a different safety standard norm class (see appendix G).

4.3.1. Answer on RQ 3

The research findings highlight the significant impact of spatially distributed evacuation fractions on flood safety standards within dike ring 48. Currently, norm sections are determined by choosing the most stringent norm between the LIR and the SCBA. However, the introduction of spatially distributed evacuation fractions, incorporating arrival times and neighbourhood-specific conditions, has led to substantial differences in safety standard determinations.

Notably, for norm section 48_1 (determined by the LIR norm), the use of spatially distributed evacuation fractions has resulted in considerably lower safety standards. This implies that both LIR and SCBA norms become normative in determining the safety standard for this particular dike section. This finding has significant policy implications, as it underscores the need for a flexible approach that considers multiple normative standards (both SCBA as LIR norms) for specific dike sections.

In conclusion, the effects of spatially distributed evacuation fractions on flood safety standards are impactful. They challenge traditional norm section determinations and emphasize the importance of considering spatial characteristics in preparedness and response strategies for dike ring 48.

5. Discussion

5.1. Limitations

One of the primary limitations of this study has to do with the assumptions made regarding **human behaviour during flood events**. The assumption that individuals will evacuate based on their proximity to floodwaters, as guided by arrival times, simplifies the complexities of real-world human behaviour during emergencies. In reality, evacuation decisions are influenced by a multitude of factors, including fear, uncertainty, the availability of information, and individual judgment. These aspects are addressed dike safety determination through conservative assumptions (high non response factor and bad evacuation execution), but there is an inherent difficulty in fully capturing the intricacies of human responses during high-stress situations. Therefore, the research's outcomes are subject to variations based on how closely the assumed human behaviour aligns with the actual behaviour of the population in dike ring 48.

Furthermore, the study introduces **conditional probabilities for the matter of evacuation execution**, encompassing three scenarios: minimal, average, and maximum execution. These scenarios serve as essential components in estimating the evacuation fraction and are closely associated with human behaviour. The minimal execution scenario takes a conservative approach, considering potential hindrances that may lead to a lower number of evacuees, such as a higher non-response factor or logistical challenges. In contrast, the maximum execution scenario assumes near-perfect execution of evacuation plans, reflecting an optimistic perspective on the evacuation process. These scenarios capture the range of possibilities in which an evacuation might occur but are inherently tied to the human responses and behaviours of the population in dike ring 48.

As a result, the underlying assumptions about human behaviour and the conditional probabilities for evacuation execution introduce variability and uncertainty into the research outcomes. This variability highlights the complexities associated with predicting human responses during flood events and underscores the need for further exploration and research on this subject, especially within the specific context of dike ring 48.

Another significant limitation that needs to be addressed relates to the **temporal factor in the research**, specifically in the context of the arrival time maps used as input data. These arrival time maps were developed utilizing the Delft-FLS inundation model, which was considered a valuable tool at the time of its creation. However, it should be acknowledged that this model has since been succeeded by the Delft3D Flexible Mesh Suite, known as D-HYDRO, a more advanced and higher-resolution model for hydrodynamic and hydraulic simulations. The use of the D-HYDRO model could result in substantially different inundation patterns, which are integral to the estimation of arrival times and, by extension, the spatially distributed evacuation fractions. Therefore, acknowledging this temporal aspect and considering the potential impacts of transitioning to more advanced modelling tools is noteworthy for interpreting the research findings and their relevance in the current context of flood risk management in dike ring 48.

Another limitation that must be addressed involves the notable **disparity in flood protection standards and policies between the Dutch and German sections** within dike ring 48. In the Netherlands, substantial efforts and investments are being made to upgrade and enhance dike systems to meet the rigorous 2050 standards outlined in the project VNK2. This project is aimed at fortifying flood defences and preparing for future climate challenges, reinforcing the Netherlands' commitment to comprehensive flood risk management. However, this proactive approach to improving dike infrastructure and flood safety measures does not extend to the German portion of dike ring 48, which lacks similar initiatives and investments. Consequently, this difference raises concerns about the resilience and overall effectiveness of the entire dike ring system, as it may leave the German section as a potential weak link. Given its upstream location along the river, the German section could become a focal point for flooding events, as improvements on the Dutch side may increase pressure on this part of the dike ring. As such, evacuation plans must prioritize preparedness for potential flooding originating from the German section, as it remains vulnerable and might continuously be the first point of impact for inundation. These divergent national policies introduce a limitation and necessitate a cross-border perspective in flood risk management strategies.

Another limitation in this study is the absence of detailed consideration for **inundation depths**. While arrival times provide essential insights into evacuation strategies, they do not necessarily reflect the full spectrum of danger posed by floodwaters. Some areas may experience rapid inundation, resulting in a short arrival time, yet the actual inundation depth might only be a few centimetres (visualised in figures 15-18). In such cases, the risk to individuals is relatively low, and evacuation may not be life-threatening or critically necessary. However, the study primarily focuses on arrival times as a sole determinant for evacuation prioritization. The exclusion of detailed inundation depth data, which was outside of the scope of this research, means that the study does not fully capture the nuances of flood risk, potentially leading to the misallocation of evacuation resources. To enhance the precision of evacuation plans, future research should consider integrating inundation depth analysis alongside arrival times, ensuring that danger is comprehensively evaluated.

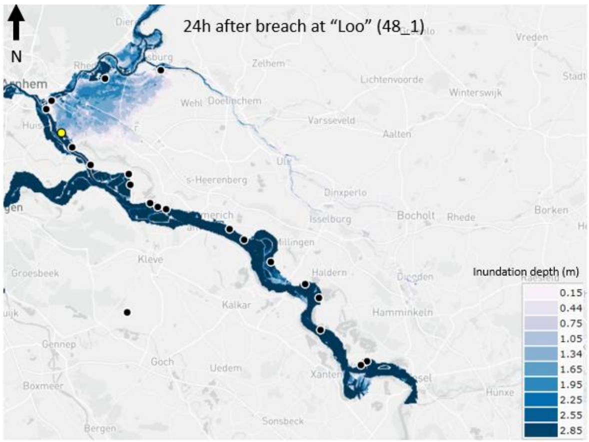

Figure 15. Inundation depth after 24h for a breach at "Loo" (section 48_1).

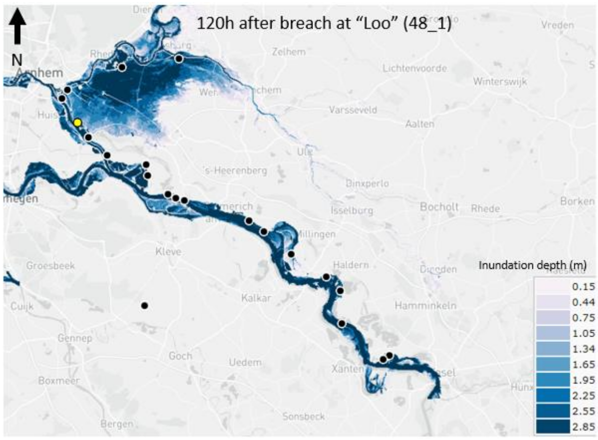

Figure 16. Inundation depth after 120h for a breach at "Loo" (section 48_1).

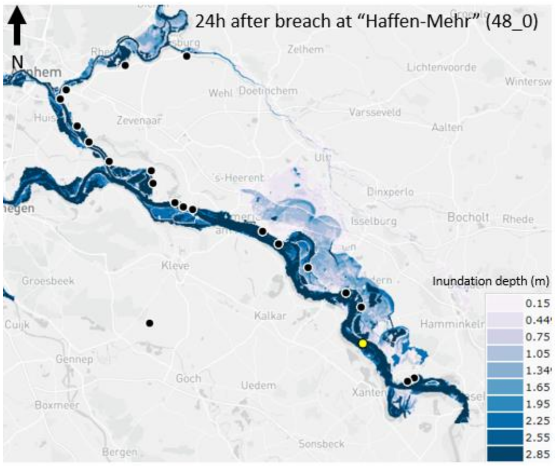

Figure 17. Inundation depth after 24h for a breach at "Haffen-Mehr" (section 48_0).

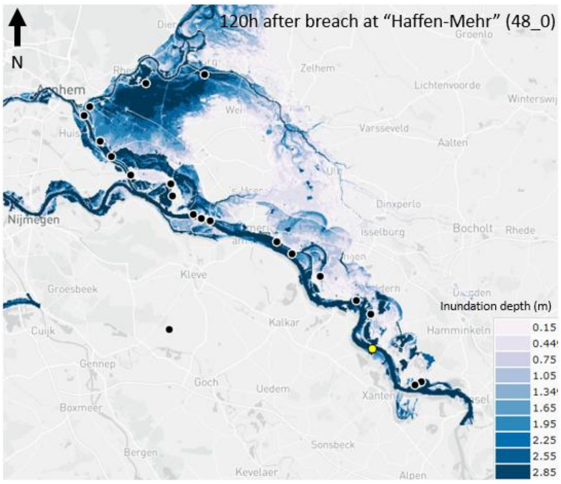

Figure 18. Inundation depth after 120h for a breach at "Haffen-Mehr" (section 48_0).

5.2 Research potential

The research presented in this report carries implications regarding arrival times for practical implementation by policymakers and evacuation planners, providing valuable information for enhancing flood preparedness and response strategies. The incorporation of arrival times into these plans offers several practical benefits as for example explained in the following paragraphs:

The utilization of arrival times allows for the creation of more precise evacuation plans based on real-time information. This information enables authorities to determine which evacuation routes and exits will be inundated (shown in appendix F), either immediately or after a specific duration, during different flooding scenarios. By identifying these details, evacuation planners can develop prioritized evacuation sequences, ensuring that individuals in high-risk areas are evacuated first, followed by those in less vulnerable neighbourhoods (appendix D). This approach optimizes the allocation of resources, minimizes response time, and enhances overall evacuation efficiency.

Furthermore, the order of evacuation based on arrival times provides a comprehensive strategy for focusing assets and resources where they are needed most. Vulnerable neighbourhoods with shorter arrival times to floodwaters can receive prioritized attention in terms of infrastructure improvement, early warning systems, and public awareness campaigns. Such targeted interventions can help save lives and reduce the economic and social impacts of flood events. This approach also ensures that evacuation routes are well-maintained and that the selected exits can accommodate the expected evacuation flow, mitigating congestion and bottlenecks during evacuation.

The research findings also help policymakers to develop more flexible and adaptable policies that consider the unique characteristics of different areas within the dike ring. This flexibility is especially valuable when dealing with a diverse range of flood scenarios and response requirements. Additionally, the ability to determine the inundation patterns in real-time and forecast their evolution over the course of an evacuation can lead to better decision-making during emergency situations.

Incorporating arrival times into evacuation plans and policies can also significantly enhance public awareness and compliance with evacuation orders. Communicating the individualized risk assessments and evacuation priorities to residents provide a better understanding of the potential threats, motivating them to respond promptly to evacuation orders. This approach encourages a sense of community responsibility and cooperation during emergencies.

5.3 Generalization

While this research has provided valuable insights into the integration of arrival times for evacuation planning in dike ring 48, it is noteworthy to consider the generalization of the findings to other dike rings, particularly those with different geographical and environmental characteristics. Dike ring 48 primarily faces the threat of river flooding, which has unique characteristics and dynamics. Therefore, the scalability of the research findings to dike rings located close to the sea, where flood threats are primarily associated with coastal or storm-related events, requires careful consideration. It can however be argued that the research results for dike ring 48 are scalable for the full dike ring cluster “rivers Rhine” since the dike rings within this cluster are considered to have similar characteristics, hence the reason for the use of a single evacuation fraction value for a dike ring cluster in the current evacuation fraction determination. Dike rings with similar aspects like population density and limited evacuation routes like bridges are prime examples for which this research is scalable for.

The study's focus on river flooding raises questions about how applicable the method with arrival times is for dike rings that have a distinct vulnerability profile. Coastal dike rings are exposed to inundation from the sea, often coupled with extreme weather conditions, such as storm surges. The dynamics of these flood events differ from river flooding in terms of onset, intensity, and inundation patterns. Coastal dike rings that are inundated by a storm surge from the sea is likely to be flooded from multiple locations instead of from a single location (dike ring breach from a river induced flood) which results in completely different inundation patterns and thus arrival times. The research conducted here did not account for this type of flooding and the associated complexities, making it necessary to assess the applicability of the arrival time methodology in such contexts.

Despite the specific focus on dike ring 48, the underlying principles and methods employed in this research have the potential for broader application. The concept of utilizing arrival times, spatially distributed evacuation fractions, and inundation scenarios can be adapted for dike rings threatened by coastal or storm-related flooding, with adjustments and considerations for the unique dynamics of these events. These adaptations may involve incorporating additional variables related to coastal conditions, storm forecasts, and other factors specific to sea-based threats.

While this research delved into the specifics of dike ring 48 and its vulnerability to river flooding, it contributes to an exploration of the broader implications of its findings on an international scale. With a background of diverse dike safety determination methods globally, the integration of arrival times into evacuation planning shows unique insights that may enrich the ongoing conversation on global dike safety standards. The comparative analysis presented earlier with Germany, the United States, and the United Kingdom provides context to the international landscape, highlighting the variances in methodologies and underscoring potential areas for improvements. It is important, however, to recognize that this study analysed river flooding, and its applicability to dike rings facing different threats, particularly those located close to the sea, warrants careful examination. Coastal dike rings have to deal with flooding dynamics associated with storm surges and sea-based inundation, demanding a nuanced evaluation of the applicability of the arrival time methodology. This study contributes to the broader international literature on dike safety, offering insights that may be useful for dike rings worldwide, while acknowledging the need for adjustments to accommodate diverse threat profiles and geographical characteristics.

6. Conclusion

Research Question 1 aimed to investigate expert opinions on the current evacuation fraction methodology. Through interviews with professionals from waterboards and safety regions, it became evident that differences in perspectives were largely rooted in issues of accountability. The conservatism observed in the current methodology was found to be influenced by a hesitancy to accept responsibility, highlighting a key challenge in the existing approach to determining evacuation fractions.

Shifting focus to Research Question 2, the study explored the effects of spatially distributed evacuation fractions on dike safety determination. By integrating spatial characteristics, especially arrival times, the research revealed a noteworthy increase in the average expected evacuation fraction from 76% to 90%. This spatial distribution allowed for a more detailed understanding of evacuation needs across different neighbourhoods and flood scenarios. The inclusion of arrival times proved particularly impactful, challenging the uniformity of current evacuation plans and highlighting the potential for a more dynamic and responsive approach.

