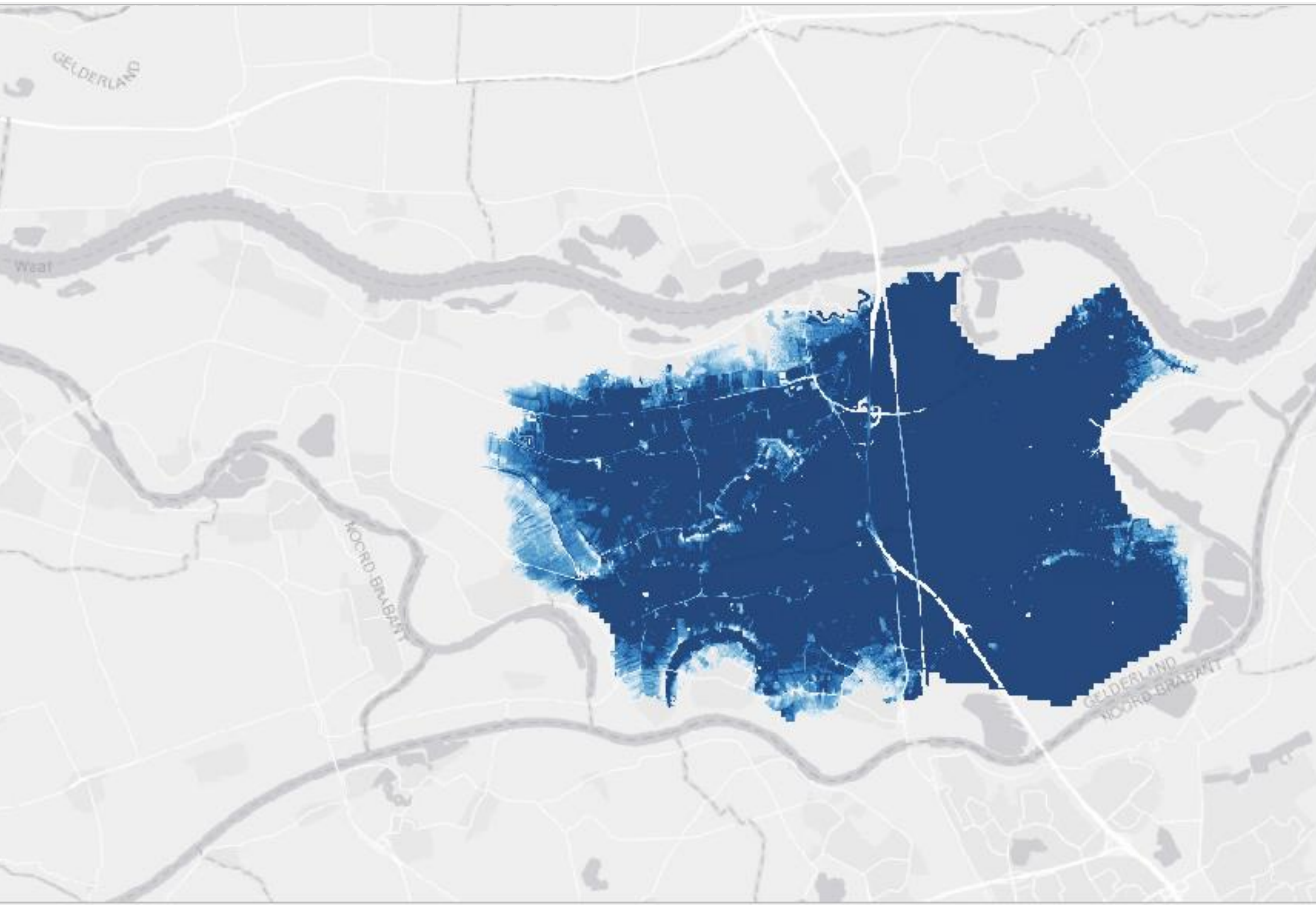


Improving flood fatality risk assessment for river flooding in the Netherlands

Implications of alternative functions and model resolution variations on mortality and fatalities in the Bommelerwaard

A.R. Brussee

TU Delft Delft University of Technology

Deltares

Improving flood fatality risk assessment for river flooding in the Netherlands

Implications of alternative functions and model resolution variations on mortality and fatalities in the Bommelerwaard

by

A.R. Brussee

in partial fulfilment of the requirements to obtain the degree of

Master of Science

in Civil Engineering

at the Delft University of Technology,

to be defended publicly on Monday June 15, 2020 at 2:00 PM.

Faculty of Civil Engineering and Geosciences

Department of Hydraulic Engineering

Date of report:	June 7, 2020	
Project duration:	September 2, 2019 – June 15, 2020	
Thesis committee:	Dr. ir. J. D. Bricker,	TU Delft (Chair)
	Prof. dr. ir. S. N. Jonkman,	TU Delft
	Dr. H. C. Winsemius,	TU Delft & Deltares
	Dr. ir. K. M. de Bruijn,	Deltares
	Ir. G. Verhoeven,	Deltares

An electronic version of this thesis is available at http://repository.tudelft.nl/.

Preface

This thesis finalizes my master's study Hydraulic Engineering at the Delft University of Technology with the specialization Flood Risk. This topic matched very well with my interest in and curiosity about flood risk in the Netherlands. Since the last Dutch flood event was many years ago, we sometimes tend to forget that we live for a large part below sea level and that we have to deal with high peak river discharges at times. The study on the consequences of a potential breach in one of our dike rings is for that matter of great importance. This thesis was a collaboration between the Delft University of Technology and the research institute Deltares.

I would like to express my gratitude to the members of my graduation committee for their time, guidance, and support during my graduation project. The feedback and discussions during the meetings have always led to improvements. I would like to thank Jeremy Bricker for initiating this project, chairing the committee, and providing valuable input (practically and academically). My thanks go out to Bas Jonkman for joining the graduation committee because of his expertise on loss of life. His guidance along with many suggestions proved to be of great importance and increased the quality of my work. I would also like to thank Hessel Winsemius for his critical view, he contributed to this study from the moment of joining and helped me form my research questions and approach.

Special thanks to the committee members and supervisors from Deltares. Karin de Bruijn was my daily supervisor and helped me a lot in asking the right questions and by giving constructive feedback. We had regular talks about my thesis and flood risk management overall; I enjoyed these conversations and they were very valuable to me. Govert Verhoeven introduced me to the new software program D-Flow FM and helped me from the start with the case study set-up and the modelling assumptions.

Besides my committee members, I would like to thank Rinske Hutten who I could go to for all the struggles with the 'interacter' of D-Flow FM. I thank Rolf van Buren for helping and showing me the possibilities within ArcGIS for quick operations of the grids. In addition, I would like to thank Dennis Wagenaar for providing me knowledge about SSM2017 and FIAT. Furthermore, I would like to thank the entire flood risk management department of Deltares for welcoming me, for the nice conversations during lunch or coffee breaks, and for making me realize, even more, the relevance of flood risk management.

My thesis was planned from September till June, but unfortunately, due to the COVID-19 circumstances, I have worked from home for the last three months. My thanks go out to everyone for their flexibility and for helping me graduate online. I would like to thank in particular my family and friends for supporting me during the process and keeping me motivated in these strange times.

Finally, I truly enjoyed my time as a student at the Delft University of Technology. I hope that this final piece of my study time contributes to the broader discussion on water safety in the Netherlands.

I wish you a pleasant read.

Anneroos Brussee
Delft, June 2020

Summary

The number of fatalities due to a potential flood event is traditionally determined utilizing 'mortality functions'. Data of recent large-scale flooding in the Netherlands are not available since the Netherlands was successful in flood prevention. Therefore, only data from the last coastal flood event in 1953 with 1795 direct fatalities are available. The mortality functions are empirical relationships to provide mortality as a function of three explicit flood characteristics, namely water depth, flow velocity, and water level rise rate. Many more factors are included implicitly since the functions were derived from 1953 data. These underlying factors are thus based on the circumstances of the coastal flooding in 1953 and might not be representative anymore for future flood events elsewhere in the Netherlands. For example, the quality of the built environment, spatial planning, communication systems, transport means, and also the socio-economic conditions have changed since 1953. Moreover, the mortality functions are derived from coastal flooding and some underlying aspects can have a different effect in river flooding.

The three flood characteristics in current flood risk assessments are determined by means of coarse flood simulations. Since modern software is becoming more advanced, more detailed flood simulations are becoming possible. Therefore, the applicability of the mortality functions needs to be studied if finer model resolutions are used. This report presents the case study of river area the 'Bommelerwaard' in which the validity of the 1953-based functions, possibilities for alternative functions, and finer model resolutions in hydrodynamic models are tested and analyzed with regards to their impact on flood fatality risk.

A hydrodynamic model is developed to simulate the flood characteristics for the mortality calculations and to analyze the impact of using finer model resolutions. The new flood simulation program D-Flow Flexible Mesh is used which is able to apply finer resolutions at locations that require more detail. The different model resolutions that are tested are 100m and 25m, and 5m for the area close to the breach.

The flood simulations with these different model resolutions resulted in similar outcomes for the number of estimated fatalities in this case study. Overall, the 100m model is preferred because it is sufficiently able to indicate the dangerous locations, provide the order of magnitude of the flood characteristics, while it demands short computation times and matches the level of detail of the data of 1953. However, it is recommended to model the area around the breach ('breach zone') with finer model resolutions because the resulting higher local peak velocities are relevant for potential building collapse. For the areas around obstacles and underpasses, it is also recommended to use finer resolutions or to make use of 1D objects or fixed weirs. This study concluded that finer model resolutions at dangerous locations have an impact on the individual risk value of the neighbourhood and this can have consequences for the maximum individual risk value and thus the overall safety standard of a large dike ring. Furthermore, the case study illustrated that compartment dikes have a significant impact on the local mortality because of the high water level rise rates just upstream. It is recommended to look into possibilities to reduce this high local mortality rate and hence, individual risk, for example by optimizing the location and number of compartment dikes or exploring the effects of openings in the dikes.

This study identified the discussion points in the current Dutch loss of life approach by a literature study, knowledge of recent flood events abroad, and loss of life approaches internationally. The most important factors for loss of life that came forward are water arrival time, people vulnerability, building characteristics (collapse), and human behaviour. Based on these factors, preliminary alternative functions or adaptations to the current parameters are proposed. These adaptations have been further investigated through sensitivity analyses. Moreover, the impact on the individual risk has also been assessed since this is the decisive risk criterion for dike trajectory 38-1 in the Bommelerwaard.

It is recommended to substantiate and take into account the factors water arrival time, improved building characteristics, and age in the loss of life approach. Preventive evacuation is already taken into account in this approach, but in addition, water arrival time can be included by means of fleeing. This study shows that water arrival time has a great effect on the number of fatalities because some areas have relatively large arrival times and this enables inhabitants to flee the area. Emergency response is thereby of crucial importance. Also in 1953 this factor proved to be relevant. The improved building characteristics compared to 1953 are shown to have a limited impact on the absolute number of fatalities in this case study but it reduced the maximum value of the individual risk and is thus of relevance, especially for dike ring areas with large water depths (>2.1 m) and high rise rates (>0.5 m/h). Moreover, this study underlines the vulnerability of the elderly during flood events. Since the age distribution has shifted since 1953 and significantly more elderly are present in society nowadays, it is relevant to take this explicitly into account. This case study shows that correcting for age can have a significant impact on the number of fatalities. The impact on the individual risk is limited, but this depends on the spatial distribution of the elderly and should be further analyzed. Finally, the individual risk is sensitive to the configuration of the neighbourhoods. It is therefore also recommended to look into more robust approaches to determine the individual risk.

Samenvatting

Het aantal slachtoffers ten gevolge van een potentiële overstroming wordt bepaald met behulp van mortaliteitsfuncties. Er zijn geen data beschikbaar van recente grootschalige overstromingen in Nederland, omdat Nederland sinds 1953 succesvol is geweest in het voorkomen van grootschalige overstromingen. De schatting van het aantal slachtoffers is daarom voornamelijk gebaseerd op data van de Watersnoodramp in 1953, een kustoverstroming met 1795 directe slachtoffers. De mortaliteitsfuncties zijn empirische relaties die de mortaliteit geven als functie van drie expliciete overstromingskenmerken, namelijk waterdiepte, stroomsnelheid en stijgsnelheid, maar bevatten aanzienlijk meer impliciete factoren die gebaseerd zijn op de omstandigheden in 1953. Deze onderliggende factoren zijn mogelijk niet meer representatief voor potentiële overstromingen elders in Nederland. Bijvoorbeeld huissterkte, ruimtelijke inrichting, communicatiesystemen, transportmiddelen en sociaal-economische omstandigheden zijn verandered sinds 1953. Daarnaast zijn de mortaliteitsfuncties afgeleid voor kustoverstroming en kunnen onderliggende factoren een ander effect hebben bij rivieroverstromingen.

De drie overstromingskenmerken worden in huidige waterveiligheidsstudies bepaald met behulp van grove overstromingssimulaties. Aangezien softwareontwikkeling steeds gedetailleerdere simulaties mogelijk maakt, is het noodzaak te onderzoeken wat de impact van hoge model resoluties is op de toepasbaarheid van de mortaliteitsfuncties. Dit rapport presenteert een case studie voor het rivierengebied de Bommelerwaard waarin de validiteit van de 1953-functies, mogelijke verbeteringen van de mortaliteitsfuncties en het gebruik van hoge model resoluties worden getest en geanalyseerd met betrekking tot slachtofferbepaling en het individueel risico.

Een hydrodynamisch model is opgezet om de overstromingskenmerken te simuleren voor de mortaliteitsberekeningen en om de impact van hogere resoluties te analyseren. Het nieuwe software programma D-Flow Flexible Mesh is gebruikt dat in staat is om lokaal hogere resoluties toe te passen. De model resoluties die getest zijn in deze studie zijn 100m, 25m en gedeeltelijk 5m voor het gebied bij de dijkdoorbraak.

De resultaten van deze verschillende overstromingssimulaties kwamen in grote mate overeen. Het aantal slachtoffers in het 25m en 5m model verschilden weinig van het 100m model. Het 100m model is over het algemeen het meest aantrekkelijk, omdat het voldoende in staat is de gevaarlijke plekken te lokaliseren, het een ordegrootte geeft van de overstromingskenmerken, het kortere rekentijden kent ten opzichte van hogere resoluties en aansluit bij de nauwkeurigheid van de datapunten van 1953. Wel wordt aanbevolen om de zone rondom de dijkdoorbaak ('breach zone') met hogere model resoluties te modelleren vanwege de hogere lokale stroomsnelheden die relevant zijn voor het instortingsgevaar van de huizen. Daarnaast wordt geadviseerd om de gebieden rondom obstakels fijner te modelleren of gebruik te maken van 1D objecten of vaste keringen ('fixed weirs'). Er dient tevens rekening te worden gehouden met de impact van het modelleren van gevaarlijke plekken met een hogere resolutie, omdat het in deze case studie van de Bommelerwaard resulteerde in een hogere waarde voor het individueel risico op buurtniveau. Hogere waarden voor het individueel risico op buurtniveau kunnen gevolgen hebben voor het maximaal individueel risico en daarmee de norm van een groot dijktraject. In de case studie is verder naar voren gekomen dat de compartimenteringsdijken bovenstrooms hoge mortaliteit veroorzaken vanwege hoge stijgsnelheden. Het verdient aanbeveling om vervolgstudies uit te voeren om dit lokale effect te voorkomen en daarmee het maximaal individueel risico te verkleinen, bijvoorbeeld door de locaties van compartimenteringsdijken te optimaliseren of door er openingen in te maken.

In dit onderzoek zijn de discussiepunten van de huidige Nederlandse slachtofferbepaling in kaart gebracht met behulp van een literatuurstudie, kennis van recente buitenlandse overstromingen en internationale slachtofferbepaling methoden. De belangrijkste factoren voor mortaliteit die uit deze studie naar voren kwamen, zijn aankomsttijd van het water, kwetsbaarheid van personen, huissterkte (instortingsgevaar) en tevens menselijk gedrag. Aansluitend zijn voorlopige alternatieve functies of aanpassingen van huidige parameters voorgesteld en zijn deze door middel van gevoeligheidsanalyses bestudeerd. Ook is onderzocht wat de impact is van deze aanpassingen op het individueel risico, omdat dit het bepalende risico criterium is voor dijktraject 38-1 in de Bommelerwaard.

Het is aan te bevelen om de factoren aankomsttijd, huissterkte en leeftijd verder uit te werken en mee te nemen in de mortaliteitsfuncties. Preventieve evacuatie wordt al meegenomen in de huidige slachtofferbepaling, maar daarnaast kan aankomsttijd worden meegenomen door middel van vluchten. Uit deze case studie is gebleken dat aankomsttijd een grote impact heeft op het aantal slachtoffers, omdat voor bepaalde gebieden de aankomsttijden lang genoeg zijn om het gebied te ontvluchten. Hierbij is crisismanagement van cruciaal belang. Ook in 1953 speelde deze factor een grote rol. De toegenomen huissterkte sinds 1953 heeft weinig invloed op het absolute slachtofferaantal in de case studie, maar verlaagt wel de waarde van het maximaal individueel risico en is daarom van groot belang, vooral voor gebieden met grote waterdieptes (>2.1 m) and hoge stijgsnelheden (>0.5 m/u). Daarnaast kan uit de literatuurstudie worden afgeleid dat ouderen extra kwetsbaar zijn tijdens overstromingen. Door de vergrijzing is het aantal ouderen in Nederland sinds 1953 aanzienlijk toegenomen en wordt aanbevolen deze verschuiving mee te nemen in de slachtofferbepaling. De case studie laat zien dat het meenemen van leeftijd resulteert in een hoger aantal slachtoffers. De impact op het individueel risico is beperkt, maar dit is afhankelijk van de ruimtelijke verdeling van de ouderen en moet verder worden onderzocht. Tot slot is naar voren gekomen dat het individueel risico gevoelig is voor de configuratie van de buurten en wordt aanbevolen om de bepaling van het individueel risico robuuster te maken.