Research Question 3 undertook a comparative analysis between spatially distributed and current evacuation fractions. The results demonstrated a positive and transformative impact on flood safety standards. Dike ring section 48_1 in particular, experienced a significant decrease, dropping by a full norm class due to the incorporation of arrival times. This comparison underscored the efficiency of spatial refinement in enhancing the precision and adaptability of dike safety determination.

This research successfully met its aim to assess the impact of spatially distributed evacuation fractions on flood safety standards within dike ring 48. By evaluating the current evacuation fraction methodology through expert opinions, introducing spatial characteristics, and incorporating arrival times, the study provided comprehensive insights. The spatially distributed evacuation fractions, informed by detailed arrival time analysis, demonstrated a significant difference from the conservative one-size-fits-all approach. The methodology not only increased the expected evacuation fraction but also highlighted substantial variations in evacuation fractions across neighbourhoods, addressing the unique dynamics of different flood scenarios. Particularly noteworthy was the impact on dike ring section 48_1, where the spatially distributed evacuation fractions led to a full norm class decrease, emphasizing the practical implications of the research outcomes regarding dike safety standard determination. This exploration contributes to advancing flood risk management strategies, advocating for a more customized, adaptable, and effective approach in determining dike safety standards.

7. Recommendations

7.1. Collaboration between water board and safety region

This research uncovers insights that have the potential to reshape flood risk management and evacuation policies. Policy makers play a pivotal role in translating these findings into practical measures that enhance disaster preparedness and community safety. The study proposes a comprehensive approach to implementing these research outcomes:

To begin, policy makers should include the integration of arrival times into determining dike safety standards. This step will transform the static nature of current safety standard determination into dynamic, adaptive methodologies, enhancing the resolution of spatially explicit dike safety standards.

An aspect to consider is how the results of this research could influence the decision-making process regarding dike strengthening projects. The findings may suggest that a significant portion of dike ring 48 can meet LIR norms with the inclusion of arrival times and effective evacuation planning. This might provide an economic alternative to extensive dike strengthening projects, which are often costly and resource intensive. Instead, decision-makers could prioritize improving evacuation management planning and disaster preparedness measures to ensure compliance with LIR norms. Such measures could include enhanced public awareness campaigns, investment in evacuation infrastructure, and the development of efficient communication strategies. This approach not only aligns with the enhanced focus on evacuation strategies but also contributes to a more resource-efficient and economically viable solution to flood preparedness and response. Therefore, the economic perspective in implementing the research findings extends beyond flood safety standards to reshape how policymakers and stakeholders approach flood risk management.

Another recommendation revolves around identifying and focusing on critical neighbourhoods within dike ring clusters. These areas, often characterized by limited self-reliance, require special attention. Comprehensive assessments of their needs and vulnerabilities are important, and policy makers should invest in initiatives aimed at enhancing self-reliance. Public awareness campaigns, community-based disaster preparedness programs, and targeted resources allocation can all contribute to this goal.

Furthermore, it is noteworthy for policy makers to recognize the importance of effective communication strategies. Evacuation plans should be communicated to residents in a way that considers individual risk levels. Tailoring communication to specific neighbourhoods and their characteristics can significantly increase the understanding and compliance of residents with evacuation orders.

The economic implications of implementing arrival times should not be overlooked. Policy makers should consider conducting comprehensive economic assessments to understand the potential impact of lower dike norms on property values, insurance premiums, and infrastructure investments. These findings will contribute to making informed decisions related to flood risk management.

As mentioned in the state-of-the-art chapter Germany is moving towards a more integrated flood management approach that has similarities than the methodology of the Netherlands. Cross-border collaboration for dike safety standards between the Netherlands and Germany, especially for dike rings that overlap on both countries, can be made uniformly as both countries are moving towards similar flood management strategies. A uniform approach for these overlapping dike rings will prevent weak spots in the dike ring and enhance effective flood management for dike ring areas as a whole.

Finally, policy makers should also explore disaster management and preparedness initiatives. These measures can complement or even replace costly dike strengthening projects and improve community resilience. The focus should shift from merely strengthening dikes to a more comprehensive approach that includes strengthening community readiness and response capacity.

7.2. Recommendations for future research

This study offers valuable insights into the integration of arrival times into flood risk management. However, there are several areas for future research to build upon these findings, contributing to a more nuanced and comprehensive understanding of disaster preparedness.

Firstly, future research should consider the integration of updated traffic models and inundation models. The traffic models used in this study, although effective, may have certain limitations. Up-to-date models can provide more accurate representations of evacuation scenarios. Additionally, the incorporation of the latest inundation models is essential to understanding the extent and depth of flooding in different areas, which can significantly affect evacuation strategies.

Secondly, future studies can explore smart location-specific evacuation strategies. Not all neighbourhoods face the same dangers in the event of flooding. By considering the unique characteristics, vulnerabilities, and self-reliance of different neighbourhoods, researchers can develop tailored evacuation plans. This approach ensures that resources are allocated efficiently, focusing on the area’s most in need of assistance during evacuations. Furthermore, the non-response factor regarding this location specific exploration should be re-evaluated since the research showed that this factor has a strong influence on the calculation of eventual dike safety standards.

Thirdly, this research primarily focused on arrival times as an indicator of evacuation urgency. Future studies could expand on this by incorporating inundation depths. This added dimension can provide more detailed information about the actual danger residents face, taking into account factors like water depths and rise rates. Such research can result in evacuation strategies that prioritize the most life-threatening situations, rather than just considering proximity to floodwaters.

Finally, an important area for future research involves conducting in-depth economic assessments of implementing arrival times in SCBA analysis. Arrival times of floodings mainly influence the LIR determination but also to a lesser extent influence the SCBA. This includes assessing the impact on property values, insurance premiums, and infrastructure investments. A thorough understanding of the economic consequences can help policymakers make well-informed decisions regarding disaster preparedness and evaluate SCBA and LIR norms with one another by including arrival times.

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Appendices

A 1.1 Average evacuation fraction calculation results for dike ring 6 (example case)

Table 12 Evacuation percentages for dike ring 6 (example case in the report)

	Evacuation percentages (%)		
Time for high water	Minimum	Average	Maximum
1 day	0	0	0
2 days	29	46	64
3 days	51	78	95
4 days	68	95	100

A 1.2 Calculation expected evacuation fraction for dike ring 48

Table 13. Contribution to expected evacuation fractions for different available time periods and their conditional chances of occurrence as well as the effectiveness of execution for the evacuation fractions in dike ring 48.

Amount of available days	Cond. Chance for available time	Cond. Chance of execution	Evacuation fractions of the execution (%)	Contribution to expected evacuation fraction (%)
4	0	0	100	0
4	0	0	100	0
4	0	0	100	0
3	0.2	0.2	100	4
3	0.2	0.6	99	11.88
3	0.2	0.2	94	3.76
2	0.5	0.2	100	10
2	0.5	0.6	98	29.4
2	0.5	0.2	90	9
1	0.2	0.2	96	3.84
1	0.2	0.6	85	10.2
1	0.2	0.2	66	2.64
0	0.1		0	0
Expected evacuation fraction				**~85%**

A 1.3 Conservative calculation expected evacuation fraction dike ring 48

Table 14. The contribution to the expected evacuation fraction for different available time periods regarding flooding, considering the worst-case scenario regarding conditional probabilities.

Amount of available days	Cond. Chance for available time	Cond. Chance of execution	Evacuation fractions of the execution (%)	Contribution to expected evacuation fraction (%)
4	0	0	100	0
4	0	0	100	0
4	0	0	100	0
3	0.2	0	100	0
3	0.2	0	99	0
3	0.2	1	94	18.8
2	0.5	0	100	0
2	0.5	0	98	0
2	0.5	1	90	45
1	0.2	0	96	0
1	0.2	0	85	0
1	0.2	1	66	13.2
0	0.1		0	0
Expected evacuation fraction				**~76%**

A 1.4 Written out interviews

A 1.4.1 Written out interview Bas Kolen

The interview with Bas Kolen, an expert in evacuation and evacuation fraction determination, provided a comprehensive understanding of the intricacies and challenges involved in flood management and evacuation planning in the Netherlands.

One of the central themes that emerged from the interview was the universal use of evacuation curves for all dike rings. Regardless of individual circumstances, these curves are applied uniformly due to a lack of differentiation between dike rings. This approach simplifies calculations but overlooks potential variations in evacuation effectiveness, raising questions about its appropriateness.

Another notable insight was the resistance to lowering evacuation norms. Bas Kolen highlighted the reluctance among stakeholders and board members to accept lower norms, even if they might lead to more frequent flooding. This resistance underscores the political and economic factors that influence evacuation planning.

The interview also shed light on the significant challenge posed by the uncertainty of arrival times during evacuations. Factors such as the width of breach locations and water height make precise determinations difficult. Bas Kolen suggested that it might be problematic to adjust evacuation fractions based on arrival times due to this uncertainty.

In terms of strategy, Bas Kolen stressed the importance of adaptive and flexible evacuation plans. He advocated for prioritizing vertical evacuation and creating real-time risk maps to guide decision-making during emergencies. This approach aligns with the idea that safety regions should empower individuals to take responsibility for their own safety and be prepared to save themselves.

The complexity of mortality functions was also discussed. These functions, which depend on variables like water depth and flow velocity, are challenging to validate due to the infrequency of floods in the Netherlands. This adds another layer of uncertainty to evacuation planning.

Looking to the future, ongoing efforts are being made to validate norms and consider factors like increased road capacity and population growth. However, the potential for re-assessing evacuation fraction norms remains debatable, suggesting that existing norms may persist.

In conclusion, the interview with Bas Kolen underscored the multifaceted nature of flood management and evacuation planning in the Netherlands. It highlighted the tension between simplifying calculations and accounting for variations in evacuation effectiveness. The resistance to lowering norms, the uncertainty of arrival times, and the complexities of mortality functions all contribute to the challenges faced in this field. The emphasis on adaptive and flexible evacuation strategies, along with the need for real-time risk assessment, reflects a growing awareness of the need to empower individuals and improve overall preparedness in the face of changing circumstances and uncertainties.

A 1.4.2 Kasper van Zuilekom

Summary of Interview with Kasper van Zuilekom, Traffic Expert, on Evacuation Fractions and Traffic Management

The interview with Kasper van Zuilekom, a traffic expert, provided valuable insights into the complexities of determining evacuation fractions and the crucial role of traffic management in the evacuation process.

One of the key points emphasized by Mr. van Zuilekom was that evacuation fractions are an outcome of the evacuation process. He highlighted that traffic management plays a pivotal role in shaping these fractions. Several scenarios are considered in this process, including preventive evacuation (equal distribution over exits), proximity-based evacuation (closest exit), and traffic management scenarios that account for road capacity and avoid crossing traffic streams. The timing of the evacuation start, known as the "vertrekprofiel," is also a critical factor.

Capacity restrictions, particularly regarding exits, were noted as essential considerations in the evacuation planning process. Traffic bottlenecks can significantly impact the efficiency of evacuations.

Mr. van Zuilekom stressed the importance of minimizing vehicle kilometers (voertuig kms) during evacuations. Efficient routing and traffic management are key to achieving this goal.

He mentioned the possibility of creating a map using his methods, although it was acknowledged that this might delve too deeply into the traffic domain.

Another noteworthy point raised was the political aspect of evacuation fractions. In cases like the Randstad in the Netherlands, practical constraints make it unfeasible to evacuate everyone during extreme events like storm surges or heavy precipitation. Evacuation fractions are, to some extent, influenced by these practical limitations.

Assessing the cost-effectiveness of flood management projects relative to potential flood damage was suggested as a valuable approach. This involves evaluating how much damage a flood could cause in relation to the cost of strengthening dikes and other protective measures.

Guiding people during evacuations was identified as an ongoing challenge, emphasizing the need for effective communication and planning.

The interview revealed that safety regions ultimately determine evacuation fractions, often relying on expert advice from Mr. van Zuilekom. However, he noted that a significant amount of "gut feeling" is still used in this decision-making process.

For Mr. van Zuilekom's own expert judgment, he proposed considering "taakstelling" (task assignment) by assessing inundation depths to determine whether people can evacuate vertically and establishing how many people must evacuate to meet acceptable criteria.

The interview also highlighted the importance of simulation environments for safety regions, such as SPOEL (Simulation Program for Evacuation Operations in the Netherlands), developed by HKV.

Lastly, it was acknowledged that expecting everyone to evacuate by car is not 100% realistic, emphasizing the need for diversified transportation options in evacuation planning.

In conclusion, Kasper van Zuilekom's insights underscored the intricate relationship between traffic management and the determination of evacuation fractions. His expertise highlighted the significance of efficient routing, capacity planning, and the practical challenges involved in evacuation processes. Additionally, the interview revealed the blend of technical analysis and practical judgment that informs the decision-making process for evacuation fractions, which ultimately aim to balance safety and feasibility during emergency situations.

A 1.4.3 Jan Bruggink

Summary of Interview with Jan Bruggink, Policy Advisor for Safety Region Gelderland Noord-Oost, on Evacuation and Safety Region Practices

The interview with Jan Bruggink, a policy advisor for Safety Region Gelderland Noord-Oost, provided insights into the practices and perspectives of safety regions, particularly in the context of evacuation and flood management.

Jan Bruggink highlighted the safety region's emphasis on clear, concise, and rapid documentation for evacuation actions. The region prioritizes efficient and transparent communication during emergencies.

Regarding the determination of evacuation fractions, Mr. Bruggink admitted to having no specific insights, indicating that this aspect may not be within the safety region's purview.

A prominent principle guiding safety region decisions is the "better safe than sorry" approach, emphasizing a proactive stance in ensuring public safety.

Collaboration is a key theme, with safety regions working closely with neighboring regions and water boards. Joint efforts are made to develop generic flood plans and realistic assessments of potential evacuees and those who may stay behind.

Mr. Bruggink acknowledged the changing dynamics of mobility and self-reliance among the population, suggesting that evacuation fractions for specific dike rings might be less relevant, as the safety region is likely to initiate evacuations.

Safety regions rely on National Dutch NAP (Normal Amsterdam Level) levels, particularly regarding Lobith, and value advice from the water board. During critical high-water waves, the safety region primarily focuses on communication and organization, with an emphasis on evacuating floodplains.

Decisions regarding evacuation routes are determined by the Regional Operational Team (ROT) in real-time based on the breach location. Inundation depth is considered, but arrival times are not a primary factor in the safety region's decision-making process.

Local residents often know their evacuation routes, while the safety region provides general guidance on potential routes to be used in emergencies.
Jan Bruggink clarified that the evacuation process is primarily handled by the police in practice. Safety regions play a preparatory role in planning and contribute to decision-making during emergencies.
Crisis communication was highlighted as a crucial aspect of interacting with the public, with a focus on proactive communication to inform and reassure citizens.
A team within the safety region addresses human behaviour in crisis situations, with particular attention to fire risks, but the topic of human behaviour in flood situations is expected to be addressed in the future.
The interview revealed that the new evacuation plan is less detailed compared to the old one. This change reflects the safety region's belief that detailed advance planning may not be practical since decisions are often made on the fly during emergencies. The focus is on clarity regarding plans that must be executed without delay.
Jan Bruggink expressed a need for concise maps that display information such as population density, inundation depths, arrival times, and critical infrastructure. This request highlights the importance of visual aids in decision-making.
Overall, the safety region operates with a practical mindset, prioritizing immediate life-saving measures over extensive planning. Flooding is not a primary concern for the safety region, which primarily activates its resources when emergencies occur, rather than focusing on potential damage or long-term flood management.

A 1.4.4 Marco van Ravenstein

Summary of Interview with Marko van Ravenstein, Policy Advisor for Flooding in Safety Region Gelderland Midden
The interview with Marko van Ravenstein, a policy advisor specializing in flooding for Safety Region Gelderland Midden, offered valuable insights into the practices and challenges of safety regions, particularly in relation to evacuation and flood management.
Mr. Van Ravenstein expressed concerns about the effectiveness of safety regions' communication with the public. He noted that technological advancements have made it challenging to predict how well people will adhere to evacuation instructions, and this may not have improved over the years. The expectation that everyone will act simultaneously due to technology-related factors raises concerns for safety regions.
Despite not directly using tools like SPOEL and the evacuation calculator, Mr. Van Ravenstein explained that the thought model behind the evacuation calculator remains relevant. This includes considerations such as converging traffic and optimizing road and exit capacities.
He highlighted the evolution of decision-making processes over the years. In the past, decisions were made on the fly, with a reliance on elevation maps. However, contemporary approaches involve comprehensive evacuation plans and detailed maps. Evacuation fractions are often determined using estimates, and it is expected that approximately 80% of the population will evacuate in planned scenarios.
Mr. Van Ravenstein discussed the complex decision-making process surrounding evacuations, emphasizing the need for pre-emptive actions. He noted that the final decision to evacuate rests with the chair of the largest municipality (e.g., Arnhem for Dijkring 48), and collaboration with neighboring regions, including Germany, is essential.

He recommended reaching out to experts such as Bas Kolen and Durk Rietstra, who have worked on pilot projects to increase evacuation fractions for Dijkring 48. However, safety regions have doubts about the practical applicability of the calculations used in these pilots.

In terms of dike norms, Mr. Van Ravenstein mentioned that safety regions are primarily concerned with the safety of the people within the dike ring rather than the specific calculations used for dike norms. Collaboration between the Netherlands and Germany is strong, but differences in dike strength make direct comparisons challenging.

The safety region's main objective is to minimize casualties. They advise rather than force people to evacuate and encourage self-sufficiency for those who choose to stay behind.

Mr. Van Ravenstein discussed the possibility of compartmentalization for evacuation planning, but acknowledged that people tend to make similar decisions regardless of their location, which complicates this approach.

Vertical evacuation was considered challenging for this region due to a lack of tall buildings. Moreover, high-water events often occur during winter, increasing the risk of hypothermia for evacuees moving through cold water.

Inundation scenarios have been developed, and more detailed scenarios with spatially distributed grids are expected. While the safety region has made plans for specific water levels, Mr. Van Ravenstein suggested that these plans should be made public to enhance public awareness and understanding.

The interview outlined specific actions taken at different water levels, with alert thresholds starting at +13m NAP (Normal Amsterdam Level) and involving various agencies, including the police, fire department, and regional operational teams (ROT). A decision to evacuate is typically made at +16.50m NAP.

Mr. Van Ravenstein expressed concerns about potential congestion during evacuations, speculating that if one compartment evacuates, others may follow suit, potentially leading to results similar to current evacuation fractions.

The safety region's biggest risk is the possibility of delayed decision-making and simultaneous mass evacuation, leading to congestion and traffic problems.

He emphasized the importance of making government information public to raise awareness among citizens, ultimately leaving the decision to evacuate or not in their hands.

A 1.4.5 Kees Jan Leuvenink

Summary of Interview with Kees Jan Leuvenink, Policy Advisor for Flooding at Waterboard Rijn & IJssel

The interview with Kees Jan Leuvenink, a policy advisor specializing in flooding for Waterboard Rijn & IJssel, provided insights into the waterboard's role, collaboration with safety regions, and flood management strategies.

Waterboard Rijn & IJssel is in the process of creating new flooding maps using the DeHydro model to update flooding scenarios with spatially distributed. This effort aims to provide more accurate predictions of flood-related parameters.

Kees Jan Leuvenink mentioned that a study, possibly by Bas Kolen, highlighted that the criteria used in existing models may not meet the Long-term Improvement and Reinforcement (LIR) norms for 2050. However, the inclusion of updated scenarios with higher resolutions could potentially help satisfy these norms.

For Dike Ring 48, economic damage is the primary contributor to the LIR norms, implying that increasing the evacuation fraction may not have a significant impact on these norms.

The waterboard plays a crucial role in updating safety regions on the movement of water, including inundation depths and flood propagation times. They provide detailed maps and information, especially concerning how long it takes for certain areas to become inundated by specific water levels. The waterboard collaborates with safety regions to explain their expectations and share flood-related components.

In advance, the waterboard considers the impact of flooding on main infrastructure, such as the A12 highway. However, decisions regarding neighbourhood-level actions are often made in real-time or "on the fly."

While safety regions tend to consider worst-case scenarios, the waterboard works with information ranges, reflecting a cultural difference in their approaches.

Kees Jan mentioned the challenge of predicting and simulating human behaviour during a flood, which remains highly unpredictable.

The waterboard is exploring possibilities for steering water, such as using large bags to delay its progress. This could potentially buy more time for crucial infrastructure, like the A12, before it becomes inundated.

The expectation is that in truly alarming situations, areas will be evacuated days in advance of a dike breach, considering the infrequency of such events.

The waterboard's primary concern is the scenario where multiple dike breaches occur during a 1/500 flood event, which could lead to extensive damages. This is a significant worry despite not being a common consideration.

Dike rings often share similar norms, which means that a critical flood can pose dangers at multiple locations, necessitating careful planning.

The waterboard has a "draaiboek" outlining the intensity of dike inspections, which become stricter as the danger level increases.

Preventive evacuation plans are prepared in advance, especially for villages close to the dike, while further inland areas of Dike Ring 48 may not require such measures.

The waterboard is cautious about sharing flood-related information due to the potential misinterpretation by the public, as well as legal concerns regarding damage claims.

Kees Jan Leuvenink expects that the conclusion drawn from his information will be that some areas are more evacuable than previously thought, with the potential for improvement in evacuation planning. However, he advises caution against working with small percentage differences, as even a small improvement in evacuation readiness can make a significant difference in critical situations.

The waterboard believes that while there may not be a substantial difference in economic damage due to continued urban expansion in low-lying areas, there is room for improvement in evacuating people effectively, particularly in areas vulnerable to flooding.

B Evacuation curves dike ring 48.

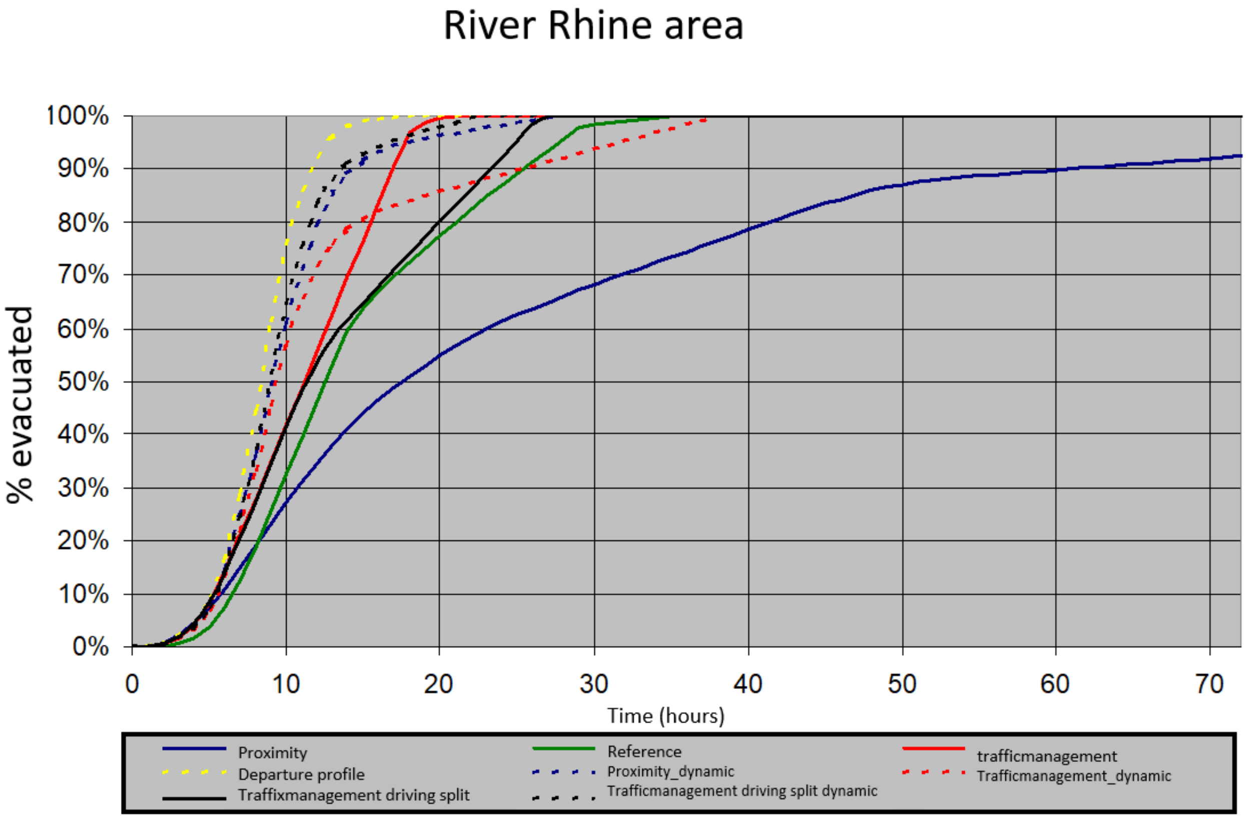


Figure 19. Evacuation curves dike ring 48 (Kolen et al., 2008)

C Location of added value by incorporating the first 24 hours of available time for evacuation regarding arrival times using the existing evacuation fraction methodology.