Table of Contents

1

Introduction

1.1. Background

In the past, the world has been confronted with enormous flood disasters with a huge number of fatalities, large economic impact, and a long aftermath with public health impact. Since a significant number of people are living in flood-prone areas, the risk of flooding will always be present. Some countries become flooded regularly due to wet seasons with heavy rainfall, some countries find difficulty in controlling their large varying rivers while other countries are surprised by coastal floods due to devastating hurricanes or a tsunami-induced flood. The number of fatalities can be tremendous. Therefore, flood risk management is an important topic all over the world.

An example of a disastrous event with a large death toll is the flooding of New Orleans after Hurricane Katrina in August 2005, when more than a thousand people died. But also in Europe, major floods have occurred in the recent past. For example, in the period between 1998 and 2009, European flood events cost the lives of 1126 people, caused at least 52 billion euros of economic damage, and the evacuation of thousands of people (Jonkman et al., 2018b). Moreover, more than five thousand fatalities are reported in the Emergency Events Database (EM-DAT) due to floods all over the world in the year 2019.

Flood protection has had special attention in the Netherlands since large parts of the country are located below mean sea level. Moreover, the Netherlands is endangered by high water levels in the rivers Rhine, Meuse, and Scheldt which flow from Europe into the Netherlands. Hence, the fight against water has been going for centuries. Fortunately, the number of flood events stayed limited in the Netherlands. The last large flood event in the Netherlands is the event of 1953 where large parts of Zuid-Holland and Zeeland have been flooded unexpectedly. This event is called the 'Watersnoodramp' and resulted in 1,795 direct fatalities. Areas in the United Kingdom and Belgium were affected as well.

Since this flood disaster, the flood protection in the Netherlands took a new direction with new technical safety standards. Among others, the Delta Works were constructed between 1954 and 1997 to protect the Netherlands against coastal flooding. However, the river discharges were also growing over the years. In 1995, more than 250,000 people were evacuated because of possible levee breaches due to extremely high discharges in the Rhine and Meuse river systems. This was a trigger to start the 'Room for the River' project (2008) in which the river literally got more room by relocating polders, set-back of dikes, removing obstacles, and lowering floodplains.

Flood risks are expected to increase in the future due to climate change and socio-economic developments in absence of protection measures (IPCC, 2012). To cope with the increased flood risk, strategies are being developed. The assessment of flood (fatality) risk must be accurate and up-to-date to support the decision-making of flood risk management strategies.

1.2. Problem definition

The Dutch flood defences must be strengthened regularly over the years to satisfy the safety standards. The safety of the defences (and the safety standards themselves) must be determined accurately to acquire a realistic view on the flood risk in the Netherlands.

Loss of life plays a large role in flood risk and depends on multiple aspects, including the mortality rate. Mortality functions are used to describe the relationship between the flood characteristics and the number of fatalities. These Dutch functions are developed by Jonkman (2007) and are mainly based on the flood event of 1953 in Zeeland.

Since 1953, many conditions have changed, such as the quality of the built environment, spatial planning, transport means, and communication; these factors are not explicitly part of the mortality functions and thus have not been updated since 1953. This means that the applicability of these functions might not be representative anymore for future flooding in other locations in the Netherlands. However, data of more recent (and deadly) flood disasters in the Netherlands to validate the current mortality functions is lacking. There is some data available from foreign flood events, but most of this data relates to other types of floods, such as floods due to a large dam break or tropical cyclone, which are not similar to floods in the Netherlands.

Additionally, the software to set up hydrodynamic models is becoming more advanced and this eases flood simulations with finer resolutions. If using finer model resolutions becomes a trend, it must be checked if the mortality functions are still applicable when finer resolutions are used as they are mainly developed for large areas. Moreover, the input of obstacles is a point of difficulty in hydrodynamic models. For example, houses are not well-implemented in the models. This has consequences for the reliability of local flood conditions such as the flow velocities. Therefore, it would be good to assess if the flood simulation models need more detail by applying a finer model resolution.

In conclusion, this study looks into the accuracy of the mortality functions and if there is a need for adaptation, explores if the flood simulations need more detail, and looks into the applicability of the mortality functions for finer resolutions.

1.3. Research objective and scope

Objective
This study focuses on the applicability of the current mortality functions for finer model resolutions in hydrodynamic models and investigates possible improvements for the current mortality functions. The main research question is therefore as follows:

> *What are the possibilities for potential alternative mortality functions for river flooding in the Netherlands and what is the impact of the level of detail of hydrodynamic models on the estimated mortality?*

This study consists of two parts: the first part focuses on the mortality functions themselves, including an analysis with possible alternatives for the state-of-the-art, and the second part focuses on the level of detail of the hydrodynamic models and the applicability of the mortality functions for finer resolutions. This can contribute to an advancement in the understanding of loss of life due to flood disasters and to support improvements of flood risk management strategies in the Netherlands.

A case study in a river area in the Netherlands is carried out to test new insights and adapted mortality functions, and to investigate the impact of the model resolution. Because the research objective is improving knowledge on the mortality functions, an area is chosen which includes a residential area to make sure that if there is an impact, it is visible in the results of the case study. The location of the breach and the hydraulic loads follow from the flood scenarios of 'Veiligheid Nederland in Kaart 2' (VNK2).

Scope
This thesis will focus on large-scale river floods due to a levee breach in the Netherlands. High water levels, a large storm or a combination of these two could cause a river flood. River floods have a low probability but have very large consequences. Other types of floods, such as overflow, flash floods, tsunami floods or floods due to cyclones will not be considered in this study.

1.4. Research questions

Based on the main research question, sub-questions are formulated which form the basis for the methodology. The research questions are:

1 **How is mortality included in the determination of flood risk in the Netherlands and what are the most important factors in the Netherlands and elsewhere?**
This question will be answered through a literature study. The literature study shows how the current mortality functions are used in the flood fatality risk assessment in the Netherlands and it shows the current knowledge, including all its factors and their relationships. The background and the motivation of the current mortality functions are provided as well. It also presents how loss of life is taken into account internationally.

2 **Which factors changed since the flood event of 1953 and what are the discussion points in the current functions?**
The literature study will show if there are new aspects since 1953 that should be taken into account in the Dutch loss of life approach. Based on new insights and the discussion points, potential alternative functions can be proposed.

3 **What is the effect of using new knowledge or adapted functions in the case study of a potential river flood in the Netherlands?**
Alternative functions will be proposed and tested on sensitivity. The outcomes of the simulated mortality and flood fatalities of the case study could give additional insights and a direction for potential improvements of the current functions.

4 **What is the sensitivity of the level of detail of the hydrodynamic model on the estimated mortality in this case study?**
In order to investigate the impact of the model resolution, a hydrodynamic 2D-model will be set up for the chosen location of the case study. Different model resolutions (coarse vs. fine) will be analyzed in this model and their impact on the simulated mortality.

5 **What is the impact of the potential alternative mortality functions on the flood fatality risk in the Netherlands?**
The last part of this study is concluding what the results mean for flood risk in the Netherlands. Will changes lead to significantly different outcomes and could that affect measures, strategies, or emergency responses?

1.5. Report outline

This thesis is divided into three parts. The first part introduces the flood fatality risk in the Netherlands. The literature study explains the Dutch loss of life approach and analyzes trends in flood mortality, past flood events, and international loss of life approaches in Chapter 2. Chapter 3 presents the background and the motivation of the current functions and which factors are (implicitly) included. Since many factors affect mortality, this is further analyzed in this chapter to gain advancement in understanding and the determination of mortality. Supported with the literature study on the discussion points, part I gives an indication of which aspects are most promising to be tested in the case study for possible improvements of the mortality functions.

The second part describes the set-up of the case study and the results. A hydrodynamic two-dimensional model is developed for the Bommelerwaard using the innovative software program D-Flow Flexible Mesh (D-Flow FM) from Deltares. Chapter 5 analyzes thoroughly the impact of the level of detail of hydrodynamic models and different roughness approaches. The flood characteristics from the hydrodynamic model are used in the next chapters about mortality. In Chapter 6, a sensitivity analysis is conducted to analyze the impact and potential of the parameters in mortality and fatality assessment. The impact of the level of detail and alternative functions on the individual risk is presented in Chapter 7.

The third and last part presents the discussion in Chapter 8 and finally the conclusions and recommendations in Chapter 9.

An overview of the content of this report is shown in Figure 1.1.

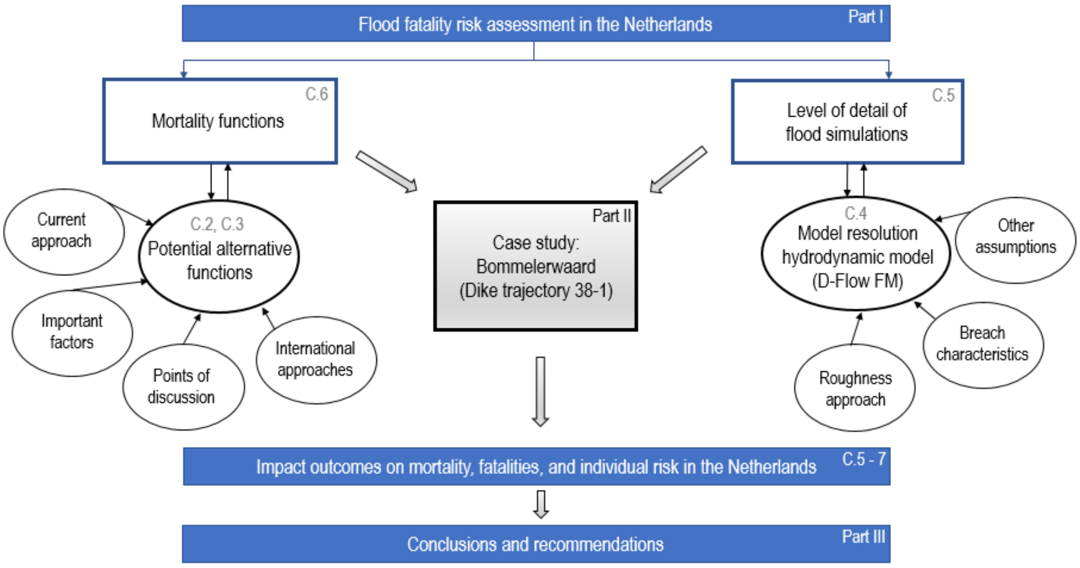


Figure 1.1: Overview of the methodology and outline of the report

Part I: Flood fatality risk

2

Overview of food fatality risks and their assessment

The literature study gives the basic concepts of flood fatality risk. Section 2.1 introduces the concept of flood risk in the Netherlands and Section 2.2 discusses the Dutch approach of loss of life. Section 2.3 describes approaches of loss of life internationally and gives an overview of the existing models. Section 2.4 analyzes the general trends of floods in Europe followed by lessons learnt from other floods in Section 2.5. Finally, the causes of death are considered in Section 2.6.

2.1. Introduction to flood risk assessment

This section presents the risk definition and explains risk analysis, flood risk management, and the relevance of flood risk assessment for flood risk management strategies.

Risk definition

Risk is determined by the interplay between hazard, exposure, and vulnerability. The hazard refers to a potential flood event, the exposure presents the population and area at risk, mostly referred to as the assets and values, and the vulnerability concerns the ability to cope with the flood event. These aspects vary per area, but also over time. In this study, risk is quantified as the probability multiplied by the (unwanted) consequences of the event. This means that the risk is high for rare events with very large consequences.

To quantify flood risk, the probabilities of flooding need to be identified and the corresponding consequences need to be assessed.

Flood risk analysis

Firstly, the probability of flooding needs to be analyzed. This is based on the occurrence of an extreme event and the reliability of the flood defences. For river flooding in the Netherlands, an extreme event could be extreme river discharges due to heavy rainfall upstream. These extreme discharges cause large water levels against the embankments. When these hydraulic loads are higher than the dikes are designed for, dike failure can occur. Examples of failure modes for dikes in the Netherlands are overtopping, piping, and macro instability.

Many flood scenarios exist: the location of the breach and the breach characteristics influence the size of the flood and thus the consequences. It is also possible that multiple breaches occur during one event, this was the case during the flood event in 1953. Therefore, different flood scenarios must be considered to determine the flood risk.

Hydrodynamic models allow us to simulate the flood characteristics of different flood scenarios. For example, SOBEK and D-Flow Flexible Mesh are programs to investigate the flood patterns of different scenarios. The flood characteristics are input for flood impact tools. These impact tools are able to estimate economic damages and flood fatalities. Flood maps can help making these consequences visual.

Flood risk management

It is not possible to reduce the probability of flooding and the consequences till exactly zero. Therefore, how safe is safe enough, is a question that must be answered in flood risk management. The minimum safety is captured in the safety standards. Before 2017, the safety standards of the Dutch flood defences were expressed in terms of the probability of exceedance of the hydraulic conditions. These standards mainly focus on the two failure mechanisms overflow and overtopping. In 2014, the decision was made by the government to change this perspective from the *probability of exceedance* to the *probability of failure* of the flood defences. This way, more focus is given to other failure mechanisms, the strength of the flood defence, and the consequences of the flood event.

The multi-layer safety concept was introduced to investigate if there is a need to pay more attention to spatial planning and emergency management next to protection. Figure 2.1 shows the multi-layer concept. The three different levels are (Slootjes and Van der Most, 2016a):

1. Protection: prevent floods from happening by using flood defences.
2. Spatial planning: reduce the consequences of floods by changing land use planning.
3. Emergency management: reduce the consequences of floods by disaster relief (e.g. organizational preparations and rescue services).

However, the National Water Plan keeps the main focus on flood protection. From January 2017, the new safety standards based on flood risk entered into force.

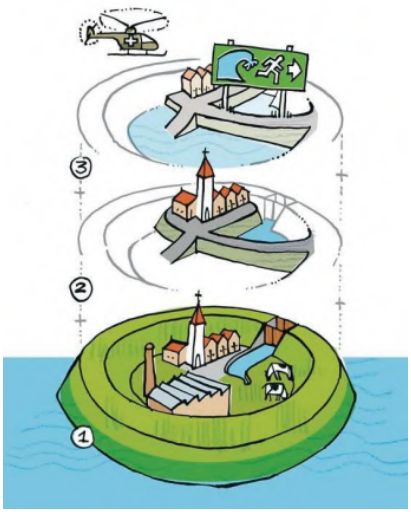


Figure 2.1: Multi-layer safety approach (Jonkman et al., 2018b)

The risk of flooding can be quantified in multiple ways. In the Netherlands, it is common to quantify it in three ways: individual risk, societal risk, and economic risk. These three concepts are introduced below.

The individual risk, in Dutch referred to as 'Lokaal Individueel Risico' (LIR), concerns the basic safety of a person and ensures a minimum safety against flooding in the country. It is also referred to as Flood Fatality Hazard. The individual risk is defined as the probability of death per year of a person at a location due to flooding. It is determined by the probability of flooding, the mortality for the given flood at the location and the probability to reach safety before the onset of the flooding (evacuation). The individual risk is not allowed to exceed 1/100,000 per year.

The individual risk takes into account one evacuation fraction, that is the lower boundary which corresponds to a poor-to-medium organized evacuation. The mortality is estimated based on flood simulations with a model resolution of 100m. To better match the level of detail of the mortality functions, the individual risk values are calculated based on neighbourhoods. Per neighbourhood, the median value of the mortality is taken to make sure outliers are not dominating the resulting individual risk value.

This means that the inhabitants are not taken into account in the individual risk. But one flood event with many flood fatalities has a bigger impact on society than multiple smaller events with flood fatalities. To prevent a large number of fatalities due to a single flood event, the societal risk is introduced. The so-called FN-curves give insight into this matter as they relate the probability of exceedance (1-F) in a year to the number of fatalities (i.e. 10, 100, 1,000 or 10,000) due to a flood event. The FN-curve is based on the summation of the (dike ring transcending) flood scenarios with N or more fatalities. The area under the curve equals the expected fatalities per year. The FN-curve needs to fall below the limit line: the more fatalities, the smaller the probability of the event has to be. This could give additional safety requirements for dense areas where there is a risk of a large number of fatalities. The choices for the limit line are made by the decision-makers.

The third risk is the economic risk: it concerns cost-benefit analyses for cost-efficiency. The economic risk is the expected economic damage expressed in euros per year. Similar to the FN-curve for the societal risk, an FD-curve can be constructed for the economic damage instead of fatalities. Damage does not only include direct damage, such as damage to residences, structures or infrastructure, but it includes also indirect damages, for example societal disruption. The damage assessment is therefore divided into four categories: tangible or intangible and direct or indirect. Human life is part of the damage assessment and has been given a value of 6.7 million euros. The loss of human life is about 30% of the total damage assessment, but it could differ significantly per dike ring (Deltares, 2011). For example, in locations with only few economical assets, the loss of life could be leading.

By using these three risks, equity, societal disruption, and economic optimization are taken into account in the determination of the minimum safety level, because the most stringent risk criterion of the three will be applied as the minimum safety standard. On top of that, if there is a risk of disruption of critical and vulnerable infrastructure in the national interest, it could receive an even stricter safety standard (Slootjes and Van der Most, 2016a).

An overview of the safety standards is given in Figure 2.2. The safety standards shown in this figure are the current standards as described in the Water Act.

Relevance for flood risk management strategies

To reduce flood risk in the Netherlands, flood risk management strategies are developed. Sometimes the emphasis must be on reducing the probability of flooding and sometimes on reducing the possible consequences. To implement the optimal measure, knowledge on flood risk is necessary. Moreover, measures cannot be implemented at once as this is too costly: flood risk maps give insight in the prioritising of the required measures. Concluding, flood risk assessment is very important to support policy decisions on cost-effective safety standards and measures.

Figure 2.2: Overview of the minimum safety standards in the Netherlands (Slootjes and Van der Most, 2016a)

2.2. Flood fatality risk analysis

This section shows how flood fatality risk is assessed in the Netherlands. 'Loss of life' is the term for the number of fatalities due to flooding. The determination of loss of life is based on three elements: the number of people at risk, the mortality rate, and the evacuation fraction.

In formula form:

$$N = F_d * (1 - F_E) * N_{PAR} \tag{2.1}$$

In which:

F_d = Mortality rate [-];

F_E = Evacuation fraction [-];

N_{PAR} = Number of people at risk [-];

N = Number of fatalities [-].

Figure 2.3 shows an overview of the approach. As can be seen in this figure, the mortality is determined by multiple aspects: the flood characteristics, fleeing/sheltering, and people's vulnerability and behaviour. The fleeing/sheltering during flooding and the vulnerability and behaviour of the people are implicitly included in the mortality functions, because the mortality functions are based on the 1953 event which included these aspects. Although this thesis focuses mainly on mortality, it is important to be also familiar with the other concepts. Therefore, some of these concepts are described briefly in the following paragraphs.

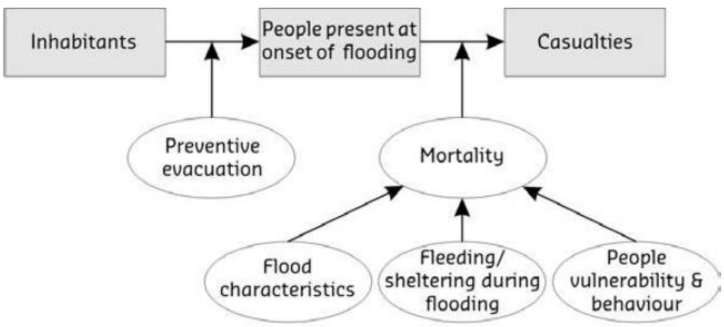


Figure 2.3: Overview approach for loss of life (De Bruijn and Van Kester, 2015)

Preventive evacuation

Preventive evacuation is described in this thesis as people moving out of the endangered area before the arrival of the floodwater. Therefore, it has an impact on the number of people exposed and thus the number of fatalities. Evacuation models are developed to estimate the number of evacuated people for an area within a time frame. Traffic models help predicting the required time for the evacuation as evacuation is partly depending on the availability and capacity of roads and exits.

Evacuation can be successful or unsuccessful which depends on the amount of available time before the dike breach, the arrival time of the water in the endangered area, and the required time for the actual evacuation. The evacuation process can be divided into four phases (Jonkman, Vrijling, and Vrouwenvelder, 2008):

1. Detection and decision making
2. Warning
3. Response
4. Actual evacuation

Based on expert judgment, evacuation fractions are developed for different areas in the Netherlands (Maaskant, Jonkman, and Kok, 2009). The evacuation fractions differ per type of flood. For example, river floods are more predictable than coastal floods and the coastal areas are more densely populated which result in a higher evacuation fraction for river areas. An overview of the evacuation fractions in the Netherlands is given in Figure 2.4. The lower value of the bandwidth is used as evacuation fraction for the estimation of the individual risk (LIR) and cost-benefit analysis, and thus used for the safety standards (Slootjes and Van der Most, 2016a).

Not all people in the area will take the advice of the government to evacuate and will decide to stay home, this is called 'non-compliance'. It differs per area how large this group is who decides to stay in the endangered area. For river areas, this is assumed to be 10% and for the rest of the Netherlands this is assumed to be 20% (Pleijter and Kolen, 2016). The case study involves a river area, so the assumption is that 90% will take the advice of the government.

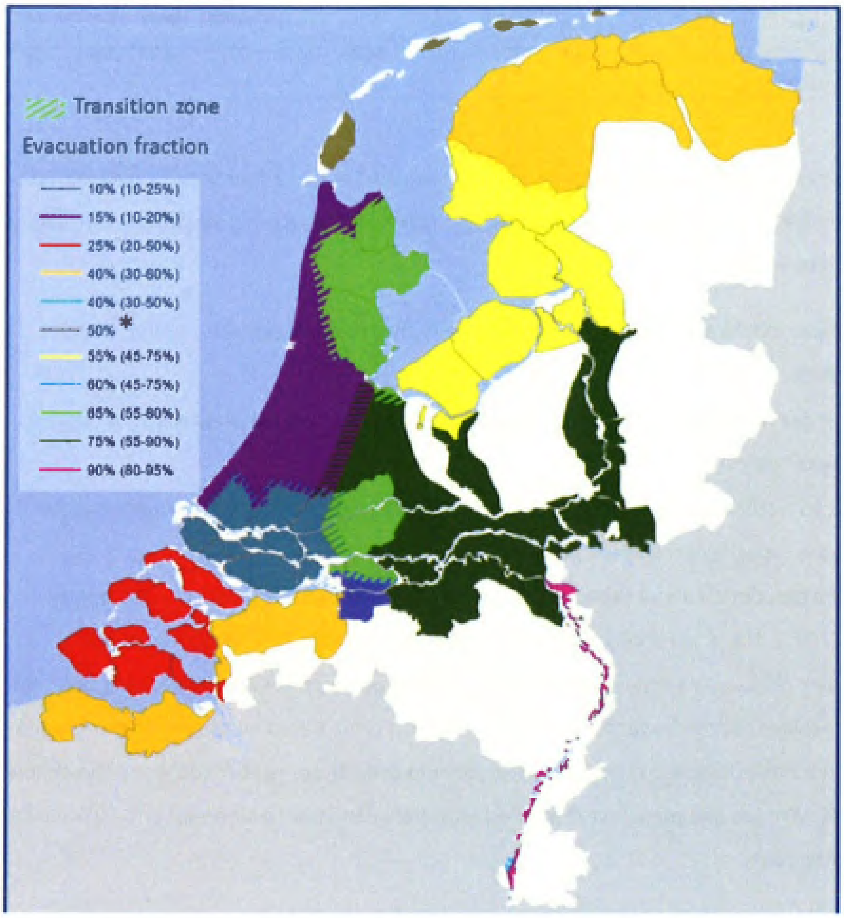


Figure 2.4: Overview of evacuation fractions (Kolen and Van Alphen, 2017)

Different studies have been done to check how many people can leave the area for an available time of 1, 2 or 3 days. When there is almost no time available and people decide to evacuate, they are more vulnerable as the floodwater could surprise them on their way out. In that case, vertical evacuation would lead to fewer fatalities. Vertical evacuation means that people are not leaving the endangered area, but seek shelter in upper areas (e.g. higher floors). Pleijter and Kolen (2016) did a study on different evacuation strategies and the effects by looking into the different locations of exposure. They made a division of four categories:

1. Fatalities by evacuation (e.g. road traffic accidents).
2. Fatalities during evacuation caused by the flood:
   a) Surprised by the flood: residents outside their houses surprised by the flood;
   b) Sheltering in the area: residents outside their houses surprised by the flood, but finding a place to shelter.
3. Sheltering: Fatalities caused by the flood in a public shelter.
4. Residents at home: Residents who did not evacuate and stayed home or in the home of others:
   a) Well-prepared;
   b) Not prepared.

For this study, categories 2 and 4 have the main focus as most flood fatalities are expected in these two categories.

Fleeing/sheltering during flood
Persons might move to a safe place during the flood event, e.g. high-rise buildings and higher grounds. This is called shelter or vertical evacuation. To estimate the number of people who find shelter, the area must be checked for shelter possibilities.

People can also be rescued. During the rescue, persons are moved to a safe place during the flood event by other persons, e.g. professionals. This depends on multiple aspects, such as the capacity of rescue organizations, the accessibility of the area, and the number of vulnerable persons in the area.

As mentioned above, the fleeing or sheltering during the flood is incorporated in the mortality functions, because the mortality functions are based on the 1953 event. However, the effectivity or possibility could have changed since 1953 and must be further investigated.

People vulnerability and behaviour
The vulnerability of the people plays a role as well in mortality, such as age, gender, health, and activity. Think of vulnerable places as schools, hospitals, and retirement houses. Especially age is an aspect that is looked into in more detail after a flood occurred. Hence, the distribution of fatalities was compared to the distribution of age of the population in 1953 which showed that people older than 60 were more vulnerable (Jonkman, 2007). This is similar to the conclusion of the study in Canvey Island: Canvey Island is an island in the United Kingdom which had 58 fatalities due to the storm of 1953. 42 out of the 58 fatalities had an age of over 60 (Di Mauro and De Bruijn, 2012). The flooding in New Orleans due to Hurricane Katrina in 2005 has also shown that the elderly formed a large part of the flood fatalities, nearly 60% of the fatalities were aged over 65 years (Jonkman et al., 2009). Age is thus an example of a parameter which must receive some attention.

Also, human behaviour is part of mortality. Think of fatalities due to activities as traveling across the floodwater, rescuing other people or rescuing belongings. Several studies show that males are more often concerned with these kinds of high-risk activities than females (Jonkman and Kelman, 2005). Boudou et al. (2016) noticed inadequate behaviour as well: during Cyclone Hyacinthe in 1980, 9 men younger than 20 years died by an attempt to cross a submersible road or by staying close to the flood.

2.3. International approaches

Flood fatality risk is also assessed in other countries. This section gives an overview of international loss of life approaches and on which knowledge it is based. The aim is to learn how important factors are included that could also be relevant for flood fatality assessment in the Netherlands. It must be noted that the conditions (flood characteristics, area characteristics, building quality, vulnerability, etc.) in other countries are different and that these differences must be kept in mind before transferring knowledge to the Netherlands.

The literature study shows that loss of life models are often based on two types of floods, floods due to dam breaking and due to levee breaching. This study focuses on levee breaching, but loss of life methods for dam breaking are also explored as this could give relevant insights.

One can point out that the approaches used worldwide can differ significantly. In the Netherlands, an empirical method is used for loss of life. Some countries, such as Canada, use an agent-based model, which means that it is based on an individual level instead of event or population level.

The main studies on loss of life methods are presented below per country as in many cases people continued on each others work. Four countries are considered as examples of international approaches: the U.S., U.K., Canada, and Japan.

U.S.

In the nineties, methods were developed for the estimation of loss of life as a consequence of dam failure. In these methods, the severity of the flood (water depth and velocity), the people at risk and warning were taken into account. Some studies on loss of life methods are shown item-wise below; note that this overview is a selection and that many more studies have been done on loss of life in the U.S.

- (Brown and Graham, 1988), U.S.B.R.: Assessed 24 dam failures and flash flood cases since 1950 to investigate loss of life. They made equations based on these historical data including people at risk and warning time in two or three categories.
- (DeKay and McClelland, 1993), U.S.B.R.: Continued on the work of Brown and Graham (1988) by adding data and they made separate equations for high and low force conditions. If more than 20% of the residences are destroyed or seriously damaged, it falls under high force conditions. Warning time is included as a continuous variable.
- (Graham, 1999), U.S.B.R.: Established a new method based on flood severity (low / medium / high), warning (no / some warning / adequate warning) and understanding of flood severity (vague / precise). In contrast to the model in 1988, now the response time to flood warnings is included. This resulted in 15 categories with each a fatality rate. Six categories are based on two or more case histories, four categories on one case and five categories are only based on judgment. This method is therefore strengthened with data in 2014, see that item below (Feinberg et al., 2016).
- (McClelland and Bowles, 2002), U.S.B.R.: Reviewed the existing methods for dam failure and proposed a new approach. In this approach, they made a distinction between three flood zones with each life-loss probability distributions, defined by available shelters, local flood depths and velocities, and debris. The zones are called the chance, compromised and safe zone and have an average mortality of 0.91, 0.12, and 0.0002 (Smith and Rahman, 2016).
- (Aboelata and Bowles, 2005), LifeSim: LifeSim, a dynamic simulation system, has been developed for the estimation of loss of life from natural floods and floods due to dam or levee breaching. LifeSim has the Deterministic Mode and the Uncertainty Mode and has four modules: Inundation, Loss of Shelter, Warning and Evacuation, and Loss of Life. The Inundation Module includes the flow characteristics (water depth and flow velocity) over the area. The Loss of Shelter Module takes into account shelter effectiveness by relating people's exposure to buildings with structural damage,

submergence of buildings, and toppling of people in damaged buildings. The Warning and Evacuation Module concerns the redistribution of the population due to warning and their exposure during evacuation. The Loss of Life Module contains probability distributions per zone, based on McClelland and Bowles (2002). In the past decade, the model has been further developed and validated, e.g. by data of Hurricane Katrina (Aboelata and Bowles, 2008; Needham, Fields, and Lehman, 2016).

- (USACE, 2006), IPET: The Interagency Performance Evaluation Task (IPET) of the USACE assessed the consequences of Hurricane Katrina. A new loss of life model was developed for New Orleans. They adapted the LifeSim model and used the Loss of Shelter and the Loss of Life Modules for that. During the flood event due to Katrina, most people died due to the submergence of buildings. Therefore, the Loss of Shelter Module is based solely on the building height with respect to the water depth. The IPET model takes people vulnerability into account as people aged over 65 are assumed to be unable to evacuate vertically above the highest habitable level. People aged under 65 can reach higher levels such as attics and roofs. The IPET model makes also use of zoning, but these differ from earlier work as it uses the walk away zone, safe zone, and compromised zone. Every zone has a mortality distribution, based on water depth, building height, and age.
- (Needham, 2010), HEC-FIA: HEC-FIA stands for Hydrologic Engineering Center - Flood Impact Analysis and is derived from LifeSim and is also developed for loss of life from natural floods and floods due to levee and dam breaching. HEC-FIA is the simplified version of LifeSim, because it does not dynamically simulate the behaviour and movement of the people during the flood event, which is the case in LifeSim. It uses three states for the distribution of the people: cleared, evacuating, and not mobilized (Jonkman et al., 2014). Cleared are the people who were able to find safety, evacuating (or called 'caught') are the people who are caught during evacuation, and the not mobilized people who stayed at their location.
- (Feinberg et al., 2016), U.S.B.R.: New (empirical) approach for loss of life modelling based on Graham (1999). It takes into account the product of depth and velocity, and the warning time. The warning time is divided into two categories: little to no warning and adequate warning. It depends on the area which category is applicable. The product of depth and velocity shows the flood severity. The method is called 'Reclamation's Consequences Estimation Methodology' (RCEM) 2014. As little data was available for flood severity understanding, see former U.S.B.R. method of Graham (1999), it is not explicitly part anymore of the new U.S.B.R. method.

Main conclusions: The parameters that are taken into account in the different methods in the U.S. are flood severity and understanding of flood severity, warning time or efficiency, age, available shelters, building collapse and when looking at micro level also human behaviour.

Brown and Graham (1988), and DeKay and McClelland (1993) concluded that loss of life is much higher in areas without or little warning compared to areas with at least a warning time of an hour. Graham (1999) states that dam failures with the highest fatality rates were events with no warning and with building collapses. This emphasizes the need to look into building collapse and warning time.

Moreover, age is taken into account (IPET model). People aged over 65 can only reach the highest habitable level and cannot reach the attic or roof. This expresses the vulnerability of the elderly and could possibly form an addition to the Dutch functions.

The development of LifeSim shows that one considers the use of more detailed models for the loss of life estimation by tracking individuals. Besides, this model takes into account the exposure of individuals in shelters in the 'Loss-of-Shelter' module (e.g. damaged buildings or submerged buildings).

The last remark applies to RCEM 2014 of the U.S.B.R., they point out that loss of life estimates "should be developed as ranges rather than single point values" (Feinberg et al., 2016). This differs from the Dutch approach.

U.K.

In the U.K., the 'Risk to People' model is in force. This model is developed by Ramsbottom, Floyd, and Penning-Rowsell (2003) for the Department of Environment, Food and Rural Affairs (DEFRA) and the Environment Agency. It is based on flood hazard, area vulnerability, and people vulnerability. The flood hazard includes the critical hydraulic conditions, the area vulnerability concerns the chance of people exposed to the flood, and people vulnerability refers to the ability of the affected people to respond to the flood.