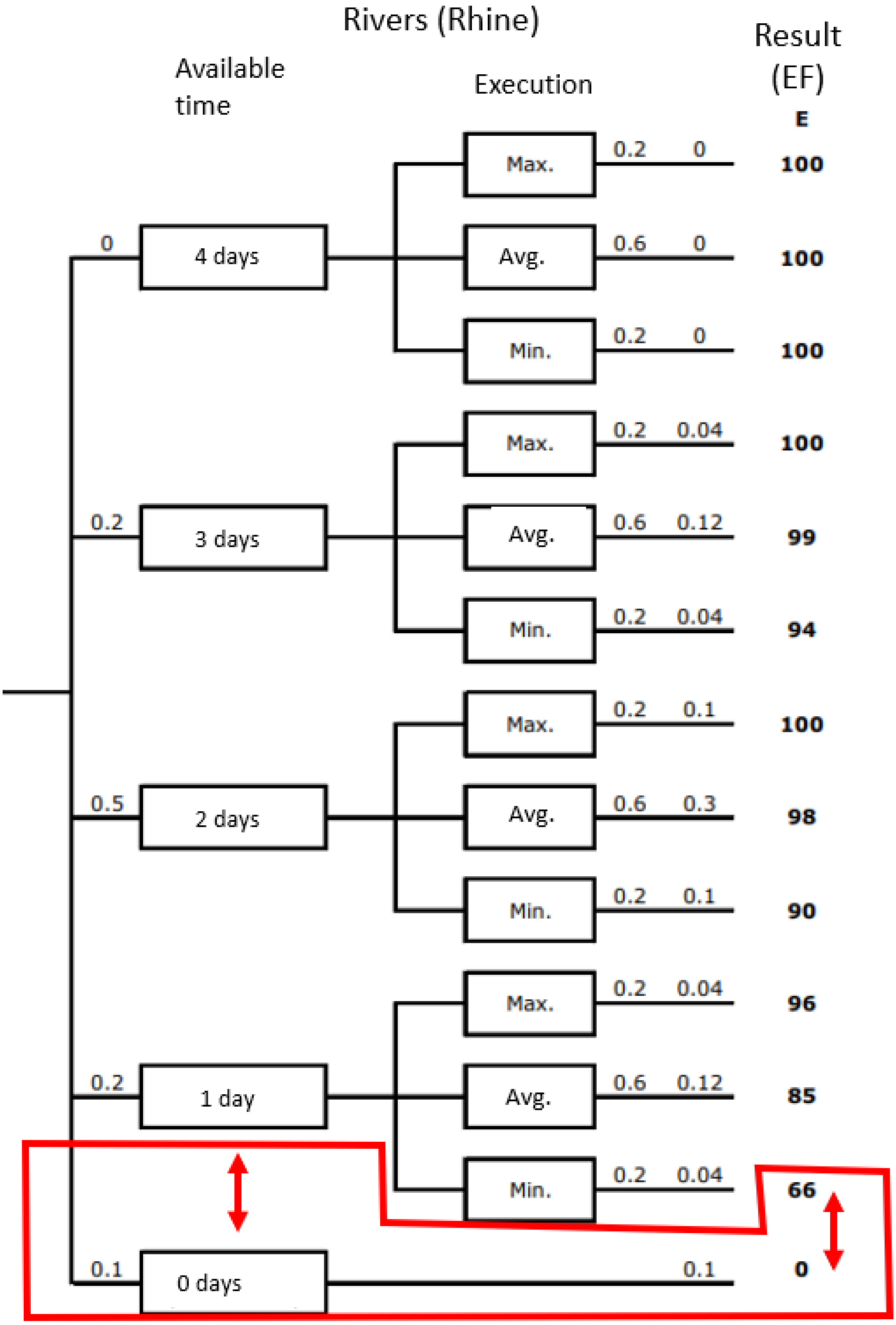
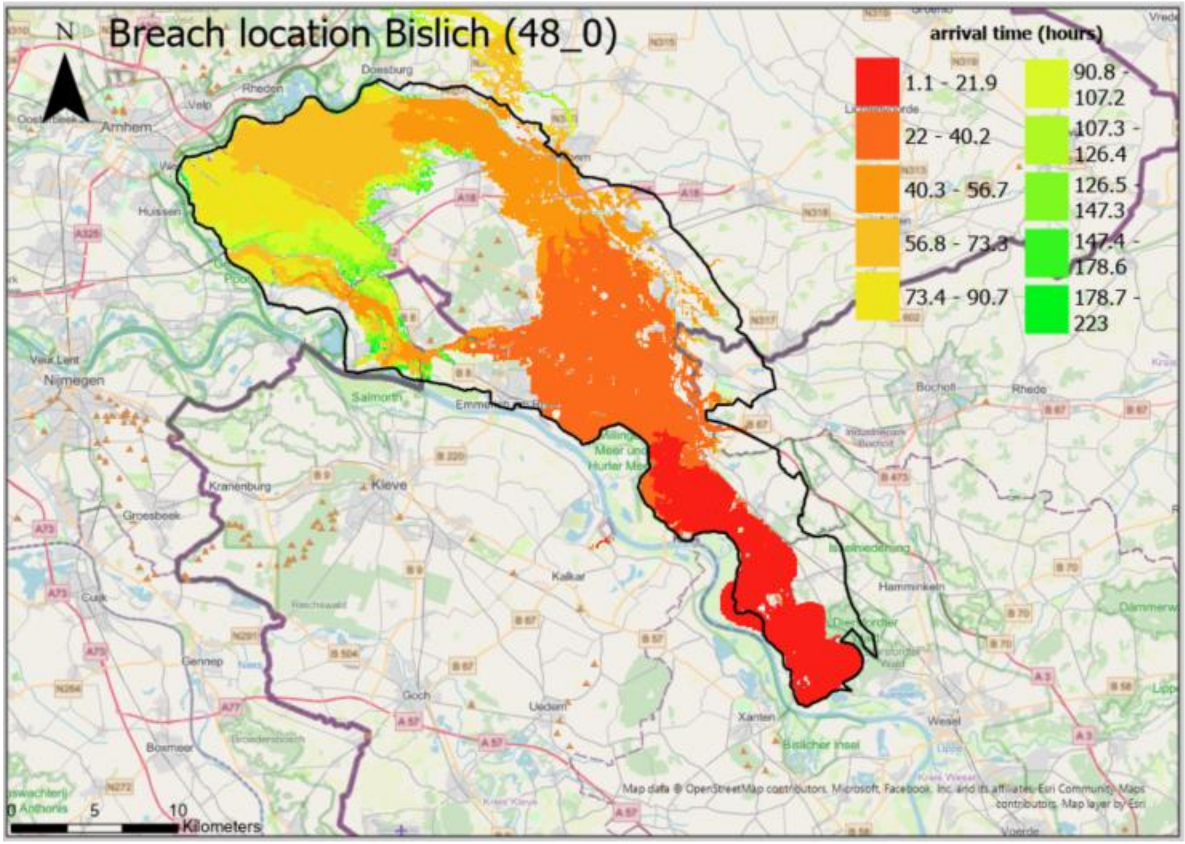


Figure 20. Location of added value by incorporating the first 24 hours of available time for evacuation regarding arrival times using the existing evacuation fraction methodology.

D Flood scenarios per breach location per norm section used to create a weighted overlay

D 1.0 Considered flood scenario’s norm section 48_0


Breach location Bislich (48_0)
N
arrival time (hours)
1.1 - 21.9
22 - 40.2
40.3 - 56.7
56.8 - 73.3
73.4 - 90.7
90.8 - 107.2
107.3 - 126.4
126.5 - 147.3
147.4 - 178.6
178.7 - 223
0 5 10 Kilometers
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Kleve
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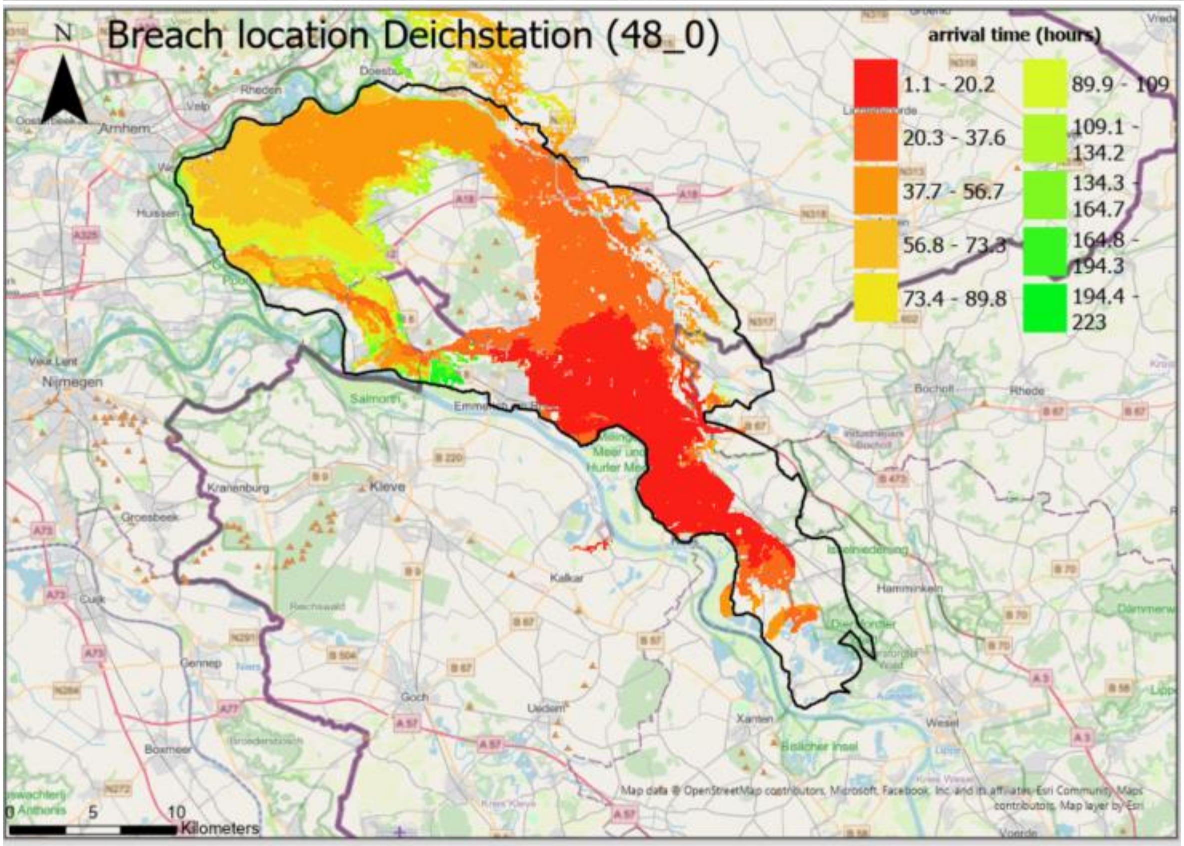
Breach location Deichstation (48_0)
N
arrival time (hours)
1.1 - 20.2
20.3 - 37.6
37.7 - 56.7
56.8 - 73.3
73.4 - 89.8
89.9 - 109
109.1 - 134.2
134.3 - 164.7
164.8 - 194.3
194.4 - 223
0 5 10 Kilometers
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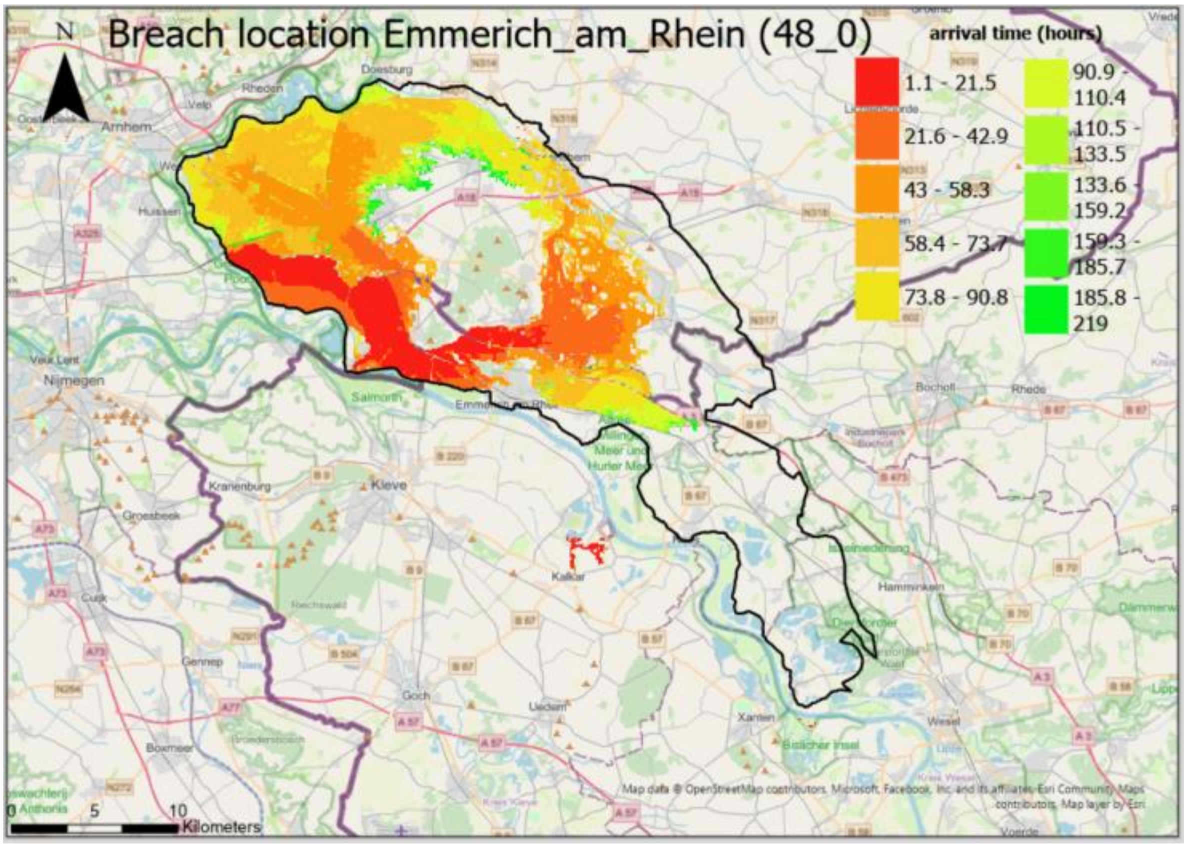
N
Breach location Emmerich_am_Rhein (48_0)
arrival time (hours)
1.1 - 21.5
21.6 - 42.9
43 - 58.3
58.4 - 73.7
73.8 - 90.8
90.9 - 110.4
110.5 - 133.5
133.6 - 159.2
159.3 - 185.7
185.8 - 219
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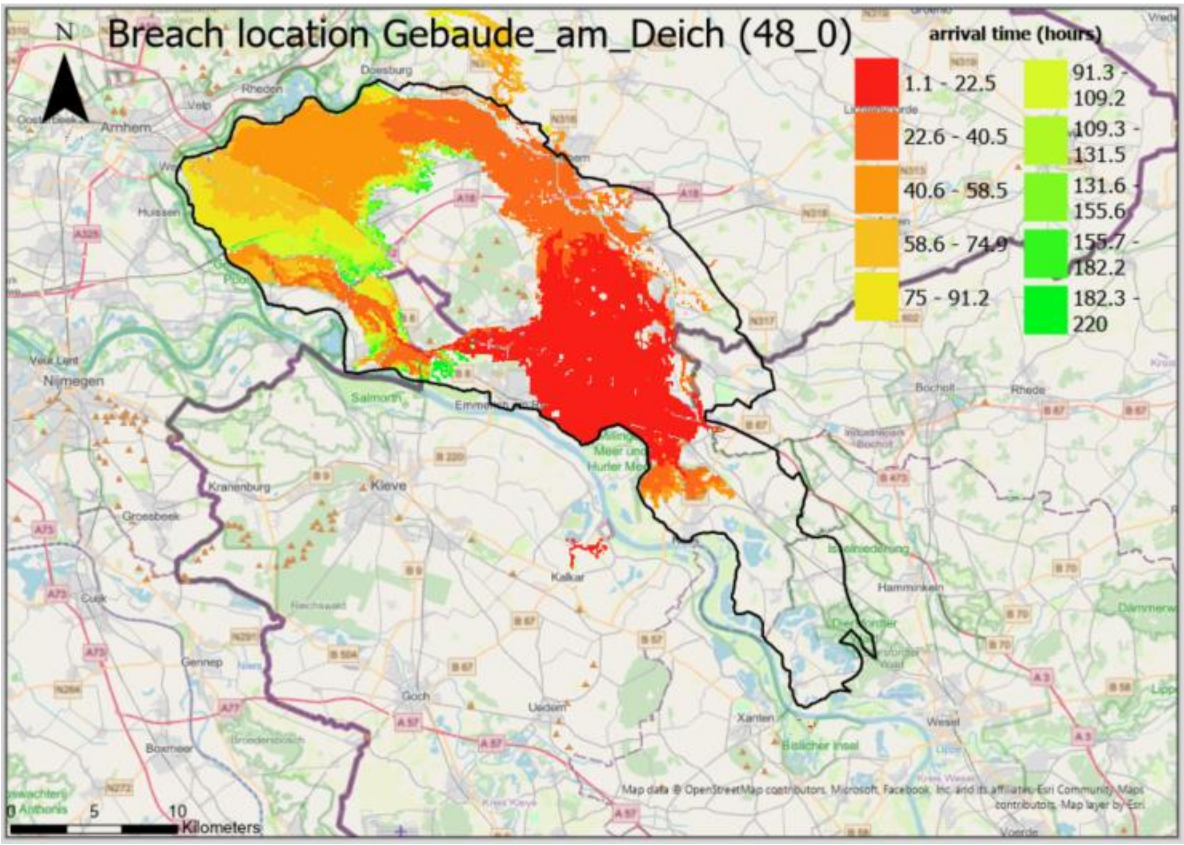
N
Breach location Gebaude_am_Deich (48_0)
arrival time (hours)
1.1 - 22.5
22.6 - 40.5
40.6 - 58.5
58.6 - 74.9
75 - 91.2
91.3 - 109.2
109.3 - 131.5
131.6 - 155.6
155.7 - 182.2
182.3 - 220
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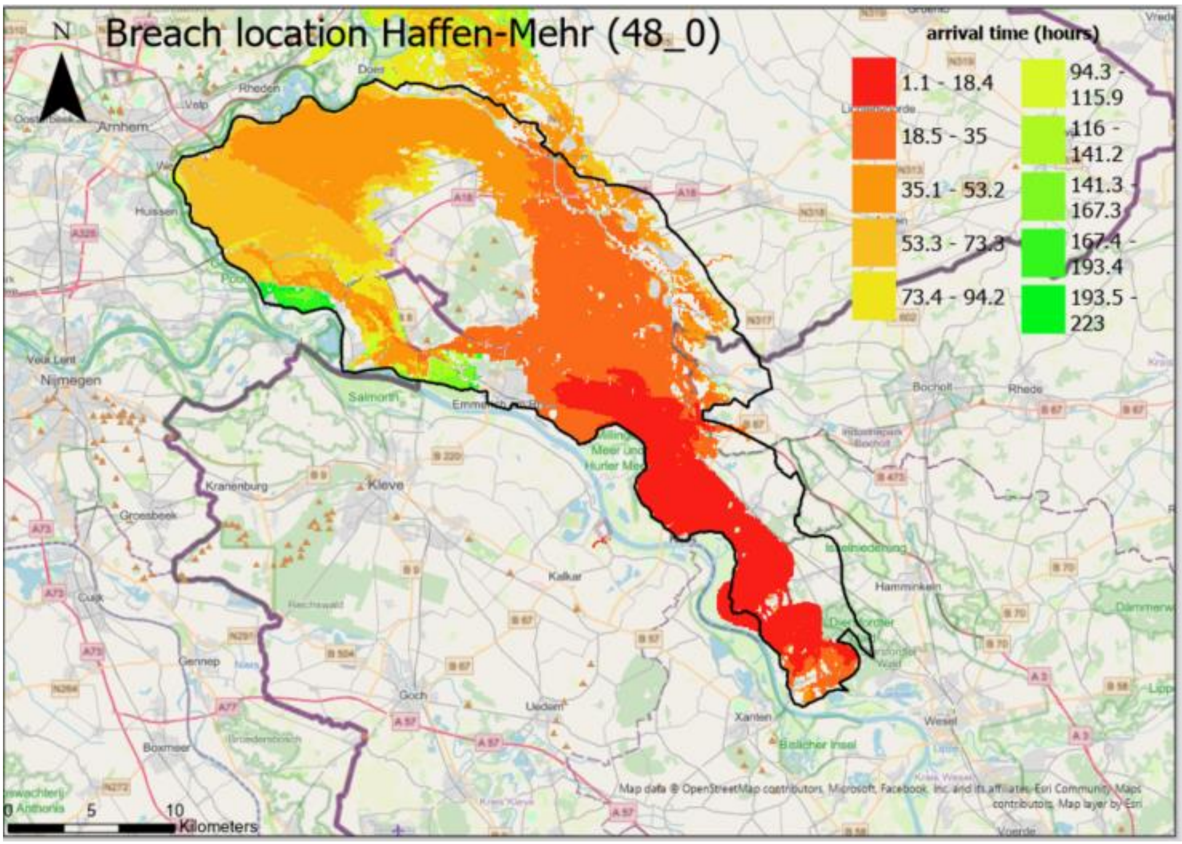
N
Breach location Haffen-Mehr (48_0)
arrival time (hours)
1.1 - 18.4
18.5 - 35
35.1 - 53.2
53.3 - 73.3
73.4 - 94.2
94.3 - 115.9
116 - 141.2
141.3 - 167.3
167.4 - 193.4
193.5 - 223
0 5 10 Kilometers
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Gennep
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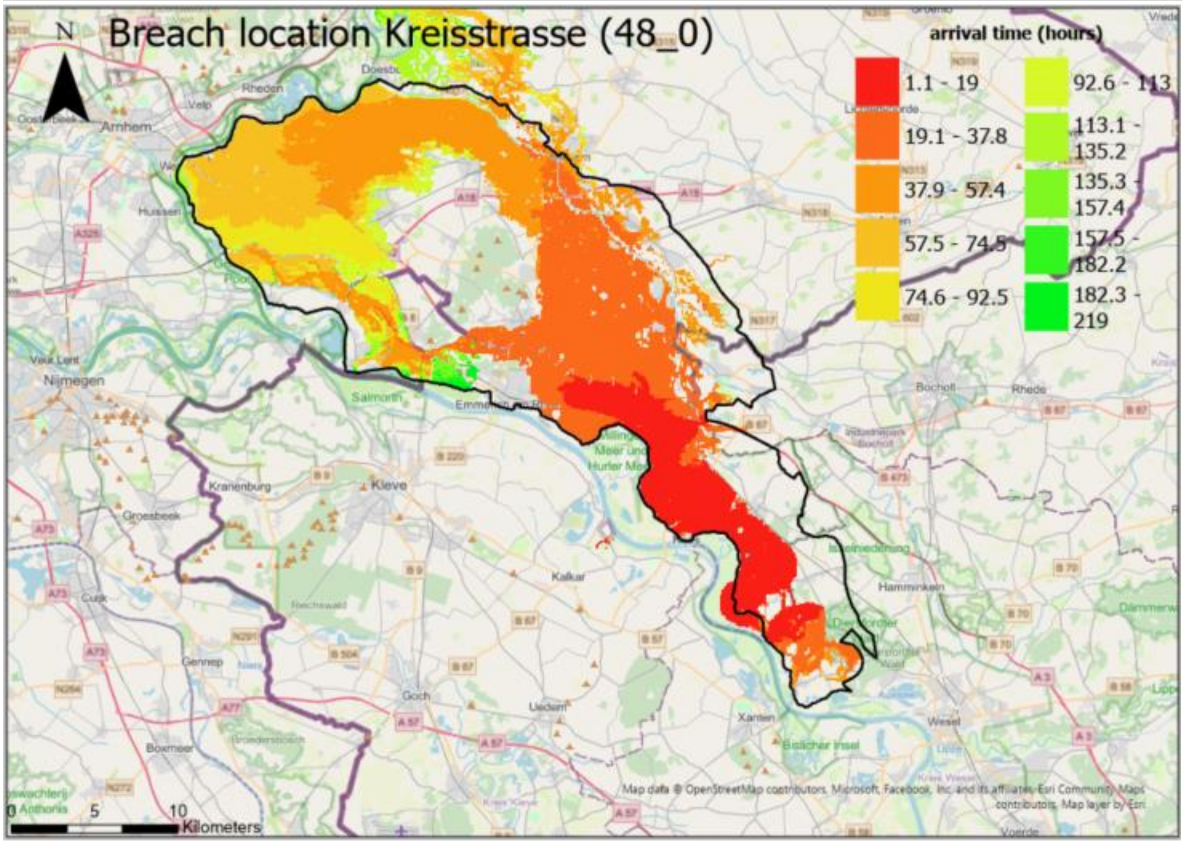
Cuijk
Doesburg
Rheden
Velp
Huissen