The model is based on data of flood events in Norwich 1912 (4 fatalities), Lynmouth 1952 (34 fatalities) and Gowdell 2000 (no fatalities) and tested on data of the flood event in Carlisle 2005 (3 fatalities), (Priest, 2007). This risk model is different than the other models, as is it is not purely empirical but uses ranking based on expert judgment as well. It also includes information on stability tests. The stability tests in flumes have presented that people find difficulties in remaining stable in the floodwater at already low depth (25 cm) and high velocity (> 2m/s), (Wade et al., 2005).

Main conclusions: Mortality is a function of water depth, velocity, rise rate, warning time, arrival time, buildings and presence of vulnerable people (long-term illness, disability or age over 75). The flood hazard also includes a debris factor as debris could increase the hazard.

This approach gives insight into an alternative approach as the U.K. does not use a purely empirical model but makes use of expert judgement. The model includes the vulnerability of elderly and long-term ill people. Taken into account people vulnerability might be a good addition to the Dutch approach.

Canada

In Canada, a model was developed by British Columbia Hydro (BC Hydro) concerning individual paths in a flood with personalized probability distributions. It is called Life Safety Model (LSM) and was initially from the scope of floods due to dam breaks. The model takes into account the location and characteristics of (virtual) individuals, so it captures the behaviour and decisions made in detail at each time step (Assaf and Hartford, 2002). The LSM requires many detailed input variables: natural environment (elevation, water bodies), socio-economic environment (people, buildings, vehicles) and flood characteristics. This model was validated with data from the dam breach of Malpasset in 1959 in Southern France (Johnstone et al., 2005).

Main conclusions: The LSM takes into account many factors as well: water depth, flow velocity, water level rise rate, and water arrival time, and also building collapse, evacuation, warning and human behaviour.

This model is agent-based, thus includes detailed data at individual level and structure-specific, and differs significantly from the Dutch approach. Behaviour plays an important role and simulating behaviour could, therefore, be insightful. However, the LSM requires a large amount of input which could result in large uncertainties.

Japan

In the eighties and nineties, the first studies were carried out on mortality because of large typhoons hitting Japan. In 1985, relationships were derived for typhoon Jane and typhoon Isewan which were purely based on water depth (mentioned in Jonkman (2007)). Mizutani analyzed historical data of Japan in the period 1946-1995 to develop parameters for typhoons (mentioned in Zhai, Fukuzono, and Ikeda (2006)).

Zhai, Fukuzono, and Ikeda (2006) have developed an empirical model for river and coastal flooding based on 269 historical flood events in Japan in the period 1947-2001. The historical data is mainly based on the disaster types heavy rain and typhoons. The model takes into account the relation between mortality and inundated residential buildings only.

Main conclusions: In contrast to the other models, this model takes into account one parameter: inundated buildings.

Japan has been hit many times by severe typhoons with flooding as a consequence. The disaster type differs significantly from the Dutch flood hazards and this makes it hard to make comparisons with the flooding in the Netherlands. Taking into account only inundated residential buildings, might not be enough as many other factors are presumed to be important in the Netherlands.

Other

Peng and Zhang (2012) introduced a new Human Risk Analysis Model (HURAM) which is based on Bayesian networks. A Bayesian network is a probabilistic (graphical) model that consists of nodes and connections with conditional dependencies and is often used for risk analyses. This way, inter-relationships are better included in the loss of life estimation. The network is based on the use of nodes and states, such as seven states for water depth (0-1.5m, 1.5-3m, and so on). In their study, they quantified the basic nodes in the network with data of 343 dam-failure cases from different countries, most of them in China and the U.S. The network is completed with regression analyses of parts of historical data (corresponding with the flood severity states), with assumptions based on literature and with Monte Carlo simulations. They state that the loss of life estimation is mainly based on flood severity, water depth, evacuation and warning time.

Boyd, Levitan, and Heerden (2005) analyzed seven flood events and suggested an S-shaped fatality curve versus water depth. They indicate that the mortality cannot exceed 0.34 (for water depths above 4 m) following the underlying assumption that there will always be survivors. The advice is to interpret this value as a rough upper limit to make a quick estimation of flood fatalities.

Main conclusions: The Bayesian network of Peng and Zhang (2012) contains 14 nodes which are summarized in this study into the main factors water depth, flow velocity, water arrival time, warning, evacuation, and shelter.

The belief that there will always be survivors could be an addition to the Dutch approach in the breach zone. Although the flood conditions in the breach zone are very severe, a mortality of 1 might be too conservative.

Overview models

Jonkman et al. (2016) made an overview that gives insight into the level of detail and the underlying model principles, see Figure 2.5. The Graham and U.S.B.R. method, used in the U.S., are empirical models on macro-scale. Many models are on meso-scale, under which the model of Jonkman for the Netherlands and the Flood Risks to People model for the U.K. When looking at micro-scale, the models become more mechanistic than empirical, and require many input variables. LifeSim and LSM are examples of these models.

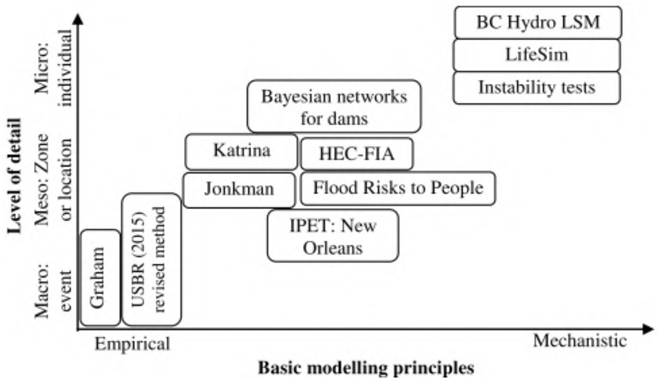


Figure 2.5: Overview of available models (Jonkman et al., 2016)

The models relate mortality in different ways to the flood and other characteristics. Some of the models are specifically for dam failure, such as the U.S.B.R. method, and are thus less suitable for river flooding. These models were mentioned to study their approaches and to see if this could give relevant insights for adaptations in the Dutch approach.

In Table 2.1, an overview is given that summarizes the concepts and the included factors. Moreover, the main strengths and weaknesses are given and a column is added to present aspects that might be relevant for flood fatality risk in the Netherlands.

In this table, also the 'PBL' method is added (Pleijter and Kolen, 2016), this model is introduced in Section 2.2. The PBL method proposed mortality functions based on spatial differentiation: people on the road (in the car), in shelters, and at home (well-prepared or not prepared).

Table 2.1: Summary loss of life approaches used internationally

(a = age; bc = building collapse; d = water depth; Db = debris; e = evacuation; fb = flooded buildings; hb = human behaviour; pv = population vulnerability; s = shelter; t = water arrival time; v = velocity; w = water level rise rate; W = warning)

	Model	General concept	Factors included (explicit or as concept)	Main strengths	Main weaknesses	Relevance for NL?
the Netherlands	Jonkman	Levee breaches, river and coastal floods Based on 1953 event Flood characteristics	d, e, v, w	Quick to apply Insight flood characteristics- mortality	Based on Zeeland in 1953, thus, implicit factors assumed representative for other potential events and locations.	N/A
	PBL	Levee breaches, river and coastal floods Looks into locations of exposure Focus on evacuation strategies	d, e, v, w	Insight for evacuation strategies and crisis management	Assumptions in division mortality categories and for mortality fractions in some categories	Improved evacuation strategies (preventive vs vertical)
U.S.	U.S.B.R. method	Dam failures Based on 60 cases Selection on warning and DV product	d, v, W	Based on many historical cases Presents uncertainty (life loss as range)	Direct evacuation not included Requires judgment on selecting fatality rates	Loss of life in ranges
	LifeSim	Dam and levee breaches, river and coastal floods Agent-based Dynamic simulation	bc, d, e, hb, t, v, W	Able to simulate different types of floods Insight at individual level Detailed output, visualisation Useful for dense populated areas (evacuation patterns)	Requires detailed input and thus, many assumptions Large preparation effort Not suitable for large-scale	Insight at individual level Includes behaviour and building collapse
	HEC FIA	Dam and levee breaches, river and coastal floods Derived from LifeSim	bc, d, e, t, v, W	Simplified LifeSim: more easy to implement	Less extended evacuation model than LifeSim	Includes building collapse
	IPET - New Orleans	Levee breach (New Orleans) Based on Hurricane Katrina Derived from HEC FIA	a, d, s, W	Specific for New Orleans area	Derived from HEC FIA, some underlying LifeSim assumptions Contains uncertainty due to complexity evacuation process and lack of information on death circumstances during Katrina*	Includes age and shelter
U.K.	Flood Risks to People	River and coastal floods Based on expert judgment and stability tests	bc, d, Db, pv, t, v, w, W	Applicable also without exact flood characteristics Applicable on different scales (e.g. event, regional or national)	Many explicit parameters Sensitive to people vulnerability	New insight method Includes people vulnerability (age/sick/disabled)
Canada	Life Safety Model (BC Hydro)	Dam and levee breaches Agent-based Dynamic simulation	bc, d, e, hb, t, v, w, W	Insight at individual level Detailed output, visualisation Useful for dense populated areas (evacuation patterns)	Requires detailed input and thus, many assumptions. Large preparation effort Not suitable for large-scale Sensitive to input parameters and initial conditions**	Insight at individual level Includes behaviour and building collapse
Japan	Empirical model	River and coastal floods Based on 269 floods Only inundated buildings	fb	Quick to apply Based on many historical cases	Very limited as single-parameter model	Insight in relation mortality-inundated buildings
Other	HURAM	Bayesian networks Based on 343 dam failures	d, e, s, t, v, W	Graphical representation of large number of parameters and their inter-relationships Based on many historical cases	Complex: one parameter influences the other parameters due to inter-relationships	New insight method

*(Link et al., 2009)
**(Di Mauro, De Bruijn, and Meloni, 2012)

2.4. Analysis EM-DAT: general trends in Europe

The Emergency Events Database (EM-DAT) is used to investigate the trends in flooding over the past recent years. This database was introduced by the Centre for Research on the Epidemiology of Disasters (CRED) and created in cooperation with the World Health Organisation and the Belgian Government in 1988 (*EM-DAT: The Emergency Events Database - Université catholique de Louvain (UCL) - CRED* 2019).

The events need to satisfy at least one of these criteria:

- At least 10 fatalities or;
- at least 100 people affected or;
- the declaration of a state of emergency or;
- a call for international assistance.

The number of affected people is used as the number of people exposed to determine the mortality to investigate general trends. The number of people affected is defined by EM-DAT as "*People requiring immediate assistance during a period of emergency, i.e. requiring basic survival needs such as food, water, shelter, sanitation and immediate medical assistance*".

Trends expected

Multiple studies have been carried out to find the general trends in flooding in the past years. Jonkman (2007) analyzed the mortality rates per flood type for events defined in EM-DAT in the period 1975-2002. It showed that the mortality rate can differ significantly per different type of flood. For example, flash floods can occur very suddenly which makes them more dangerous than a well-predicted flood. The average mortality rate for flash floods is 3.6%. For coastal floods, this is 1%. This is similar to the mortality rate of the 1953 event which was also 1%. For river floods, it is around 0.5%.

Paprotny et al. (2018) analyzed European flooding data from the HANZE database for the period 1870 – 2016 and found (after making corrections for flood exposure) a significant reduction in the number of fatalities, but an increase in inundated area and the number of persons affected. More specifically, they found a decrease in flood fatalities of 1.4% per year since 1870 and 4.3% since 1950. This reduction could be explained in many ways, such as the improvement of early-warning and communication systems, transport means, etc.

Bouwer and Jonkman (2018) investigated the trends on global mortality for coastal floods. They concluded that the mortality for storm surges has decreased in the period 1900-2015. Jongman et al. (2015) looked at the trends of river floods on a global scale in the period of 1990-2010 from data of the NatCatSERVICE database and found declining mortality rates as well. Their results show that the average mortality decreased relatively faster in lower income countries than in higher income countries.

Analysis

The EM-DAT database makes a division in coastal, riverine and flash floods. In this analysis, the focus is on riverine flooding in the past years, hence flash floods are not a part of it. There is a significant difference in the number of reported events per decade. In the period 1950-1990, only 21 events are available in total. Therefore, the focus of this study is on the period 1990-2019.

In the period 1990-2019, 248 riverine floods are reported in the database. The total number of fatalities is 1,941 and the average event mortality is 0.3%. Lots of events have zero fatalities and/or do not have data on the number of people affected. When removing these events, a number of 125 flood events remain for which the event mortality can be calculated. The average event mortality is then 0.5%. This is the same outcome as the average event mortality which is expected based on earlier research of Jonkman (2007) on data in the period 1975-2002.

The overview is given in Figure 2.6 and the distribution of the event mortality in Figure 2.7. There are a few outliers in the event mortality, namely the flood event in Portugal in 2010 with an event mortality of 7.17% (43 out of 600), Spain in 2010 with 6.67% (2 out of 30), and France in 1994 with 4.76% (10 out of 210).

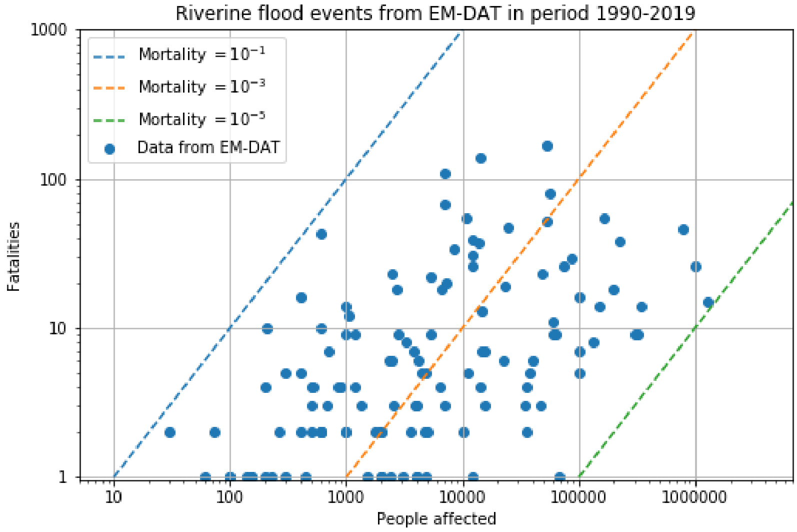


Figure 2.6: Riverine flood events: people affected and fatalities

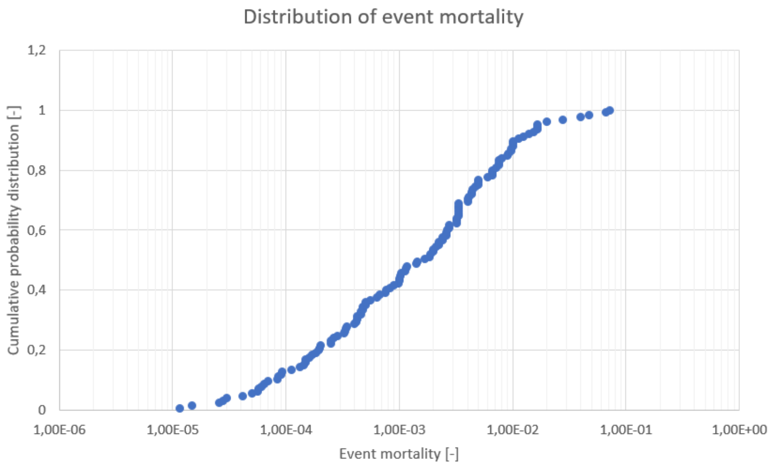


Figure 2.7: Riverine flood events: distribution of event mortality

The Russian Federation had to cope with large riverine flood events. The three largest are in 1993 with 138 fatalities, in 1994 with 46 fatalities, and in 2002 with 168 fatalities. Also Romania had suffered large flood events, such as in 1991 with 108 fatalities, in 2005 with 79 fatalities, and in 2006 with 37 fatalities and many more (smaller) floods with fatalities.

The five deadliest riverine floods in the database are:

1. Russian Federation 2002 with 168 fatalities
2. Russian Federation 1993 with 138 fatalities
3. Romania 1991 with 108 fatalities

4. Romania 2005 with 79 fatalities
5. Italy 1994 with 68 fatalities

Figures 2.8 and 2.9 give an overview of the number of fatalities and affected people over the past recent years. Note that the vertical axes have a different scale.

The year 2002 has the highest number of fatalities. In this year, major floods occurred in Europe due to heavy rainfall as a result of rain-bearing depressions, in literature referred to as the 'Central European floods'. Flood fatalities occurred in many countries, such as Austria, Czech Republic, and the Russian Federation.

The year 2013 stands out because of the large number of total people affected. Especially the Czech Republic was hit hard and account following EM-DAT for 1,300,000 people affected. The year 2014 is also standing out due to the 'Southeast Europe floods' which affected Serbia and Bosnia and Herzegovina the hardest. The number of people affected of 1,000,600 is enormous in Bosnia and Herzegovina. Many countries in Europe helped out in the disaster relief (UNICEF, 2014).

Conclusion
When looking at a relatively small time scale (1990-2019), there is no clear decline visible in the number of fatalities, but research of Paprotny et al. (2018) and Jongman et al. (2015) have shown that there is a trend of a declining number of flood fatalities. The analysis of the EM-DAT data from 1990-2019 confirms that mortality of river flooding is relatively low, in the order of 0.3 - 0.5%.