N
Breach location Kreisstrasse (48_0)
arrival time (hours)
1.1 - 19
19.1 - 37.8
37.9 - 57.4
57.5 - 74.5
74.6 - 92.5
92.6 - 113
113.1 - 135.2
135.3 - 157.4
157.5 - 182.2
182.3 - 219
0 5 10 Kilometers
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Rhede
Hamminkeln
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Rheden
Velp
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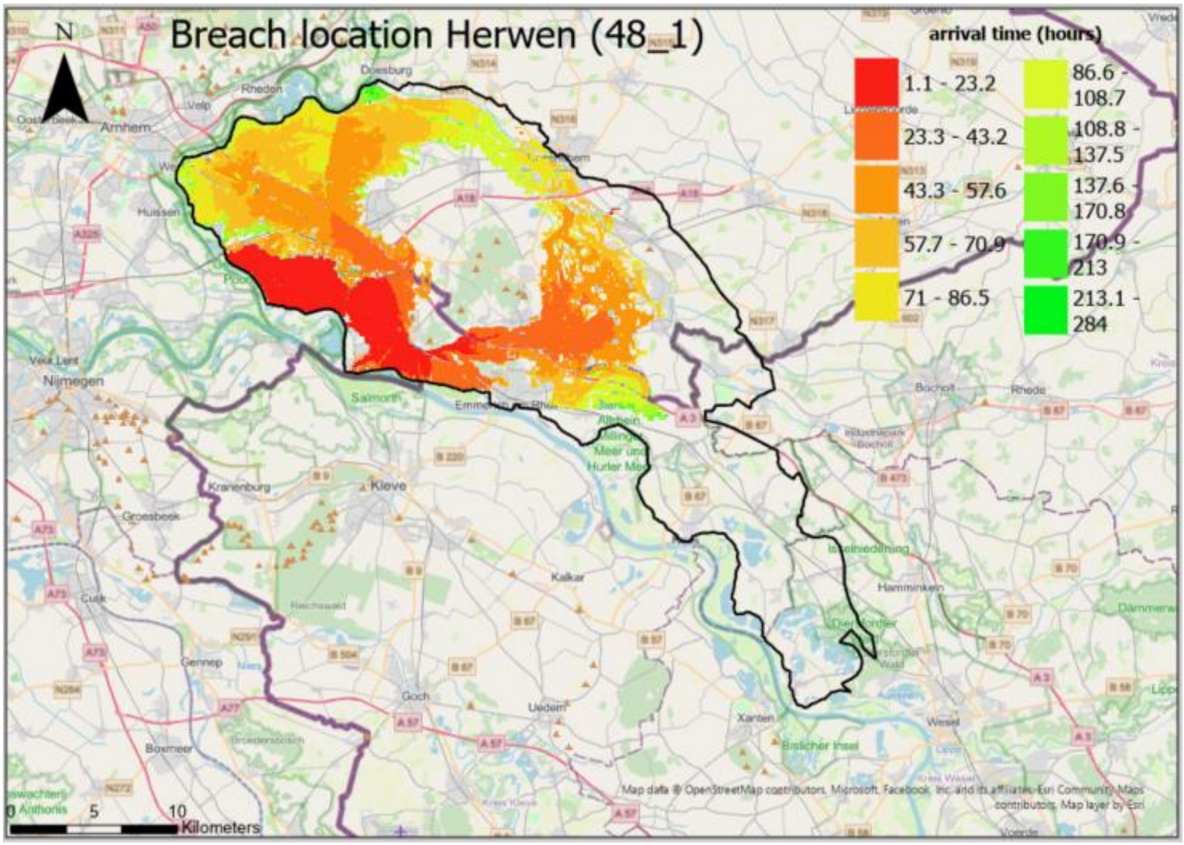
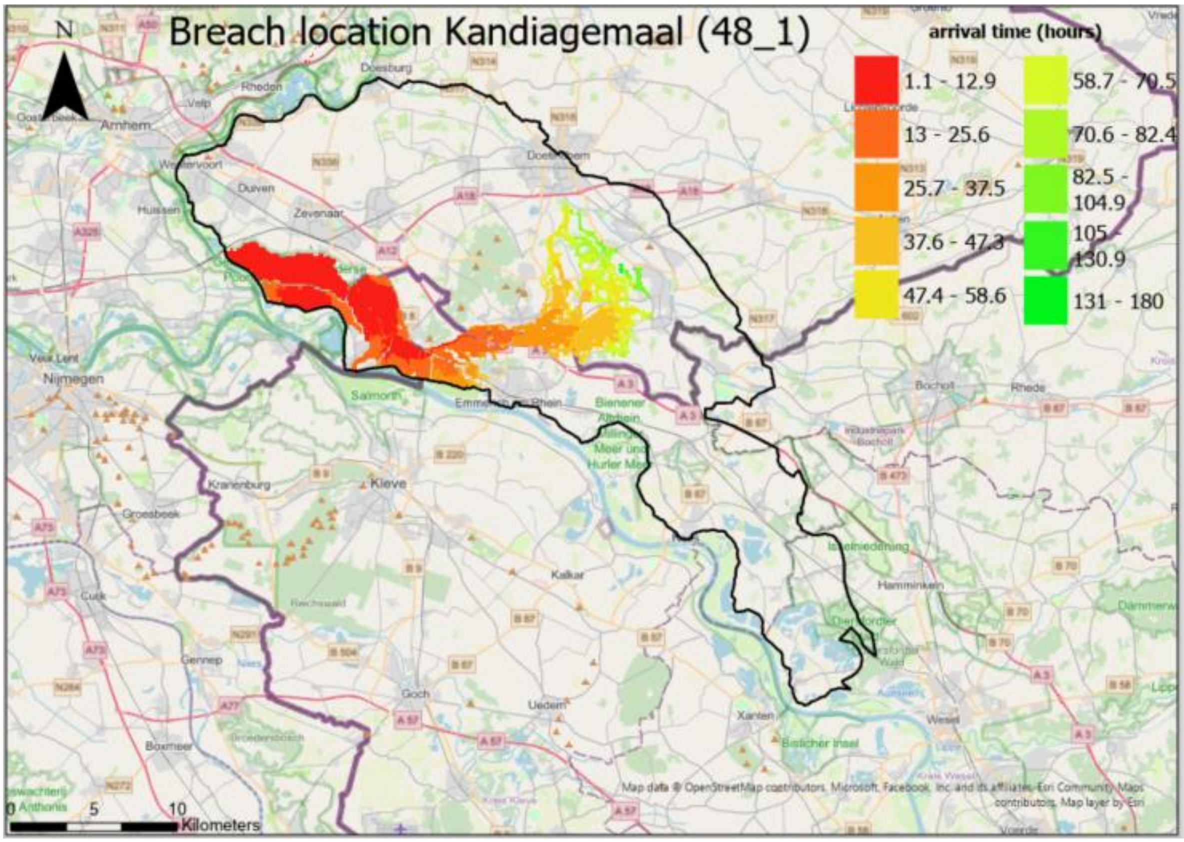
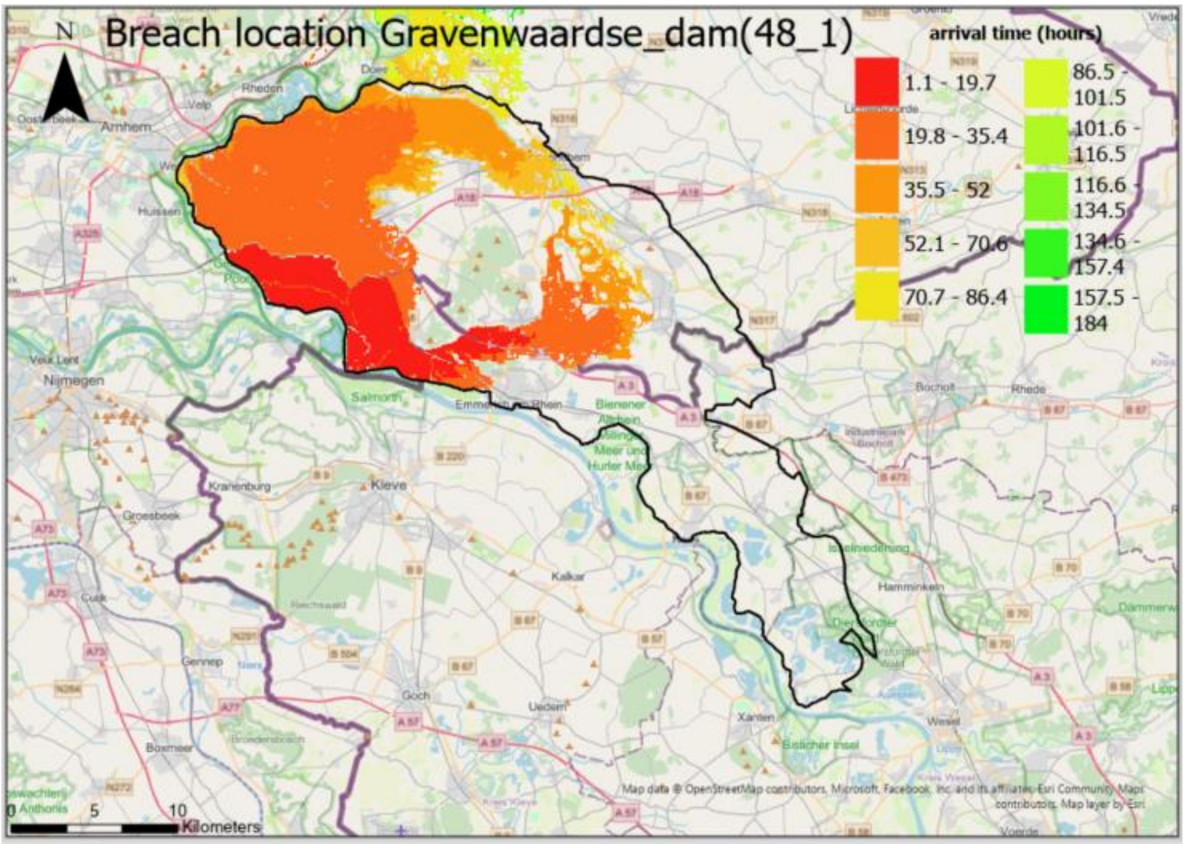
D 1.1 Considered Flood scenario's norm section 48_1






Breach location Gravenwaardse_dam(48_1)
N
arrival time (hours)
1.1 - 19.7
19.8 - 35.4
35.5 - 52
52.1 - 70.6
70.7 - 86.4
86.5 - 101.5
101.6 - 116.5
116.6 - 134.5
134.6 - 157.4
157.5 - 184
0 5 10 Kilometers
Arnhem
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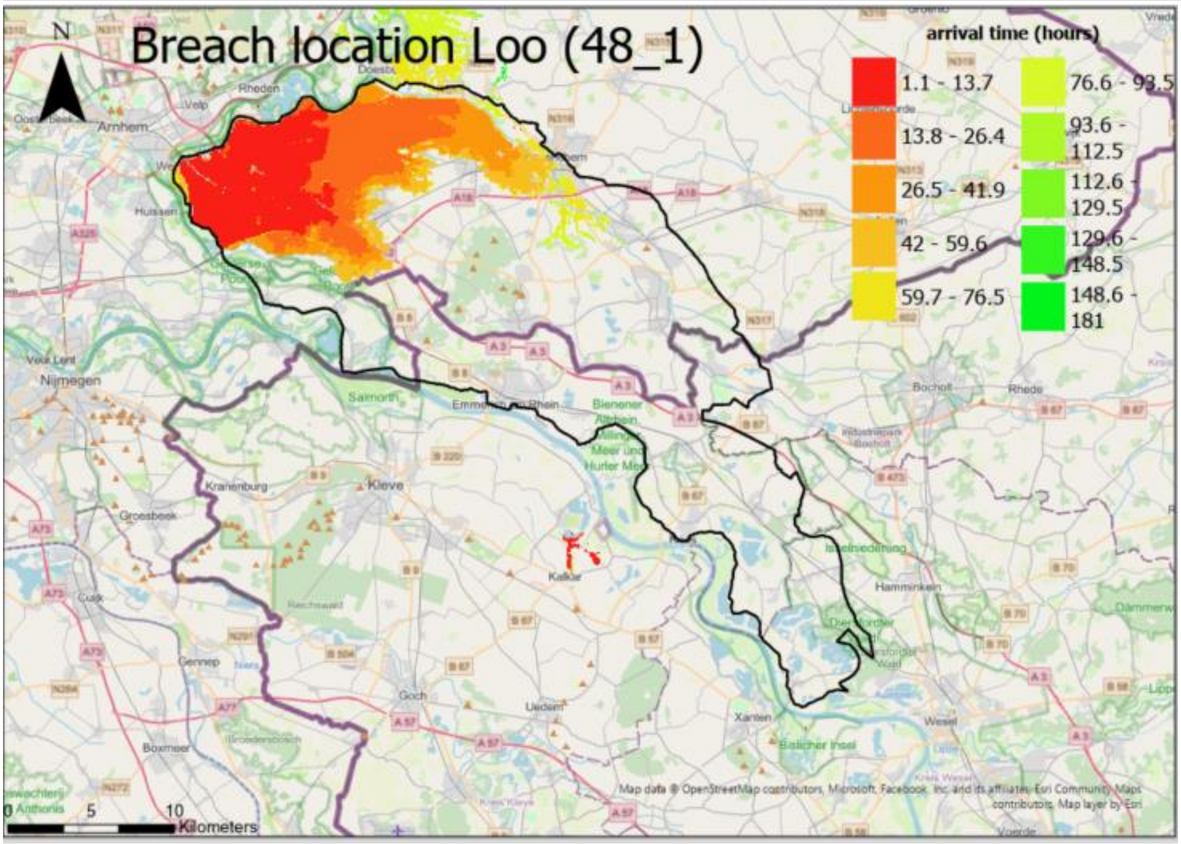
Breach location Loo (48_1)
N
arrival time (hours)
1.1 - 13.7
13.8 - 26.4
26.5 - 41.9
42 - 59.6
59.7 - 76.5
76.6 - 93.5
93.6 - 112.5
112.6 - 129.5
129.6 - 148.5
148.6 - 181
0 5 10 Kilometers
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Nijmegen
Kleve
Kalkar
Emmerich am Rhein
Goch
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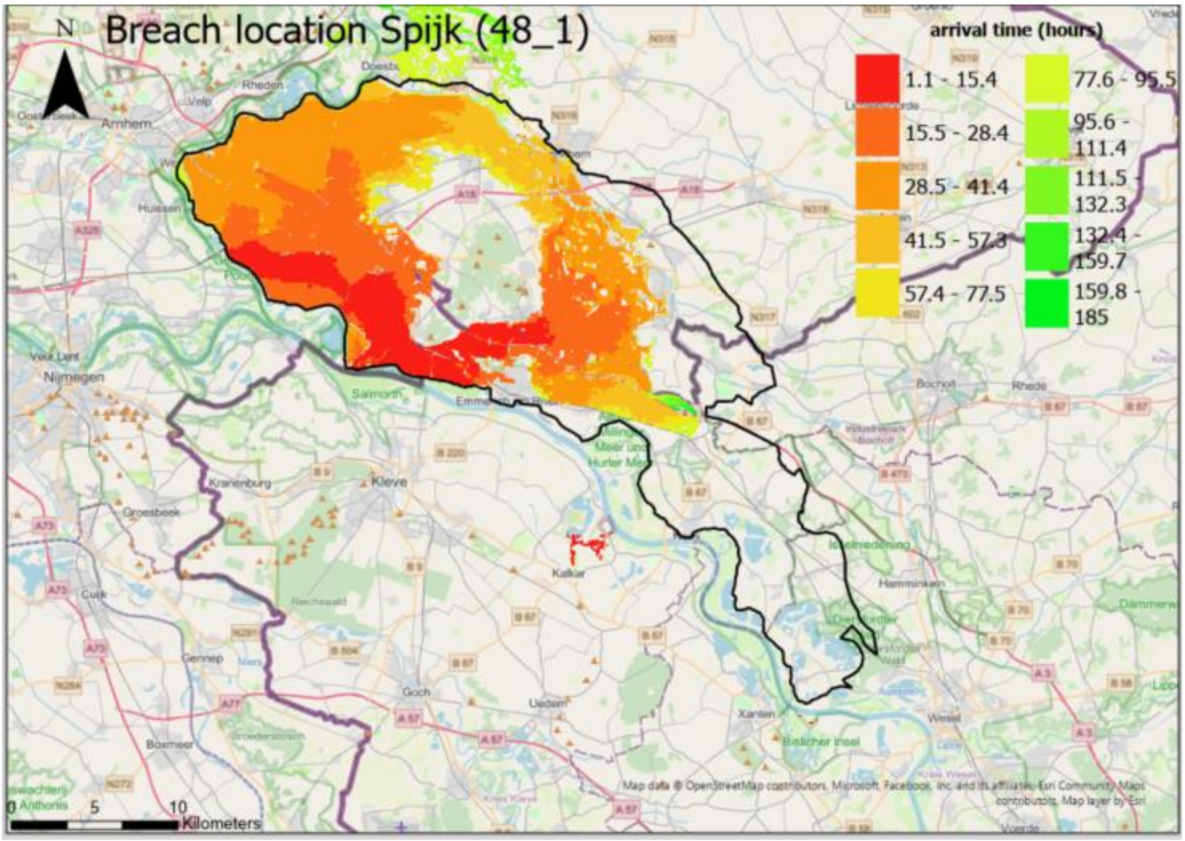
N
Breach location Spijk (48_1)
arrival time (hours)
1.1 - 15.4
15.5 - 28.4
28.5 - 41.4
41.5 - 57.3
57.4 - 77.5
77.6 - 95.5
95.6 - 111.4
111.5 - 132.3
132.4 - 159.7
159.8 - 185
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Nijmegen
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Kalkar
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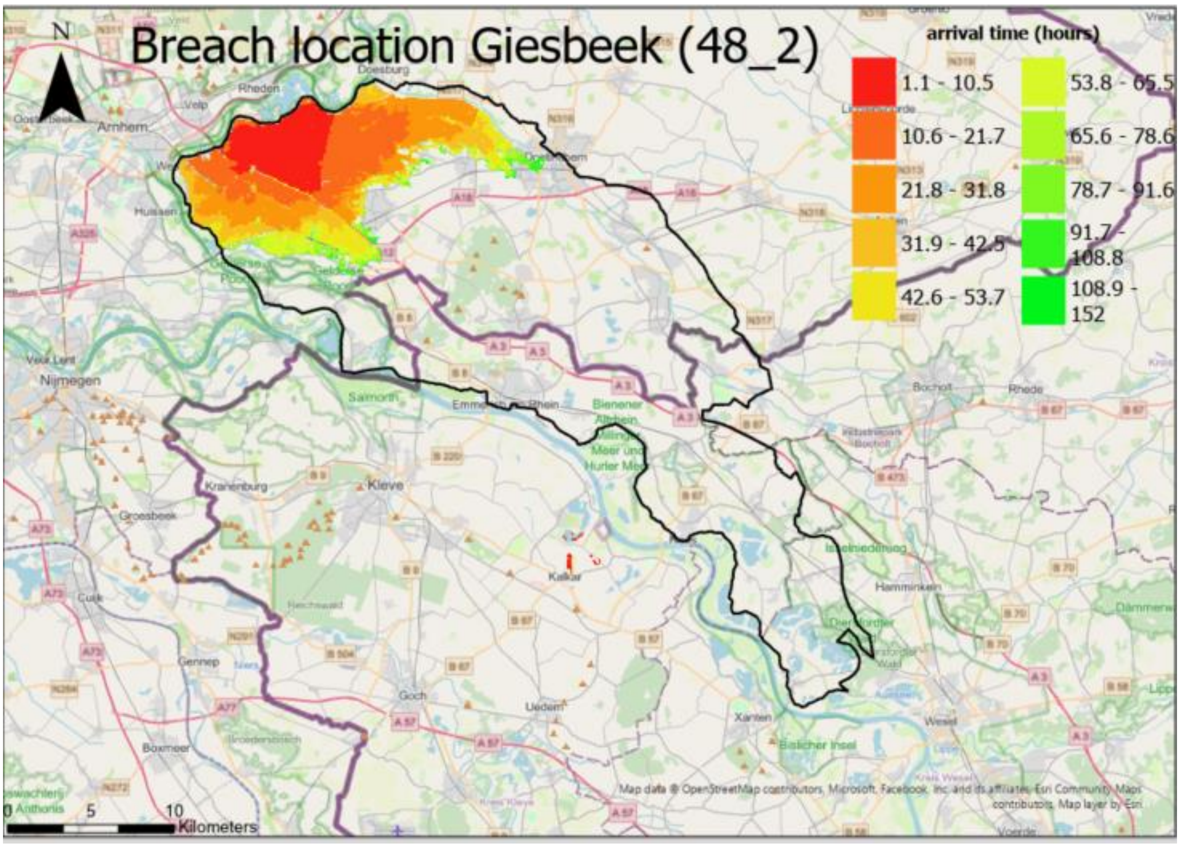
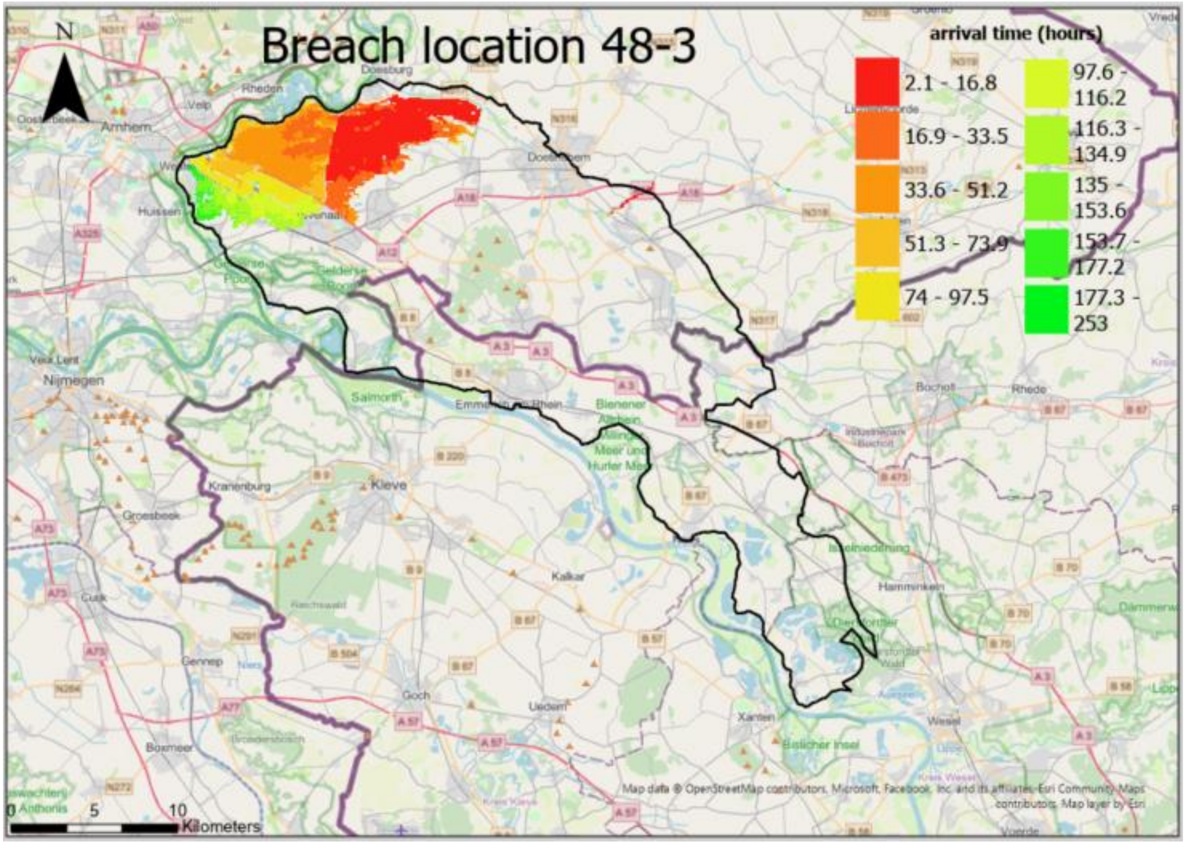
D 1.2 Considered Flood scenario's norm section 48_2