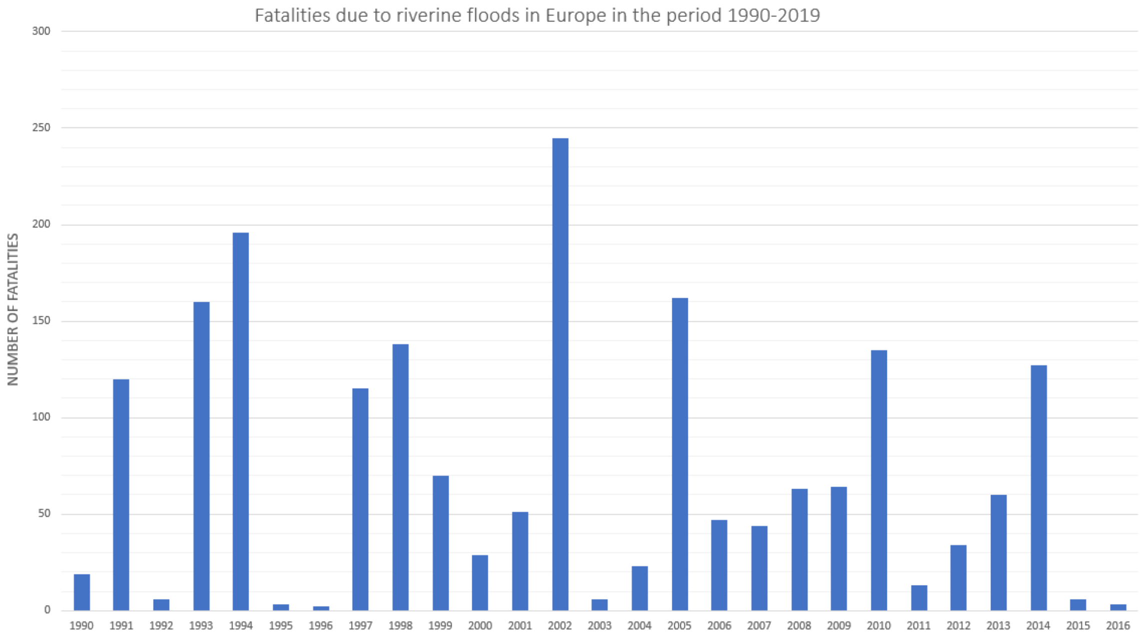


Figure 2.8: Number of fatalities over the years

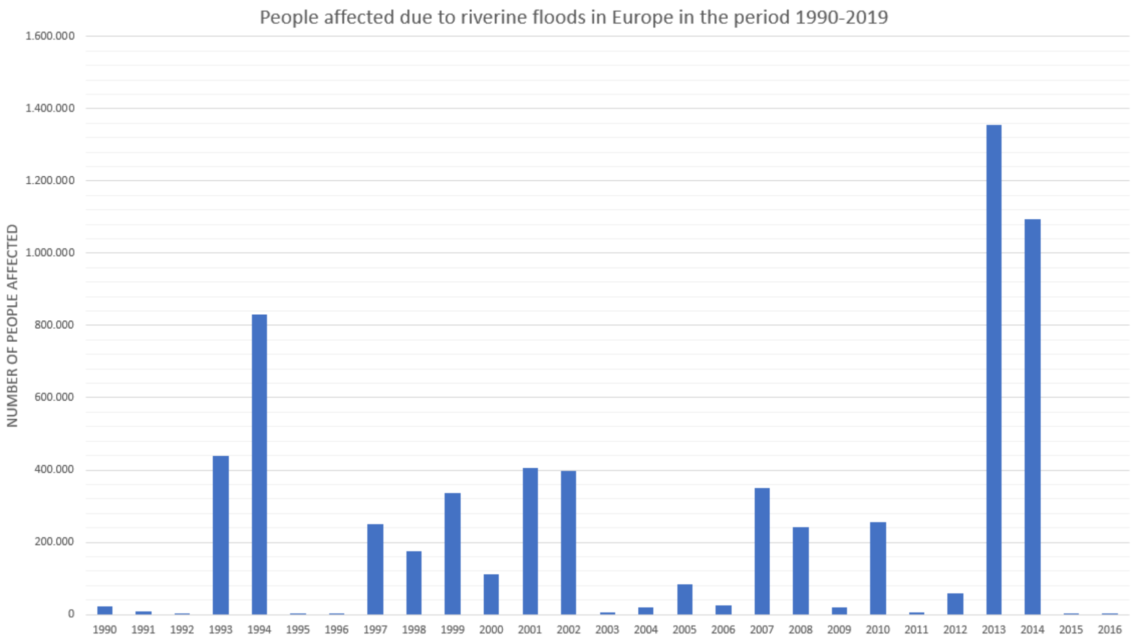


Figure 2.9: Number of affected people over the years

2.5. Lessons learnt from other floods

This section presents some important lessons learnt for this study from other floods elsewhere in the world. The selected floods are based on levee breaches, some of them are comparable with the 1953 event or are in another way relevant to this study. The flooding due to Hurricane Harvey is included because a study has been done about the loss of life.

Canvey Island, U.K. - 1953: The 'Watersnoodramp' affected the U.K. as well: it caused 58 fatalities on Canvey Island due to levee breaches (Di Mauro and De Bruijn, 2012). Almost all fatalities had drowning as a death cause (Di Mauro and Lumbroso, 2008). Similar to the Netherlands, the people were not warned about the coming flood. What stands out, is that 42 out of the 58 fatalities had an age over 60 which suggests that elderly people are more vulnerable to floods. This has to be compared to the age distribution to check if this conclusion is justifiable.

New Orleans, Louisiana - Hurricane Katrina, 2005: In August 2005, Hurricane Katrina hit the coast at New Orleans with a large storm surge resulting in a large-scale flood. The flood led to more than 1,100 fatalities in Louisiana. About 80% of the residents were evacuated and about 10% stayed in shelters which suggests that about 10% of the people were still in the endangered area (Miller, Jonkman, and Van Ledden, 2015). The mortality rate for the flooding of New Orleans is approximately 1.1% which is similar to the mortality rate of the 1953 event in the Netherlands. The flooded area was enormous, about 260 km^2, and the water depth was in some places even more than 5 meters (Jonkman, 2007). Jonkman et al. (2009) showed that age was a remarkable characteristic: 85% had an age over 51 years, 70% over 60 years, and almost 50% over the 75 years.

France - Storm Xynthia, 2010: In February 2010, the storm Xynthia hit the French coast causing several dike failures and with that a large flood with 47 fatalities (Kolen et al., 2010). Just like the 1953 event, the people were not warned (for the flood, only for the storm) and were surprised by the floodwater. Kolen et al. (2010) states that some houses in La Faute-Sur-Mer experienced 2.5 meters of water level rise within half an hour. The flooded buildings were built in flood-prone areas and consisted mainly of only a ground floor with (electric) shutters or steel bars on the windows which caused that the people were trapped in their own houses and drowned. Rescue teams consisting of emergency workers, firemen, and people from the army saved over 500 people. Some of the houses had a hole in the ceiling which formed an escape. The fatalities in La Faute-Sur-Mer were related to poor policy decisions as 85% of the fatalities lived in one-storey houses, so without a refuge floor, and the houses were built just below the coastal dikes (Boudou et al., 2016). Another important aspect is the relatively high age of the residents as this area was a popular place for many retired people. As mentioned in Section 2.2, most victims were aged over 60 years. One of the other lessons learnt is that the warning must be simple and explicit so all people understand the message and can act on it.

Houston, Texas - Hurricane Harvey, 2017: Hurricane Harvey caused very heavy rainfall, and in combination with dam releases, it caused floods with major consequences. It caused 70 fatalities and an analysis is made about the causes of death by Jonkman et al. (2018a). 81% of the fatalities were caused by drowning from which the most people were found outside with unknown details (16 out of 57 drowned fatalities) and were drowned in a vehicle or swept away by the current (21 out of 57 drowned fatalities). Again, people above 50 years old turned out to be more vulnerable. The fatalities were for 70% male, similar to the findings of Jonkman and Kelman (2005). Regarding the flood characteristics: the water depths, flow velocities, and rise rates were lower than with the flooding of New Orleans. The mortality rate for this storm is 0.1% (Jonkman et al., 2018a). The fact that people were better warned could also play a role.

2.6. Causes of death

This thesis focuses on possible improvements of the current mortality functions, therefore, it is important to have a good understanding of the circumstances of flood fatalities. Every loss of life is a tragedy, but the cause of death could differ significantly. Old, vulnerable people drowning in their apartments ask for different improvements then young, risk-seeking people. The latter suggests looking into the awareness of the people for the danger of floods. This section aims to examine these circumstances based on the available literature as multiple studies have been carried out about this topic.

Jonkman and Kelman (2005) made an overview of the classification of flood disaster deaths. They made a division in medical causes and (corresponding) activities, timing, gender, age, and lack of judgment. They analyzed 13 small-scale floods (less than 50 fatalities) and categorized the data following the classification they suggested. The 13 events are from the U.S. and from Europe; in the U.S. mostly events with wind storms and in Europe mostly river flood events. The 13 events together had a total number of 247 fatalities. The results of the distribution are shown in Figure 2.10 or more elaborately in Appendix A. This figure reveals that most people die because of drowning in their vehicle and on foot, circa 68% in total. Most people die in their vehicle, this is explained by Jonkman and Kelman (2005) as fatalities due to attempts to travel across the floodwater on roads and bridges. However, this is mainly the case in the U.S. and the number is much lower in Europe; 45% drowning in the vehicle in the U.S. vs. 13% in Europe.

This study also shows that one-third of the fatalities are due to different causes of death than drowning. This part consists of physical trauma and other causes, see Figure 2.10.

Increased vulnerability based on age could not be found in this research in contrast to other studies. However, they did find an increased vulnerability for gender: 70% of the fatalities were male. This is especially the case for the vehicle crashes and drowning. They indicate that more males drive and work for the rescue services and have more risky behaviour.

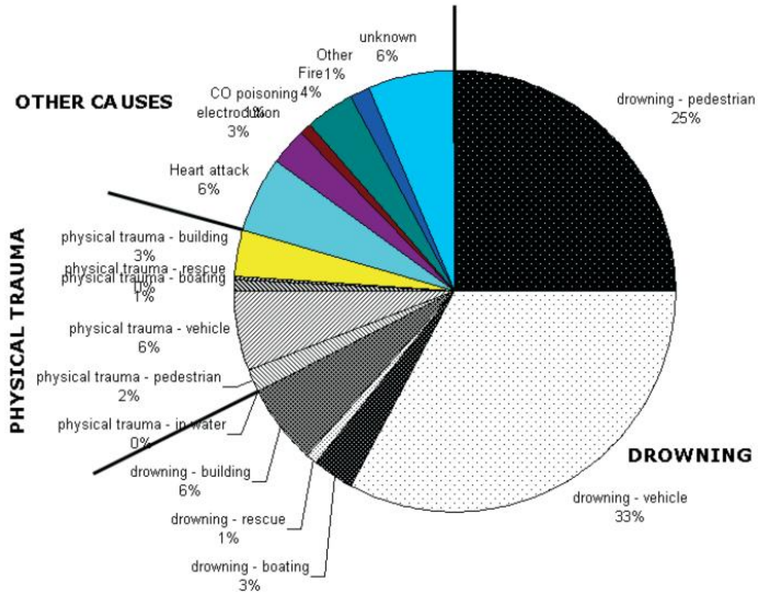


Figure 2.10: Distribution of causes of death for 13 flood events (Jonkman, 2007)

Priest (2007) analyzed the fatalities of the European flood events in 2002 regarding age and cause of death, Figure 2.11 shows the overview. It shows that the cause of death differs per age category. The age categories 10-29 are fully vehicle-related while the elderly are mostly drown in their homes or outside.

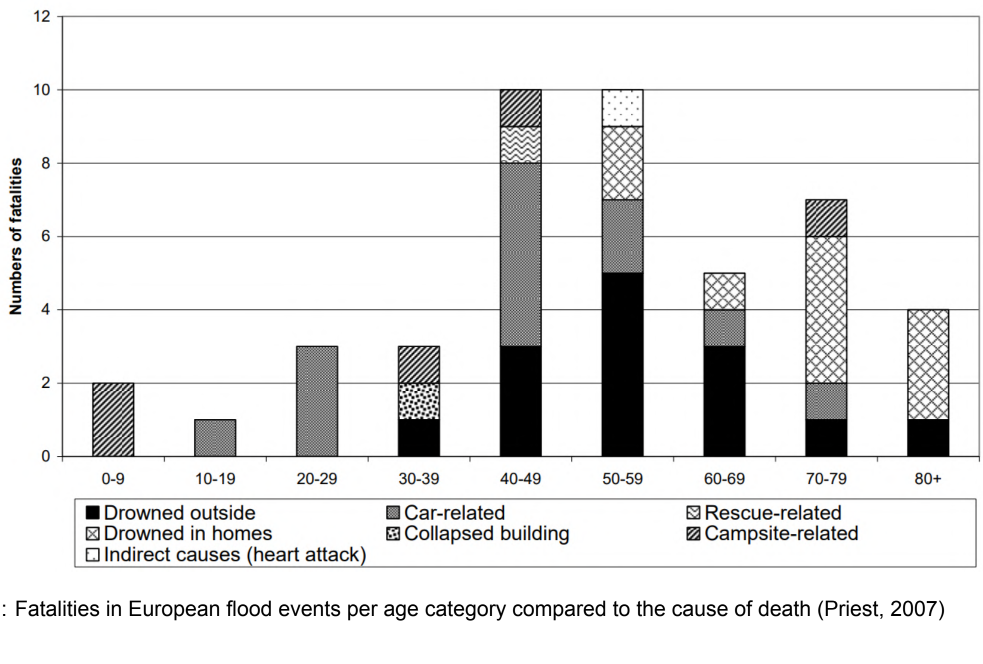


Figure 2.11: Fatalities in European flood events per age category compared to the cause of death (Priest, 2007)

S. T. Ashley and W. S. Ashley (2008) did research on flood fatalities in the U.S. based on data in the period 1959-2005. Flash floods and floods associated with tropical storms were the types of flood they found to be most dangerous as the number of fatalities is large. They have some conclusions on the circumstances of all deaths reported.

63% of their data was vehicle-related, 14% occurred outside, and 9% was in water. 'Outside' is defined as people accidentally falling or being swept away and 'in water' is defined as people attempting to walk through the floodwater. From the 9% of flood fatalities in water, 16% had the purpose to evacuate or to rescue another person, but as much as 43% tried to reach a certain destination. This underlines the importance of flood awareness and behaviour. They also concluded that people between 10 and 29 years or older than 60 years are more vulnerable to flooding. This was compared and checked with data of the U.S. population.

Diakakis and Deligiannakis (2017) assessed the circumstances of 151 flood fatalities based on 53 flood events in Greece in the period 1970-2010. In this period, they found a declining event mortality rate that is partly due to increased building quality associated with the stricter building codes in Greece. The main cause of death is drowning (79%). The other causes of death (physical trauma, heart attack, and electrocution) formed a considerably lower part. Furthermore, this research presents vehicle-related fatalities as main activity (40%) and occurred in situations related to the road network. Regarding gender, there is an over-representation of male victims (63%) against female victims (31%), the other cases do not have the gender reported (6%). Furthermore, the research shows that approximately 33% of the flood fatalities were due to risk-taking behaviour (e.g. travelling through floodwaters).

Petrucci et al. (2019) did research on 458 fatalities of Mediterranean flood disasters in five study areas in the period 1980-2015. The main findings were that the majority of the fatalities were male, occurred outdoor, and had an age between 30 and 49. The main cause of death was drowning.

FitzGerald et al. (2010) also noticed an over-representation of men and in the drowning cases an over-representation of people aged between 10 and 29 and aged over 70 years. This research was based on flood fatalities in Australia in the period 1997-2008. Again, a large part was due to risk-taking behaviour (27%).

In addition, research of Salvati et al. (2017) in Italy and research of Pereira et al. (2016) in Portugal showed a majority of male flood fatalities with an outdoor location and in Portugal also inside of buildings in rural areas.

2.7. Conclusions and discussion

This section provides the conclusions and discussion concerning flood fatality risks and their assessment.

2.7.1. Conclusions

The literature study presented the basic concepts of flood (fatality) risk and concluded that flood risk assessment is very important to support policy decisions on cost-effective measures and safety standards.

General trends were hard to identify for river flooding making use of data of EM-DAT for the period 1990-2019, but the literature study has shown that there is a declining trend of flood fatalities.

Section 2.3 presented an overview of international loss of life approaches including their possible relevance for the Dutch approach. The factors that are taken into account in these international approaches are considered in the next chapter. They are shown item-wise below.

<u>Factors:</u>

- Behaviour
- Building characteristics
- Debris
- People vulnerability, such as age over 75 and long-term illness

- Shelter possibilities
- Warning
- Water arrival time

Also, the circumstances of flood fatalities were analyzed in the literature study and in lessons learnt of other floods. The lessons learnt related to the circumstances of flood fatalities are shown item-wise below.