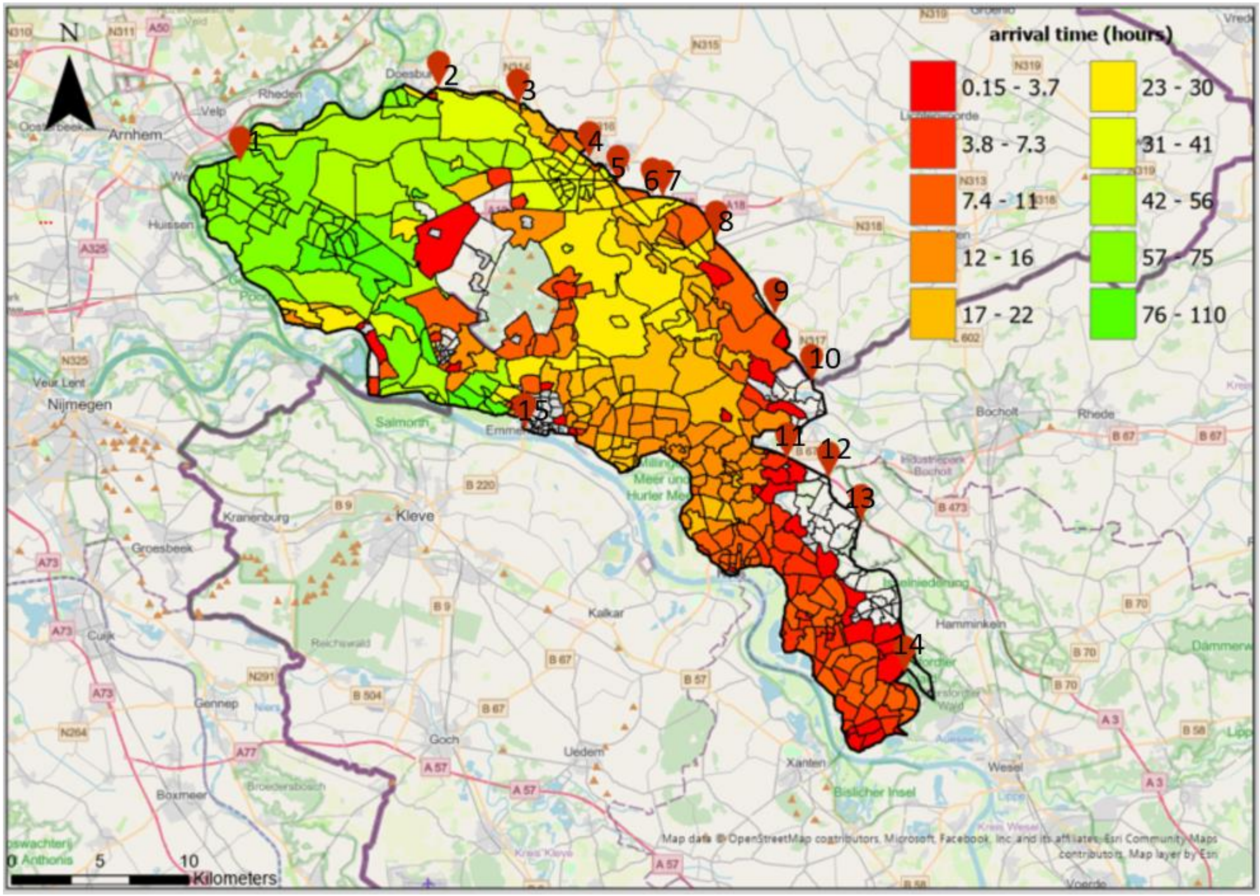


D 1.3 Considered Flood scenario’s norm section 48_3

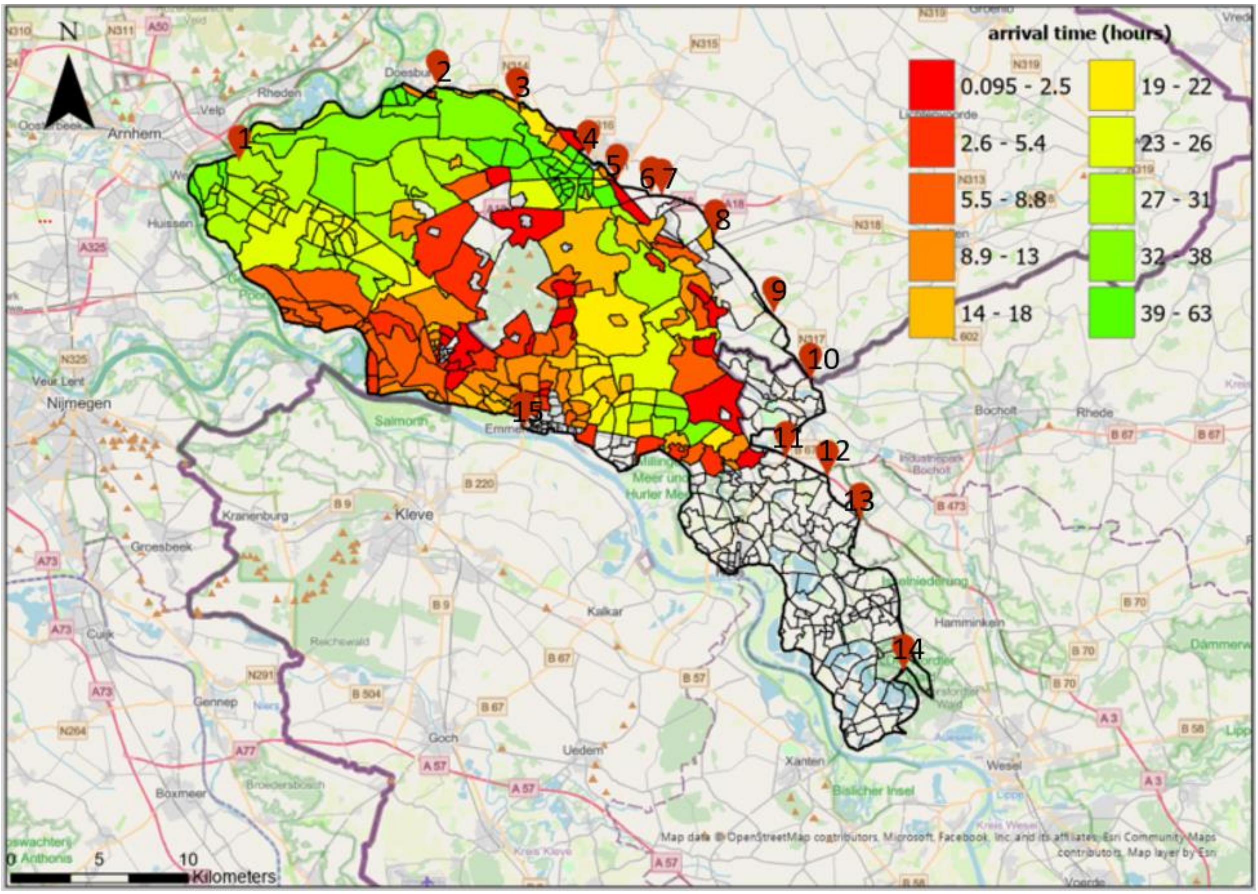


E Arrival time maps in combination with evacuation exits

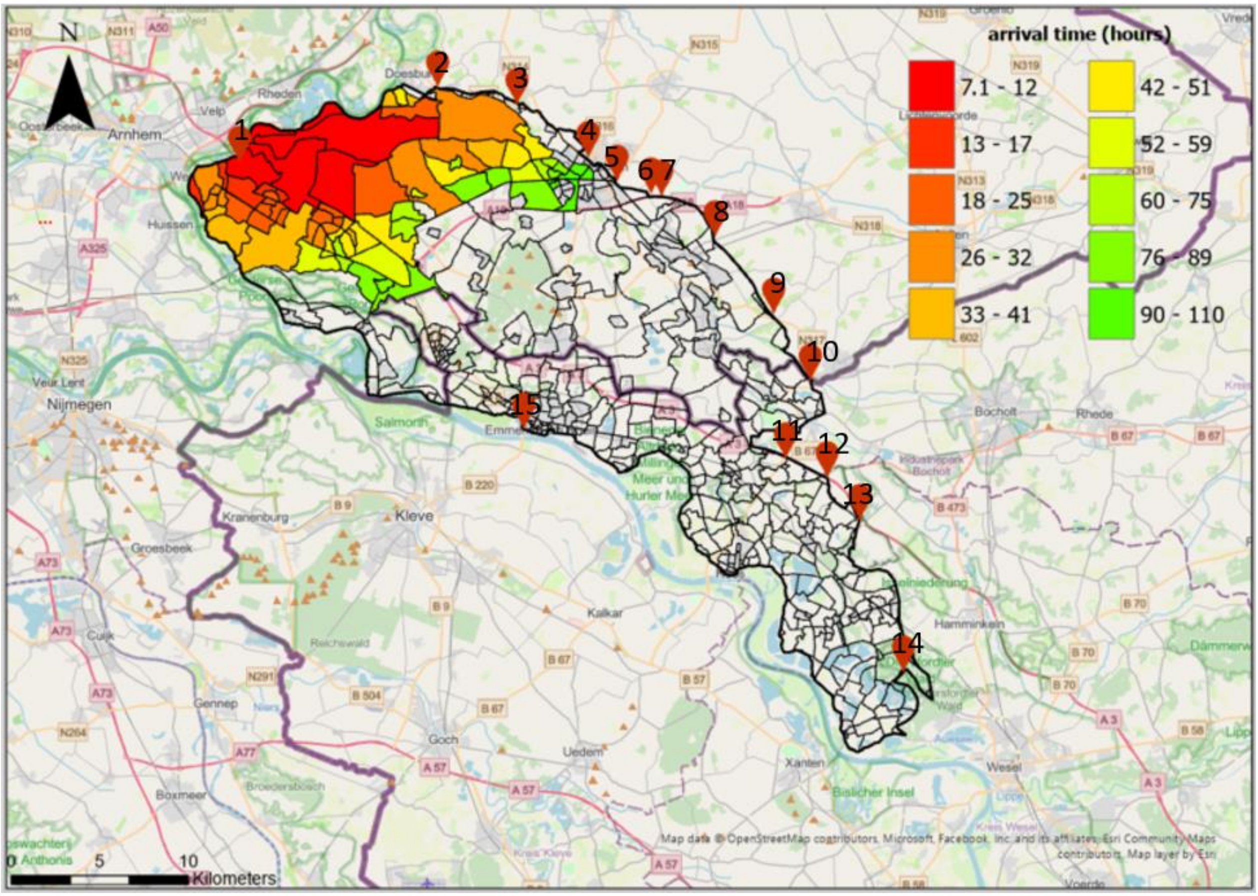
E 1.0 Arrival time maps in combination with evacuation exits for norm section 48_0



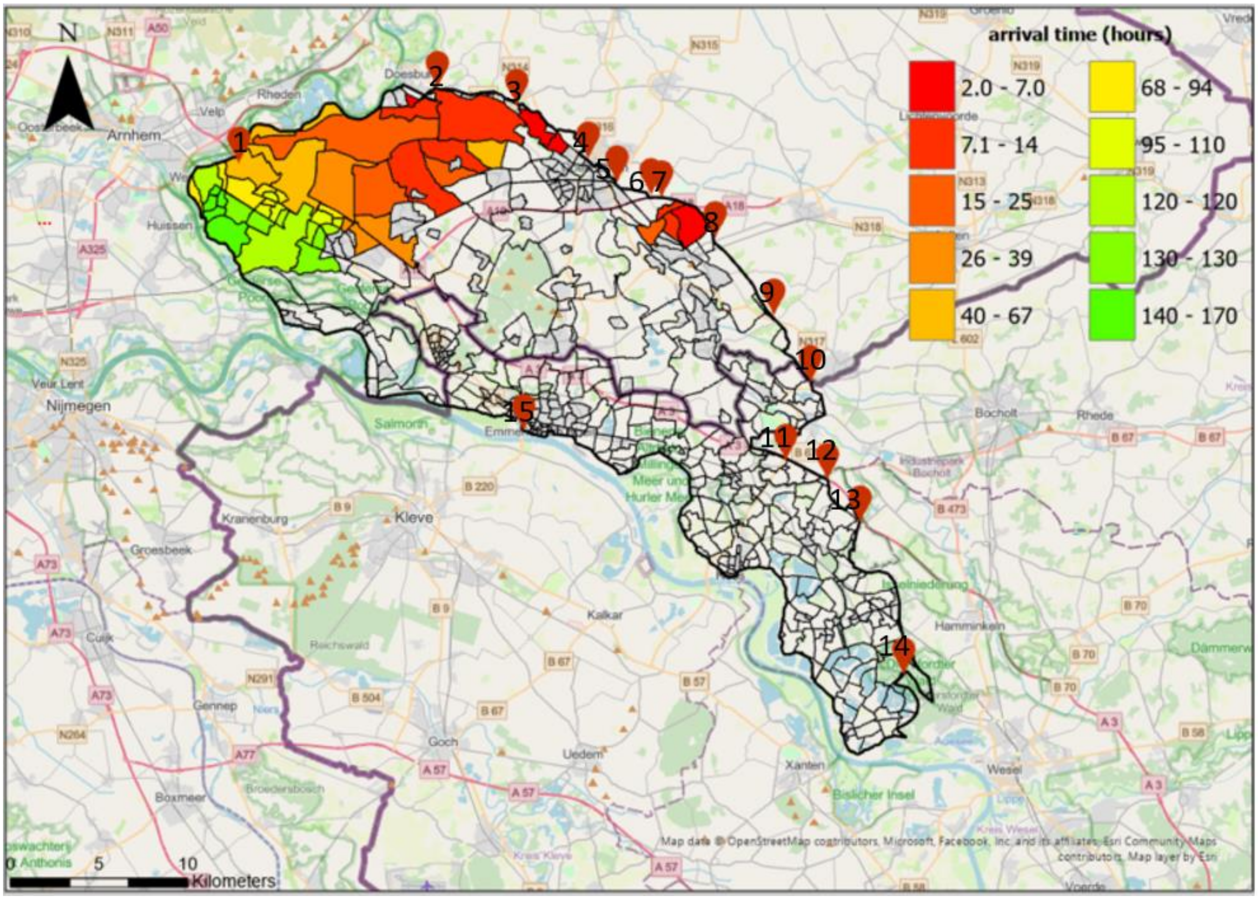
E 1.1 Arrival time maps in combination with evacuation exits for norm section 48_1



E 1.2 Arrival time maps in combination with evacuation exits for norm section 48_2



E 1.3 Arrival time maps in combination with evacuation exits for norm section 48_3



F Safety standards used for dike ring 48

Table 15 Current safety standard determination per norm section within dike ring 48.

Dike section	Norm determined by (SCBA/LIR)	Lower boundary safety standard class, flooding probability (1/year)	Signal value safety standard class, flooding probability (1/year)
48_0	SCBA	1/3.000	1/10.000
48_1	LIR	1/10.000	1/30.000
48_2	SCBA	1/3.000	1/10.000
48_3	SCBA	1/3.000	1/10.000

G Arrival time maps in combination with evacuation exits

G 1.1 Difference that spatially distributed evacuation fraction make towards norm classes considering signal values and lower boundary LIR values per norm section

Table 16 norm class determination/comparison considering spatially distributed evacuation fractions per norm section

Method	Using the expected evacuation fraction method	Using the expected evacuation fraction method -20% non-response factor
Signal value 48_0	1/6070	1/1738
Lower boundary LIR value 48_0	1/3166	1/869
Corresponding signal value safety standard class (1/year), (+/- norm class compared to current safety class)	German class unknown	German class unknown
Corresponding lower boundary LIR value safety standard class (1/year), (+/- norm class compared to current safety class)	German class unknown	German class unknown
Signal value 48_1	1/4277	1/15609
Lower boundary LIR value 48_1	1/2138	1/8143

	1/3000 **(-2 norm classes)**	1/10.000 **(-1 norm class)**
Corresponding lower boundary LIR value safety standard class (1/year), (+/- norm class compared to current safety class)	1/3000 **(-1 norm class)**	1/10.000 **(same class)**
Signal value 48_2	1/1102	1/276
Lower boundary LIR value 48_2	1/575	1/138
Corresponding signal value safety standard class (1/year), (+/- norm class compared to current safety class)	1/1.000 **(same class)**	1/300 **(same class)**
Corresponding lower boundary LIR value safety standard class (1/year), (+/- norm class compared to current safety class)	1/1.000 **(+1 norm class)**	1/300 **(same class)**
Signal value 48_3	1/450	1/111
Lower boundary LIR value 48_3	1/225	1/55
Corresponding signal value safety standard class (1/year), (+/- norm class compared to current safety class)	1/300 **(-2 norm classes)**	1/300 **(-2 norm class)**
Corresponding lower boundary LIR value safety standard class (1/year), (+/- norm class compared to current safety class)	1/300 **(-1 norm class)**	1/300 **(-1 norm class)**

H. Invulnerable neighbourhoods

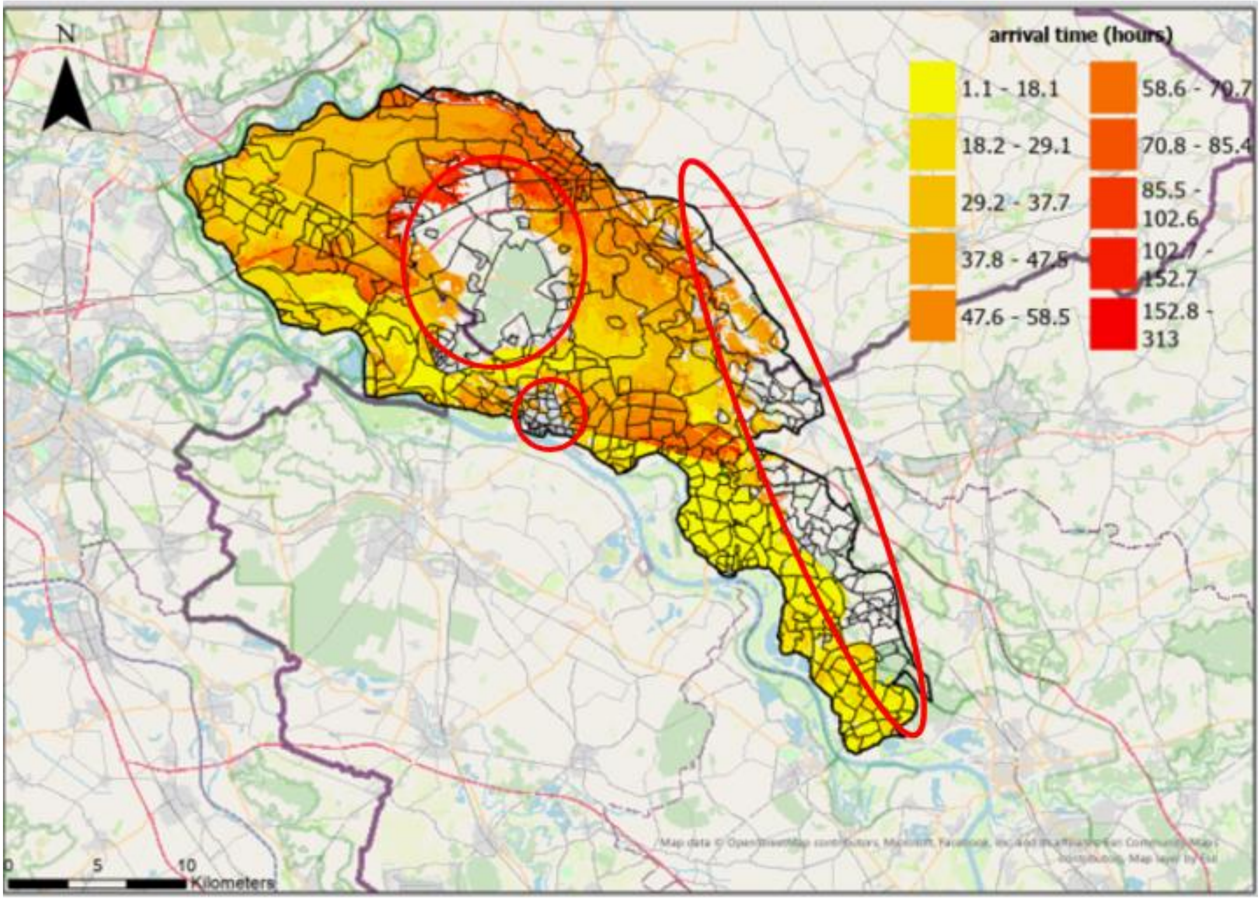


Figure 21. Neighbourhoods that will not be inundated regardless of the location of a dike breach.

I. Inundated evacuation exits.

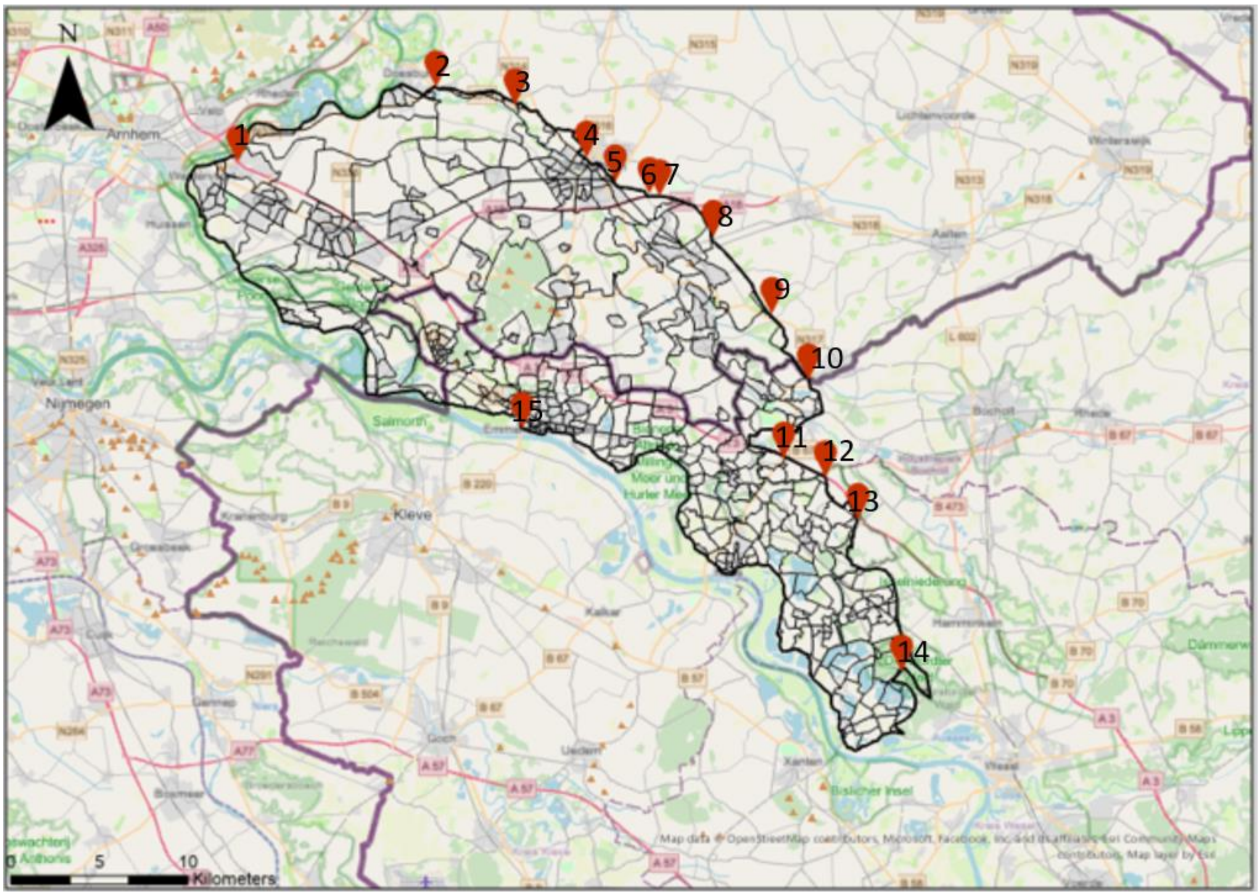


Figure 22. Dike ring 48's exit locations.

Table 17. Usable evacuation exits regarding different flood scenario's from norm sections.

Evacuation exit number (figure 22)	Road description	Capacity (person vehicles)	Usable for norm section flood scenario (norm section)
1	A12 ri. Arnhem	4644	-
2	N338 Provincialeweg 51	1500	-
3	N814 Wehisedijk	1500	-
4	N316 Europaweg	1500	48_3,
5	N315 Zelhemseweg	1500	48_3, 48_2
6	N315 Varseveldseweg	1500	48_3, 48_2, 48_1
7	A18 ri. Varsseveld	4644	48_3, 48_2, 48_1
8	N818 Terborgseweg	1500	48_3, 48_2, 48_1
9	A18 ri. Varsseveld	1500	48_3, 48_2, 48_1
10	N317 Aa Stangrondweg	1500	48_3, 48_2, 48_1, 48_0
11	A3 Oberhausen	4644	48_3, 48_2, 48_1

12	R67 Empeler Strasse	1500	48_3, 48_2, 48_1, 48_0
13	R8 Weseler Landstrasse	1500	48_3, 48_2, 48_1, 48_0
14	R8 Duisburger Strasse	1500	48_3, 48_2, 48_1
15	R220 Emmericher Strasse	1500	48_3, 48_2, 48_1. 48_0