Causes of death:

- The main cause of death is drowning.
- A significant part of the causes of death is due to other causes than drowning.
- Floods in the past show that a large part of the fatalities are the elderly people, which suggests age vulnerability.
- One-storey houses: people can be trapped in their homes and drown as there is no refugee floor.
- A large part of drowning is vehicle-related.
- A large number of fatalities were found outside.
- In some flood events, males were over-represented partly due to risk-taking behaviour. Awareness of flood risk is, therefore, important.

2.7.2. Discussion

The literature review looked into both large-scale flooding and small-scale flooding. It was observed that large-scale flooding involves different circumstances compared to small-scale flooding. In small-scale flooding, the literature showed that a large part of the fatalities (less than 50 fatalities) were found outside and related to risk-taking behaviour and gender (Jonkman and Kelman, 2005). In large-scale flooding, such as the 1953 event in the Netherlands and the flood event in New Orleans in 2005, building collapse can play a large role; many buildings were destroyed due to the severe flood conditions because of breaches in the dikes in these events. While in small-scale flooding many fatalities are found outside, the New Orleans flood shows that 54% of the fatalities were found in their residences and only 7% outside (Jonkman et al., 2009). Especially elderly turned out to be more vulnerable, while the factor gender did not play a role in these events (more or less 50-50 division).

This study focuses on large-scale (unexpected) flooding due to dike breaching, hence, building collapse and people vulnerability are expected to be more relevant than risk-taking behaviour, and age more relevant than gender.

3

Current mortality functions and potential directions for improvement

This chapter gives the background and motivation of the current mortality functions and provides knowledge on how they are derived (Section 3.1). Important factors are identified and further discussed based on literature review in Sections 3.2 and 3.3. Section 3.4 summarizes the factors and presents the main focus, then the points of discussion are translated into potential preliminary alternative mortality functions in Section 3.5 which can be tested in the case study.

3.1. Background and motivation

Mortality is defined as the proportion of the number of fatalities and the number of exposed people in the flood zone, in literature also referred to as death or fatality rate. The mortality is used to calculate the number of fatalities caused by a flood event.

The first question is which fatalities are counted and which are not. Some studies make the division in direct and indirect fatalities where others divide the fatalities in the timing of death. This thesis follows the definition of De Bruijn et al. (2011), which only takes into account the direct fatalities, such as drowning and physical trauma, but also other direct causes such as heart attacks or electrocutions as a result of the flooding. This means that post-flood mortality, such as diseases, famine or house collapse on the longer term, is not part of the mortality functions and thus out of scope.

The mortality rate is mainly based on the flood characteristics of the event, such as the water depth, water level rise rate, and the flow velocity of the water. Flood simulations can be used to analyze the development of the flood pattern. However, not only the flood characteristics determine the mortality, there are many other (implicit) factors that have an influence. This will be further investigated in Section 3.2. The mortality is thus a function of multiple aspects, then referred to as mortality functions. Thus, the mortality functions relate the flood characteristics to the mortality rate and help to identify the risky locations in the Netherlands and thus which locations risk suffering most fatalities.

3.1.1. Flood characteristics

There are many flood characteristics that could contribute to mortality, such as flow velocity, water depth, water level rise rate, flood duration, water temperature, waves, water quality, etc. Unfortunately, there is a lack of data to implement all these factors in the mortality functions. The most reliable data is available for the water depth and this factor plays an important role in the determination of the mortality rate. But also the flow velocity and rise rate play an important role. In the 'Watersnoodramp' in 1953, 61% of the fatalities occurred in an area with rapidly rising water, 15% in an area with high flow velocities and the other

25% in other flooded areas (Asselman, 2005). The factors water depth, rise rate, and flow velocity will be further discussed in the following paragraphs.

Water depth

Some parts of the Netherlands are low-lying areas where the water depth can be rather high. It can be up to around 6 meters in some of the very low-lying polders. The larger the water depth, the more unsafe the situation as the possibility to find shelter will decrease. One could say that if the water depth is larger than 1.5 m, the water is located between chest and head which results in a dangerous situation for people. Especially in combination with high rise rates or high flow velocities. These variables will be explained next.

Water level rise rate

The water level rise rate gives an indication of how fast the area is filled with water. This parameter depends on the flow velocity as well as the water depth. High rise rates are expected in small, deep areas, so the rate is also influenced by the size and elevation of the area. These areas could be closed off by a dike, an elevated (rail) road or a natural slope that prevents the water flow of escaping the area, resulting in a large water depth. A high rise rate could cause dangerous situations as people are surprised by the water and do not have much time to find shelter. The combination of a high rise rate and a large water depth is extra dangerous as higher floors could also be affected. An example is a small, low-lying polder.

As mentioned in the previous paragraph, a water depth of 1.5 m is considered as dangerous, and the rise rate is therefore advised to be averaged till this level is reached, see Figure 3.1. Generally, rise rates larger than 0.5 m/h (till a water depth of 1.5 m) are considered high.

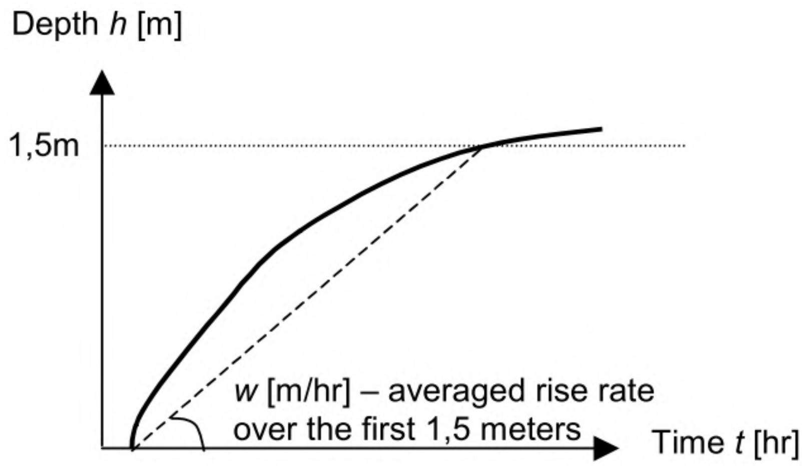


Figure 3.1: The rise rate is averaged over the first 1.5 meters (Maaskant, Jonkman, and Kok, 2009). The counting starts when the depth is 2 cm (arrival time is not included).

Flow velocity

High flow velocities are expected close to the location of the breach. Besides the fact that high velocities are dangerous for people as they could lose their balance, it could also result in the collapse of buildings (Waarts, 1992). Very high flow velocities could, therefore, increase the mortality.

These flood conditions (or combination of flood conditions) determine the mortality fraction for locations within a flooded area. The depth-velocity product, the combination of water depth and flow velocity, is also included as criterion to divide the flood area into different zones. This is further explained in the next section.

3.1.2. Development of mortality functions over the years

Multiple studies have been done on the mortality functions over the past years. It all started with Duiser in 1989, he introduced the relation between water depth and the mortality rate after the collection of the data of 1953. Waarts elaborated more on the work of Duiser in 1992 by adding more data and aspects. He studied the event of 1953 and found out that the rise rate was the deadliest cause of this event. Moreover, he decided to divide the area into three areas: an area with large water depths and high rise rates, an area with high flow velocities and an area with fatalities due to other causes, mainly due to large water depths. He worked also on a model that includes warning, evacuation, high flow velocities, and building collapse (Waarts, 1992).

Vrouwenvelder and Steenhuis (TNO) developed a model for sea and river floods taking into account three types of drowning: (1) drowning because of building collapse near breach; (2) drowning because of building collapse due to wave attack; and (3) other causes of drowning. They included the probability of a river or coastal storm and linked it to building collapse. As the probability for a river storm is smaller than for a coastal storm, the number of fatalities for river floods were lower.

Also others derived functions, see Table 3.1. Jonkman (2004) reviewed all these models and did research on the set-up of a new loss of life model. He continued with the zoning as already introduced by Waarts in 1992, and mentioned also three areas which are called: the breach zone, the zone with rapidly rising water, and the remaining zone, an example is shown in Figure 3.2. These areas have each a separate mortality function, based on the flood characteristics. The flood conditions have been translated to criteria, the criteria and corresponding mortality functions are given for the current approach in Section 3.1.3. The model of 2004 has been implemented into a computer model (HIS-SSM) which can estimate the expected damage and number of fatalities.

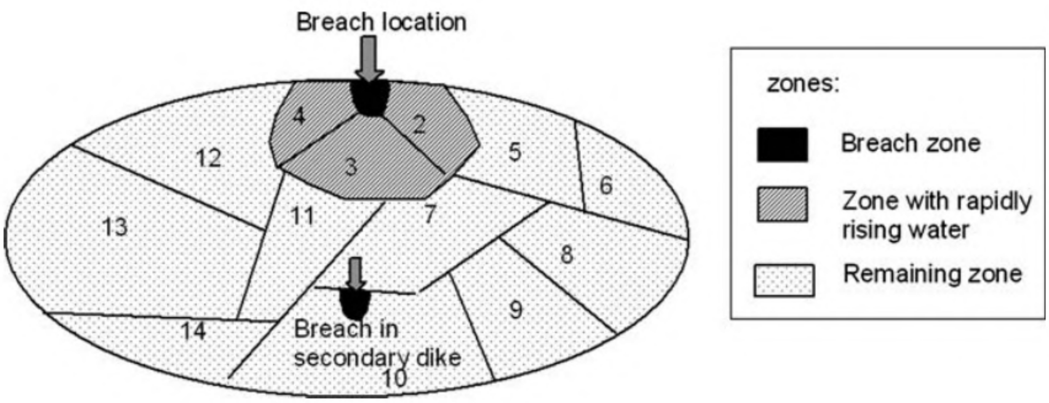


Figure 3.2: An example of the division of the mortality zones (Jonkman, Vrijling, and Vrouwenvelder, 2008)

Later on, Jonkman (2007) proposed several adjustments for his loss of life model, for example, the type of distribution. The adjustment for the limit w = 0.5 m/h between zone 2 and 3 was later on replaced by using a transition zone (Maaskant, Jonkman, and Kok, 2009). The computer model (HIS-SSM) has been updated corresponding to the developments of the mortality functions. The newest model which is used nowadays is called SSM2017.

All activities are presented in Table 3.1.

Table 3.1: Overview of the main activities on mortality functions in the Netherlands

Year and source	Activity or finding
1989: Duiser	Relation water depth and mortality rate.
1992: Waarts	Extra data, more aspects. Classification of three zones.
1992: Vrouwenvelder and Wubs	Mortality in single-family homes and farms (Jonkman, 2004).
1994: Van Gelder and Kraak	Added the water level rise rate in model above (Jonkman, 2004).
1997: Vrouwenvelder and Steenhuis	Extended model with effect of rise rate. Proposed method for sea and river floods.
2004: Jonkman	Used data from 1953 to compare models above. Mentioned different types of death cause. Proposed new model, which became the "Standard method 2004".
2006: Jonkman	Adjustment: lognormal distribution instead of exponential.
2007: Jonkman	Adjustment: limit at w = 0.5 m/h.
2009: Maaskant	Adjustment: addition of the transition zone based on interpolation between the rapidly rising water zone and remaining zone.

3.1.3. Description of the current approach

The mortality functions are mainly based on the data of the flood event of 1953. The most recent mortality functions, as they are used nowadays, are based on the functions of Jonkman (2007) and adapted by Maaskant, Jonkman, and Kok (2009). The mortality functions consist of four zones with each their own characteristics and thus their own distribution of mortality. The mortality rate is always between zero and one. The four zones and distributions are given below.

It is important to keep in mind that the main aim of the current approach is to get insight into the hazards and into the dangerous locations and not to predict the exact number of fatalities (Jonkman, 2007).

1) Breach zone: zone with high flow velocities and rise rate combinations

The breach zone is the most severe zone. The product of the velocity and water depth is higher than 7 m^2/s and the velocity is higher than 2 m/s. Under these conditions, the buildings will collapse and the people who are assumed to be indoors will die as a consequence. The area is located very close to the breach, around several hundred meters. The mortality equals 1 in this situation:

$$F_{D,B} = 1 \\ \text{if} \quad hv \geq 7\ m^2/s \ \text{ and } \ v \geq 2\ m/s \tag{3.1}$$

2) Zone with rapidly rising water

This is the second most severe zone. Rapidly rising water is dangerous as people are surprised by the water and thus have little time to find a safe haven in the endangered area.

The mortality function:

$$F_{D,S}(h) = \Phi_N\left(\frac{ln(h) - \mu_N}{\sigma_N}\right) \\ \mu_N = 1.46 \quad \text{and} \quad \sigma_N = 0.28 \\ \text{if} \quad (h \geq 2.1\ m \quad \text{and} \quad w \geq 4\ m/h) \ \text{ and } \ (hv < 7\ m^2/s \quad \text{or} \quad v < 2\ m/s) \tag{3.2}$$

3) Transition zone: zone between high and low rise rate

The transition zone was added later on by Maaskant, Jonkman, and Kok (2009). This way, the sudden change between the zone with rapidly rising water and the remaining zone with a low rise rate is reduced. The corresponding mortality function is based on interpolation between the rapidly rising water zone and the remaining zone.

The mortality function for the transition zone:

$$F_D = F_{D,O} + (w - 0.5)\left(\frac{F_{D,S} - F_{D,O}}{3.5}\right)$$
$$\text{if} \quad (h \geq 2.1\ m \quad \text{and} \quad 0.5 \leq w < 4\ m/h) \ \text{and} \ (hv < 7\ m^2/s \quad \text{or} \quad v < 2\ m/s) \qquad (3.3)$$

4) Remaining zone: zone with a low rise rate
The remaining zone is a zone with a low rise rate. Compared to the previous zones, the exposed people have a better chance to find shelter. The mortality function:

$$F_{D,O}(h) = \Phi_N\left(\frac{ln(h) - \mu_N}{\sigma_N}\right)$$
$$\mu_N = 7.60 \quad \text{and} \quad \sigma_N = 2.75$$
$$\text{if} \ \left(w < 0.5\ m/h \ \text{or} \ (h < 2.1\ m \ \text{and} \ w \geq 0.5\ m/h)\right) \ \text{and} \ (hv < 7\ m^2/s \ \text{or} \ v < 2\ m/s) \qquad (3.4)$$

In which:

F_D = Mortality [-];
$F_{D,B}$ = Mortality in the breach zone [-];
$F_{D,S}$ = Mortality in the zone with rapidly rising water [-];
$F_{D,O}$ = Mortality in the remaining zone [-];
h = Water depth [m];
v = Flow velocity [m/s];
w = Water rise rate, averaged over the first 1,5 m water depth [m/h];
Φ_N = Lognormal distribution;
μ_N = Mean value from ln(h);
σ_N = Standard deviation of ln(h).

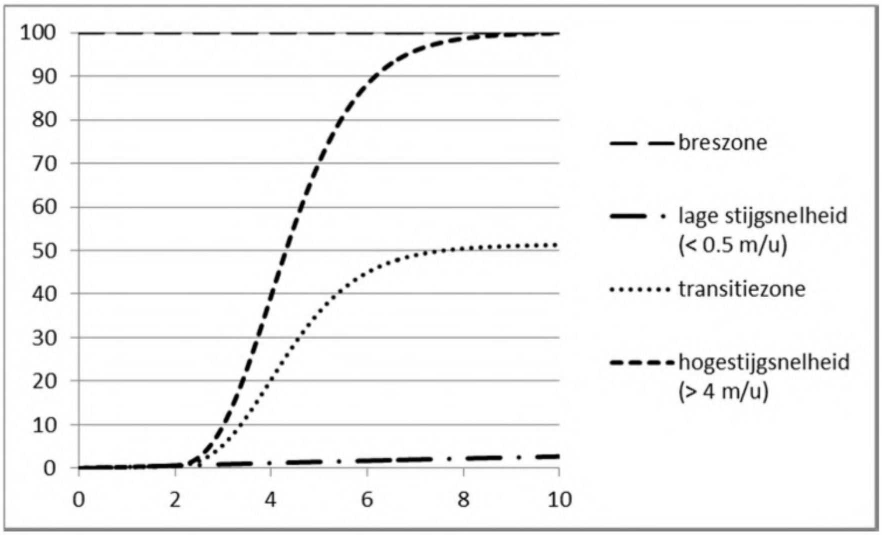


Figure 3.3: The mortality functions with on the y-axis the mortality [%] and on the x-axis the water depth [m] as implemented in SSM2017 (Slager and Wagenaar, 2017). Translation of legend from top to bottom: breach zone, low rise rate (<0.5 m/h), transition zone, high rise rate (>4 m/h).

3.2. Important factors

This section discusses the factors resulting from Section 2.3 and all other possible factors in the mortality functions, whether explicit, implicit or not yet included. As the Dutch mortality functions only take into account the flood characteristics, it means that all other factors are implicitly (or not) included. By analyzing literature and by reasoning, the relevance of these factors can be assessed. The main goal is to have more insight into the contributing factors and to analyze if there are any factors that need to be made explicit in the current mortality functions. The factors are categorized and shown in Table 3.2. They are briefly discussed considering their relevance and how the factor changed since 1953 in the Netherlands.

Table 3.2: Factors to be further analyzed in conjunction with the points of discussion

Flood hazard characteristics	Flood exposure characteristics	Social vulnerability characteristics	Other characteristics
Debris	Building characteristics	Age	Animals
Depth-velocity product	Infrastructure and transport	Alcohol content	Nature of warning
Flood duration	Shelter possibilities	Awareness of flood risk	Rescue capacity
Flow velocity	Water arrival time	Behaviour and activity	Warning time
Water depth		Clothing worn	Water contamination
Water level rise rate		Gender	
Waves		Health	
Weather (storm, temperature, etc.)		Household composition	
		Knowledge of the area	
		Previous flood experience	
		Swimming ability	
		Timing of flood	

Flood hazard characteristics

The flood hazard characteristics provide information about the severity of the flood influencing mortality. The water depth, water level rise rate, and flow velocity are already explicitly included in the mortality functions, but more aspects might be relevant.

- Debris
  Debris can have a positive or negative effect. On the one hand, floating debris can act as a safe haven if people are able to climb on it. This is a risk because of unexpected turbulence or undercurrents, waves, collapses against a structure or getting stuck at a bridge, etc. On the other hand, debris can wound people, especially in fast-flowing waters. Then, it forms an extra threat, also to buildings. Overall, debris is considered dangerous. For that reason, a debris factor is added in the Flood Risks to People method in the U.K. (Ramsbottom, Floyd, and Penning-Rowsell, 2003).

- Depth-velocity product
  This factor is the product of the factors water depth and water flow velocity. It is included as factor because it is often used as a measure for the forces on buildings (thus related to building collapse) and human stability. The depth-velocity product is one of the criteria used to divide the flood area into different zones with the corresponding mortality functions. Therefore, it is a very relevant factor.

- Flood duration
  The longer the flood duration, the higher the risk of dying from hypothermia, exhaustion or drowning. However, because river flooding is expected to occur in winter, hypothermia plays a role in the short term. The total flood duration is therefore, presumed to be of little relevance because the increased mortality is expected to be more dependent on the season and the weather conditions and to a lesser extent on the flood duration. This is further discussed under 'Weather'.

- Flow velocity
  The flow velocity (in combination with the water depth) influences the stability of people as people will be swept away by the floodwater in case of high velocities. It also increases the risk of building collapse. The flow velocity is already explicitly included in the mortality functions because of its relevance.

- Water depth
The water depth plays one of the most important roles during floods. The larger the water depth, the more unsafe the situation will be because the shelter possibilities will decrease. It is therefore related to shelter possibilities. When a house has no higher floors, people can drown in their houses. When the flood conditions are severe (high rise rate, high flow velocities), it can be extra dangerous as it can lead to building collapse. The water depth was very relevant in the estimation of mortality during 1953 and is expected to also play a large role during potential flooding in the future.

- Water level rise rate
Fast-rising water, expected in small and deep areas, causes dangerous situations as people are surprised by the floodwater and have little time to find a safe place to shelter. In 1953, a relationship is found between mortality and water level rise rate and is therefore included in the mortality functions. It depends on the area characteristics if it plays a role during flooding.

- Waves
Waves are expected to be severe during coastal flooding but could be absent during river flooding. It depends on the weather conditions if waves are to be expected. For example, during the possible river floods in 1993, there was a favourable wind direction and a small wind force with a small wave attack as a result (TAW, 1994). During 1953, the breaches were caused by the storm surge, but the specific influence of waves on mortality is not clear. Moreover, the wave impact could play a role in building collapse.

- Weather (storm, temperature, etc.)
This factor includes the presence of a (severe) storm, the weather conditions (heavy rainfall, wind, etc.) and the temperature outside and of the floodwater as these have an influence on the survival chances. In the Netherlands, floods mainly occur during the winter with low (water) temperatures which influence mortality due to hypothermia. During winters, a person who ends up in the floodwater, has an expected survival time of 1 to 3 hours (Jonkman, 2007). The storm season in the Netherlands is officially from September 1 to April 15. During river flooding, a storm does not necessarily have to occur, while this is mostly the case during coastal flooding. The presence of a storm or the weather conditions might influence the willingness of people to evacuate, but this is captured under ‘behaviour’. The weather is presumed to be of large relevance, but not very uncertain.

Flood exposure characteristics
This category considers the situation of the people, the built environment, infrastructure, and other assets, values, or factors related to the endangered area.

- Building characteristics
A high rise building can function as a place to shelter for many persons. In contrast, a one-storey building has the risk of being submerged by the floodwater with possible drowning of the residents as a consequence. Moreover, building collapse played a big role during the event of 1953. These houses consisted of single brick, working-class cottages (Asselman, 2005). The quality of the buildings today is not of that kind anymore. The building strength has increased which could result in fewer building collapses and thus less fatalities during a flood. Building characteristics, such as the height, quality, structure, date, etc. have an influence on building collapse and hence, on mortality and are assumed to be very relevant.

- Infrastructure and transport
In 1953, the use of a car as transport means was not integrated into society as it is nowadays. The change over time is thus large. The usage of a car gives an opportunity to evacuate the area to a safe place elsewhere via the existing infrastructure. However, during the event of 1953, the people were surprised by the water and were not aware of the danger, hence there was no preventive evacuation. This suggests that transport means were not that relevant in 1953. Nowadays, better infrastructure and transport

means are of relevance and can play a big role before and/or during a flood disaster.

- Shelter possibilities
  Shelter possibilities have a large impact on mortality. If people in the endangered area have places to shelter (and know where to find these places), the risk of dying decreases. Shelter possibilities are already implicitly involved in the mortality functions as people had to find shelter there as well, for example, on their rooftops. As nowadays there are more high-rise buildings, the shelter possibilities might have increased since 1953, but this depends on the population and land use in the area. The definition of shelter possibilities is important: in this study, people in public shelters are excluded in the estimation of people at risk. People staying inside their homes are taken into account. This corresponds with the situation in 1953 as people were surprised by the floodwater then and did not evacuate or go to public shelters. Reaching a public shelter is related to the persons' knowledge of the area, but also the vulnerability. Elderly or disabled people might not be able to move from the location where they are and need help.

- Water arrival time
  The water arrival time is defined as the time of breaching until the moment that the floodwater arrives. The further away of the breach, the more time to prepare and/or leave the area. Especially in large dike rings, it could take quite some time before the water arrives. Water arrival time could, therefore, play a very large role in (reducing) mortality.

Social vulnerability characteristics
The social vulnerability characteristics are related to the ability to cope with the flood event. The factors mentioned in this section can have an influence on the susceptibility. This can concern an individual person, such as the behaviour and activity of a person that could lead to death, but this could also concern the population as a whole, for example the timing of the flood.

- Age
  Children and elderly are more vulnerable to flood disasters than an average resident. The vulnerability due to age has been mentioned multiple times in this study as flood fatalities are often aged over 60. The age distribution of Dutch people has been changed over the years. More people are growing older, this is called 'ageing'. Based on flood events in the past, age is considered to be relevant and the age distribution has changed since 1953.

- Alcohol content
  In the past, there were a few events with flood fatalities with alcohol in their blood (Jonkman and Kelman, 2005). This suggests that blood alcohol content could influence the risk of dying. However, this did not become clear during 1953 and the expectation is that it is not very relevant for potential floods.

- Awareness of flood risk
  Especially in well-developed countries, such as the Netherlands, people tend to feel safe against flooding. However, the Netherlands is a low-lying country with flood defences, and the higher the defence, the larger the consequences can be in case of a breach. The awareness of flood risk has very much to do with how people behave. If people are aware of the risk, for example, because of previous flood experience or because they have lived in that area for a long time and know it well, will behave more responsibly. This factor is, therefore, strongly related to previous flood experience and knowledge of the area. If a person is not aware, it could result in poor decision-making, such as flood disaster tourism. Behaviour and activity are considered next and are a result of this underlying (absence) of awareness.

- Behaviour and activity
  The behaviour is related to previous flood experience and the awareness of flood risk as this influences the attitude towards a potential flood and how to behave in such a situation. People could decide to stay indoors on a higher floor or leave the area if there

is enough time before the water arrives. However, in Europe, a part of the fatalities in small-scale flooding is due to risky behaviour. People go outside to see the floodwater on foot or by vehicle. Moreover, people stay too long or return to rescue their belongings or are delayed because of their pets. It is also related to the time of flood, as people could be surprised by the floodwater when the breach happens during a traffic rush hour. Age, gender, health condition, household composition, knowledge of the area, nature of the warning, warning time are all factors that influence the behaviour and activity as well.

- Clothing worn
  During the flood in Bangladesh in 1991, female flood fatalities were over-represented (Jonkman and Kelman, 2005). One of the possible reasons for this was ascribed to clothing worn. The relevance of clothing worn in the Netherlands is assumed to be low in 1953 and in the future.

- Gender
  This factor has for small-scale flooding a strong relation with behaviour because several studies have shown that males are more often concerned with high-risk activities (see 'Behaviour and activity'). The number of male fatalities is significantly higher for causes of death related to high-risk activities. In 1953, a male over-representation was not found. For small-scale river floods, it could be relevant to take it into account.

- Health
  The general health condition influences the physical fitness of a person. Disability or reduced mobility reduces the ease of evacuation or the process of finding shelter. These persons might be dependent on people in their close environment or rescue teams. Health is related to age.

- Household composition
  The composition of a household can differ a lot. For example, people can live alone, can be a single parent of young children, or can have (an) ill or disabled family member(s). These examples could increase the vulnerability of the persons in the household.

- Knowledge of the area
  When having a good knowledge of the area, it is not only more likely to find a place to shelter in case of a flood event, it is also more likely that people recognize the hazard. Moreover, with a good knowledge of the area, the evacuation process might be more efficient. The relevance of this factor is assumed to be limited.

- Previous flood experience
  Previous flood experience influences the way people behave in threats of flooding as they have experienced the serious nature of the consequences. In the Netherlands, previous flood experience cannot play a big role as the last (deadly) flood was in 1953. Fortunately, the number of flood events in the Netherlands is limited, but this also means that people can find more difficulties in coping with such stressful situations or even behave irresponsibly.

- Swimming ability
  Swimming ability influences the vulnerability of flood victims. When water rises fast, people could end up in situations where they have to swim. The risk of drowning becomes significantly larger if people are not able to swim. The ability to swim is less relevant in case of severe flood conditions as even good swimmers will be swept away and will drown. It receives a score of low relevance because mostly hypothermia due to the cold water or strong undercurrents, unexpected turbulence or floating debris will take the upper hand. The age and health situation is also related to the swimming ability. The ability to swim has changed a little over time as swimming is mostly part of the education nowadays.

- Timing of flood
  When the flood occurs during the night, most people are asleep and surprised by the

floodwater. During the week, most people are at school or at work. During the weekends, families are most likely together and this is also the case for holidays. The time of the flood thus has a strong relation with where the people are located in the area. The time of the flood is for these reasons presumed to be relevant.

Other characteristics
The factors that could influence mortality but do not fall under the first three categories, are collected into 'other characteristics'.

- Animals
  During flooding, it is possible that dangerous animals, such as alligators, snakes and, fire ants are chased out of their habitat as a direct cause of the flood and cause fatalities. Fortunately, there are no dangerous animals in the Netherlands which could be of such danger during a flood. If considering animals, it could be that pets are in the floodwater and that the owners try to rescue them, but this is captured under the factor 'Behaviour'. The danger of animals was not of relevance during the event of 1953 and is not to be expected to be relevant in the future for river flooding in the Netherlands.

- Nature of warning
  The nature of the warning could also play a role in the loss of life as it is related to warning effectiveness. If the warning is not clear or not complete, people do not recognize or understand the threat of flooding. This could have as a result that people do not evacuate or not as fast as they should. This means that the nature of warning must be urgent, for example by broadcasting images of previous flood disasters with submerged houses to convince people to evacuate. It is also related to the frequency of warnings as this could influence the credibility of the warnings.

- Rescue capacity
  During a flood, most likely a state of emergency is declared and all rescue capacity nearby, or when it is a very large flood (inter)nationally, needs to go to the area, such as helicopters, boats, other equipment and people: the military, police officers, firefighters, etc. The higher the capacity, the more people can be rescued which results in lower mortality. This is related to the population density and size of the area. In very severe and long-lasting flood and weather conditions, it is hard and dangerous for the rescue teams to operate which could result in less efficient operations. This can result in higher mortality rates.

- Warning time
  The warning time is defined as the time that the people are informed by the threat of flooding until the moment of the levee breach. The longer the warning time, the more time people have to prepare themselves and/or leave the area and this could result in lower mortality. If the warning time is very short, the people are not prepared for the flood. Moreover, it could be a very stressful situation that could increase the percentage of fatalities by physical trauma. Generally, river flooding is well-predictable which suggests a relatively long warning time in comparison to coastal flooding with less foreseeable storm surges. In 1953, the people were not warned. However, some people were warned for the second flood wave which resulted in lower mortality. Warning time is therefore presumed to be very relevant. As the warning systems changed since 1953, this change needs to be taken into account. Moreover, the rise of social media could influence the speed and range of the warning issue.

- Water contamination
  In industrial areas, water contamination by for example chemicals or oil could pose extra danger to flood victims. It could cause large damages and long-term health effects, but it was not of relevance for (direct) flood fatalities in 1953 and is not expected to cause many (direct) flood fatalities in the future by river flooding.

All possible important factors are mentioned and briefly described. Table 3.4 summarizes the analysis of the factors by ranking them based on relevance and change over time. The ranking is shown in Table 3.3. Note: the ranking is based on the Dutch situation. When applied to foreign flood event data, the ranking must be reconsidered.

The scoring of the relevance ranges from zero to five and for the change from zero to three. When adding these two scores, the influence of the relevance is larger. The change over time is taken into account, because (almost) all factors are implicitly included in the mortality functions as it is based on the event of 1953. When the change over time is large, it is assumed that a closer look into that factor is needed. Concluding, if a factor received a score of [5] for relevance, or a score of [3] for change over time, or has a summation of scores of [6], [7], or [8], it will be further analyzed in the next section.

This means that the following factors need to be investigated: building characteristics, infrastructure and transport, shelter possibilities, water arrival time, age, behaviour and activity, and warning time.

Moreover, a column is added to highlight if there is a difference between river and coastal flooding. The 1953 event was a coastal flood, but this study focuses on river floods. For that reason, it is relevant to look into these differences. The factors debris, waves, weather, water arrival time, and warning time are different for river flooding than for coastal flooding.

Table 3.3: Score and meaning for the ranking of the factors. Left: relevance, middle: change over time since 1953, right: difference between river and coastal flooding

Score	Meaning	Score	Meaning	Score	Meaning
0	Not relevant / Not applicable / Unknown	0	No change / Not applicable / Unknown	0	Not different / Not applicable
1	Very low	1	Small	1	Different
2	Low	2	Medium		
3	Medium	3	Large		
4	High				
5	Very high				

Table 3.4: Analysis of factors for river flooding in the Netherlands. Relevance must be reevaluated if used for foreign flood events.

Category	#	Factor	Relevance	Change over time since 1953	Summation of scores	River/coastal difference	Related to
Flood hazard characteristics (H)	H1	Debris	2	0	2	1	H8
	H2	Depth-velocity product	5	0	5	0	H4, H5
	H3	Flood duration	2	0	2	0	H5
	H4	Flow velocity	5	0	5	0	
	H5	Water depth	5	0	5	0	
	H6	Water level rise rate	5	0	5	0	
	H7	Waves	2	0	2	1	H8
	H8	Weather (storm, temperature, etc.)	4	0	4	1	
Flood exposure characteristics (E)	E1	Building characteristics	5	3	8	0	
	E2	Infrastructure and transport	4	3	7	0	
	E3	Shelter possibilities	5	3	8	0	H5, H6, E4, V1,7,9, O4
	E4	Water arrival time	5	0	5	1	H4
Social vulnerability characteristics (V)	V1	Age	4	2	6	0	
	V2	Alcohol content	0	0	0	0	V4
	V3	Awareness of flood risk	2	1	3	0	V9, V10
	V4	Behaviour and activity	4	2	6	0	V1,2,3,6,7,8,9,10,12, H8, O2, O4
	V5	Clothing worn	0	0	0	0	V1, V6
	V6	Gender	2	0	2	0	
	V7	Health	2	0	2	0	V1
	V8	Household composition	2	1	3	0	
	V9	Knowledge of the area	2	0	2	0	
	V10	Previous flood experience	2	1	3	0	
	V11	Swimming ability	1	1	2	0	H1-8, V1, V7
	V12	Timing of flood	4	0	4	0	
Other characteristics (O)	O1	Animals	0	0	0	0	
	O2	Nature of warning	1	0	1	0	
	O3	Rescue capacity	3	2	5	0	H8
	O4	Warning time	5	3	8	1	
	O5	Water contamination	0	0	0	0	

3.3. Points of discussion

In Section 3.2, the important factors were categorized and prioritized. The factors with a high prioritization following Table 3.4 are further investigated in this section. The main goal of this section is to give insight into possible improvements of the current mortality functions based on literature.

Table 3.1 in Section 3.1.2 summarized the main studies that form the background of the current mortality functions. Many other studies have been done regarding the flood fatality risk in the Netherlands, Table 3.5 gives an overview of these studies. The most important points of discussion, mostly based on these studies, are discussed in the following paragraphs.

Table 3.5: Overview of the main studies on the Dutch mortality functions or important aspects

Year and author	Study on:
Asselman and Jonkman (2003)	Development mortality functions
Asselman (2005)	Improved building quality since 1953
Van den Hengel (2006) (MSc thesis)	Application of mortality functions to check consequences of 1953 event
Maaskant (2007) (MSc thesis)	New Orleans: no clear relationship rise rate and mortality. Made different mortality functions based on water depth.
Jonkman (2007)	Development of loss of life model including mortality functions
De Bruijn, Van Buren, and Roscoe (2008)	Case study on Drechtsteden area in the Netherlands. Sensitivity mortality functions.
Maaskant, Jonkman, and Kok (2009)	Proposed the transition zone, but also considered other possible adjustments
De Bruijn et al. (2011)	Relation mortality and flood characteristics
Di Mauro and De Bruijn (2012)	Case study on Canvey Island in the UK (1953). Sensitivity building characteristics.
De Bruijn and Slager (2014)	Water arrival time and water level rise rate
De Bruijn and Van Kester (2015)	Case study on Calgary in Canada (2013)
Pleijter and Kolen (2016)	Division between locations of fatalities, main focus on evacuation

Difference between river and coastal flooding

Differences exist between river and coastal flooding. Table 3.4 shows that there are differences in debris, waves, weather, water arrival time, and warning time. River flooding is caused by a long duration of (extreme) high waters. The discharges from upstream areas due to extensive rainfall are well-predictable. The situations in 1993 and 1995 are examples of that: the water levels were so extreme that the safety of the dikes could not be guaranteed and that resulted in the decision for preventive evacuation. Wave run-up can worsen the hydraulic load conditions. In contrast to river flooding, waves are always present in coastal flooding as breaches occur due to severe storms with large storm surges. This is thus related to the season and weather conditions. In storms, more debris is to be expected, this can pose extra danger to people outside.

Additionally, coastal areas are mostly more densely populated than river areas. In the case of a dense population, it could be harder to have an efficient evacuation and for rescue teams to help survivors. However, densely populated areas are more likely to have places to shelter.

Moreover, in large river areas, it could take quite some time before the floodwater reaches all areas. This means that besides the warning time, people have possibly more time to prepare or leave before the actual floodwater arrives. This is further discussed below.

One could say, based on these differences, but also based on the lower mortality found in literature (0.5% average for river flooding vs. 1% for coastal flooding), that river flooding is expected to result in lower mortality than coastal flooding.

Water arrival time

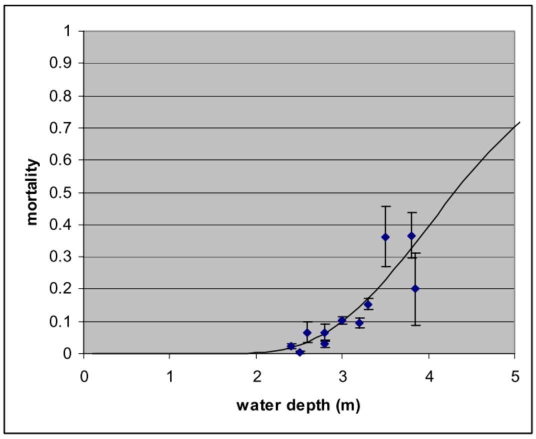
The water level rise rate (averaged over the first 1.5 m water depth) is calculated from the moment when the water depth has reached 2 cm, this means that the water arrival time is currently not implemented in the mortality functions. The water arrival time shows how much time people have to respond. The closer to the breach, the smaller the available response time. Generally, the expectation is that if people have more time to respond, they have more time to flee or to find a safe haven which reduces the number of fatalities.

De Bruijn and Slager (2014) presented with a sensitivity analysis that including the water arrival time has a large impact on the flood fatalities, especially in areas that are elongated such as the Betuwe area. They looked at the water arrival time in different categories, such as less than 3 hours, 3-6 hours, 6-12 hours and so on, ending at > 48 hours. Every category has a flee fraction: this is the percentage of people who reach safety after the start of the levee breach. The longer the water arrival time, the larger the flee fraction and thus the larger the correction for (reducing) mortality due to fleeing. The flee factor reduces the mortality in river areas significantly, resulting in different flood fatality risks. Their advice is to make the factor water arrival time explicit in the current mortality functions.

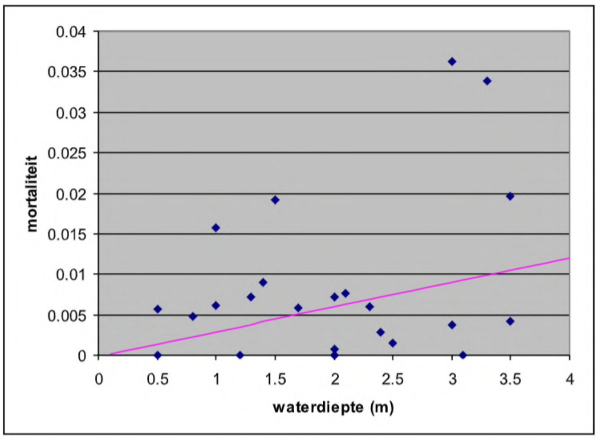
Maaskant, Jonkman, and Kok (2009) also found during the case study for dike ring 48 in the Netherlands that most fatalities occur in areas with a high rise rate ánd small arrival time (<6 hours). This emphasizes the need to look into the water arrival time.

Water level rise rate

Figure 3.4 shows the relationship between water depth and mortality for a high (>0.5 m/h) and low rise rate (<0.5 m/h). For a high rise rate, there is a strong correlation, but for the low rise rate, the correlation is weak. This suggests that for the zone with low rise rates, mortality is influenced by other aspects, such as water arrival time and warning. Moreover, there is noticed that for the plot for high water rise rates (Figure 3.4a), the two most determining points are not that reliable because these two locations are from outlying areas, 'Oude Tonge Buiten' and 'Nieuwerkerk Buiten' (De Bruijn and Van Kester, 2015).



(a) Mortality against water depth with high rise rates (R^2 = 0.76)



(b) Mortality against water depth with low rise rates (R^2 = 0.09)

Figure 3.4: Fit to data points (De Bruijn and Van Kester, 2015)

Maaskant (2007) applied the mortality functions to the flooding in New Orleans after Hurricane Katrina and did not find a clear relationship between the water rise rate and the mortality. It turned out that the number of fatalities was mainly dependent on the water depth. Jonkman (2007) gives as one of the possible explanations that the hazard of fast rising water is the surprise effect and thus that the people have little time to find shelter, but the people in New Orleans were warned for the coming hurricane Katrina and could have been prepared.

The rapidly rising water zone is dangerous because of the surprise effect, resulting in little time for people to find shelter. It makes sense that the dangerous surprise effect has less effect in cases that people are warned or that the arrival time is very long and thus that the people are aware that there is a threat of flooding.

Currently, the water rise rate is calculated over the first 1.5 m water depth. Maaskant, Jonkman, and Kok (2009) and Di Mauro and De Bruijn (2012) investigated the impact of this threshold when it is changed to for example 2 m. It turned out that the impact on the number of fatalities was limited.

De Bruijn and Slager (2014) performed a sensitivity analysis including a scenario where the water rise rate was left out. They made a mortality map that shows that for some locations in the Netherlands, this makes a significant difference in mortality.

Building characteristics

In 1953, the flooded area consisted of many single brick, working-class cottages (Asselman, 2005). Lots of persons died during the flood event, because they stayed indoors and the buildings collapsed. The main thought is that if the buildings would be built with the quality of today, the number of collapses and consequently the number of fatalities would be reduced.

Asselman (2005) did research on building collapse in relation to mortality regarding the 1953 event as the current mortality functions do not include the effect of improved building quality. During the 1953 event, the people were surprised by the floodwater as no warning had been issued. However, there was a second flood wave and the affected people by this wave had been warned. Figure 3.5 presents the difference in mortality because of this warning in relation to building collapse.

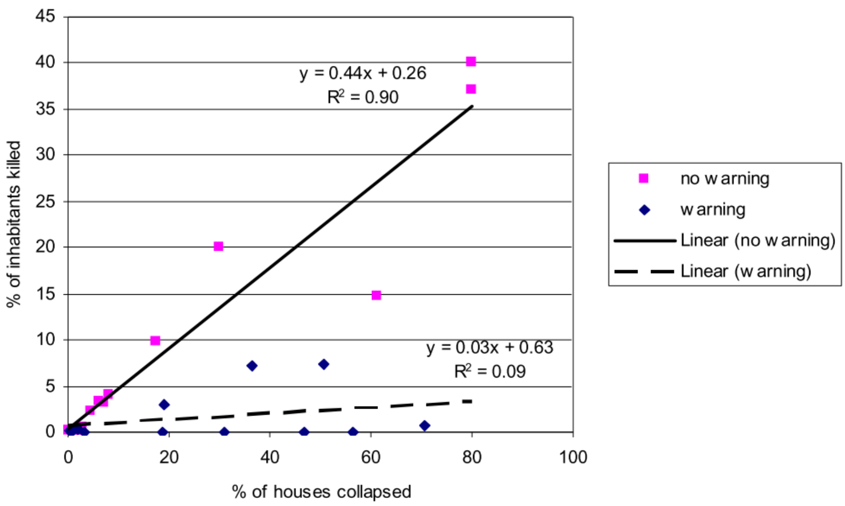


Figure 3.5: Fatalities due to building collapse in Goeree and Schouwen-Duiveland in 1953 (Asselman, 2005). It also indicates that the effect of warning is relevant.

The factor 0.44 (see Figure 3.5) links mortality to building collapse in case of no warning. The areas without warning are the areas with rapidly rising water levels. The factor for areas with warning (remaining zone) is very low: 0.03. The correlation is very weak and this suggests that other factors are more important in these areas. The factor 0.44 can be used to derive the relation between mortality and water depth. A linear relationship exists between building collapse and mortality for this zone, which suggests that the mortality can be corrected with the same factor.

Asselman (2005) also analysed building collapse based on different types of buildings in 1953 at Goeree and Schouwen-Duiveland. She concluded that if all houses in 1953 were built of cavity walls, it would result in a reduction of 19% of the number of collapsed buildings and if it were concrete walls 93%. Jonkman (2007) assumed a 50-50 distribution of concrete and cavity walls for the buildings nowadays in the Netherlands, resulting in a reduction of around 57%.

Using the linear relation (factor 0.44) between mortality and building collapse, the data can be transformed. After transforming the data, the mortality function for the rapidly rising water zone has the parameters μ_N and σ_N equal to 1.68 and 0.37 (Jonkman, 2007), resulting in a less steep curve. Figure 3.6 shows the possible improved mortality function.

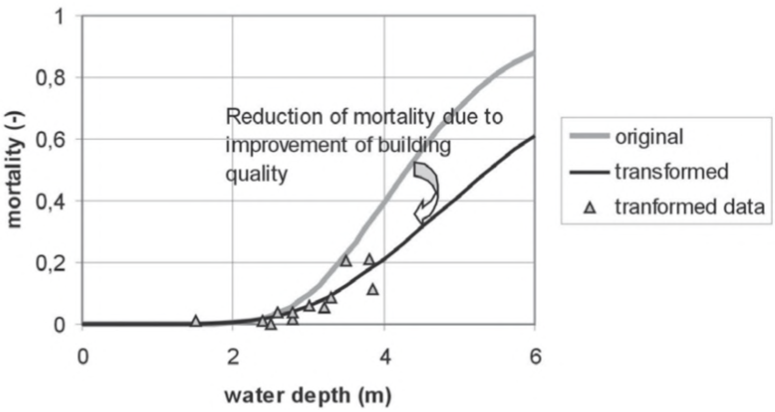


Figure 3.6: The mortality function for the rapidly rising water zone with a correction for improved building quality (Jonkman, 2007)

Di Mauro and De Bruijn (2012) did a sensitivity analysis in a case study of the Canvey Island flood event in 1953. They used the current mortality function for the rapidly rising water zone, the corrected mortality function suggested by Jonkman (2007) shown in Figure 3.6, and a hypothetical shape for 'weaker buildings' with a higher fatality rate. Figure 3.7 shows the overview. Their analysis showed that the corrected function for improved buildings had 67 fatalities (29 in the rapidly rising water zone), the current function 71 fatalities (35 in the rapidly rising water zone), and the hypothetical 'weaker buildings' had 75 fatalities (39 in the rapidly rising water zone). Based on these results, they concluded that the shape of the second function had limited influence. However, they advise to also perform sensitivity analyses to other test sites as this outcome might have been related to their chosen case study area.

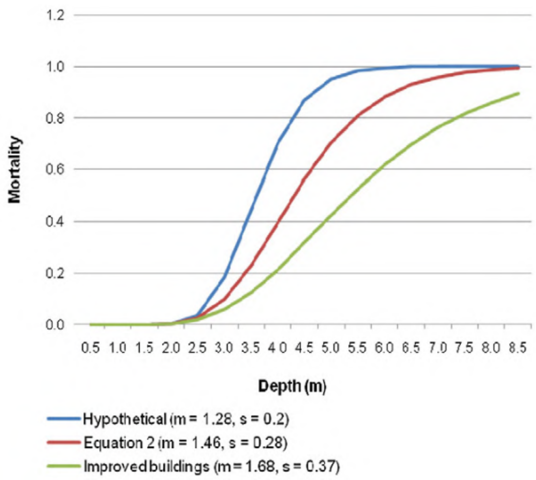


Figure 3.7: Overview of the mortality function for the rapidly rising water zone, the corrected function for improved building quality, and a hypothetical shape (Di Mauro and De Bruijn, 2012)

Warning time

The effect of warning could be explained in multiple ways. The most relevant effect is that warning time gives people the opportunity to prepare and/or evacuate. The effect of warning is partly shown in the paragraph of building collapse (Figure 3.5) where warned people had a much lower mortality rate. Besides, Jonkman and Kelman (2005) stated that if the people are warned in time and thus able to prepare themselves, it gives less stressful situations and this could reduce the loss of life due to heart attacks. This is related to the time of the day, as people are more likely to be surprised by the floodwater in the night than during the day.

The level of warning is assessed for the remaining zone in relation to water depth and mortality for the Netherlands 1953 and Japan 1959 by Jonkman (2007), see Figure 3.8. The line in this figure presents the mortality function for the remaining zone and is highest for categories C and D, so short before onset or no warning given at all. Based on this, it seems that the level of warning is of relevance in the remaining zone (Jonkman, 2007).

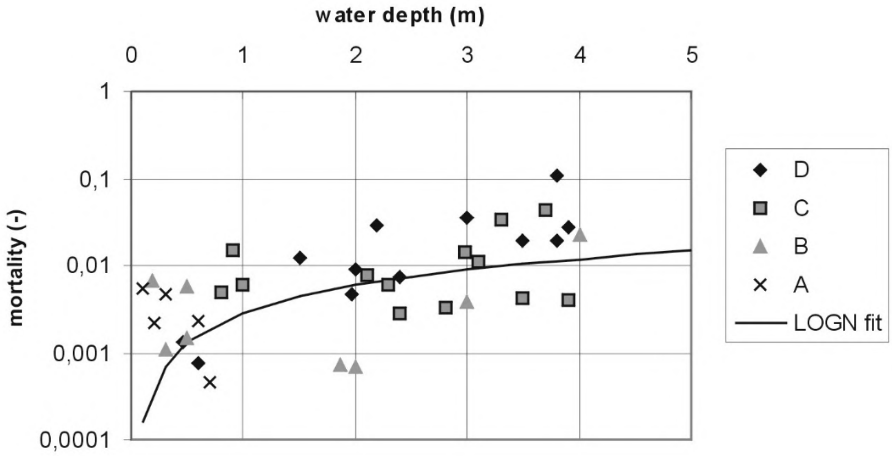


Figure 3.8: Level of warning in relation to water depth and mortality (Jonkman, 2007). A: Warning well in advance, B: Some warning, but preparations not completely finished, C: Warning short before or during flood onset, D: No warning. Based on data of the event in 1953 in the Netherlands and in 1959 in Japan. The LOGN fit line represents the mortality function in the remaining zone.

Van den Hengel (2006) simulated the 1953 flooding and noticed an overestimation of fatalities in his simulations for areas with a long arrival water time and where the people were warned (De Bruijn and Slager, 2014). This underlines also the need to look into these factors.

Infrastructure and transport

Since 1953, infrastructure and transport means changed enormously. In 1953, the province of Zeeland was quite isolated from the rest of the Netherlands, some islands could only be reached by water. After the flood disaster in 1953, the Delta Works were constructed. Due to these Delta Works, Zeeland became more connected, for example via the Haringvliet sluices, Brouwersdam and Eastern Scheldt Barrier. The 'Drie-eilandenplan' was a project (also part of the Delta Plan) to connect Walcheren, Noord-Beveland, and Zuid-Beveland. Another example (not part of the Delta Plan), is the 'Zeelandbrug'. This bridge was built in 1965 to connect Noord-Beveland with Schouwen-Duiveland as the Eastern Scheldt was finished in a later stage. Figure 3.9 shows an overview of the Delta Works.

In addition, the transport means changed incredibly, especially car ownership. Based on the data of CBS ('Centraal Bureau voor de Statisiek'), about 188,000 passenger cars were present in 1953 in the Netherlands. In 2019, it was about 8,500,000 passenger cars. These numbers demonstrate that the transport changed enormously between then and now in the Netherlands.

From these facts, one could assume that the possibilities to evacuate have increased since 1953 and that could result in fewer fatalities.

Figure 3.9: Overview of the Delta Works (*Deltawerken Online* 2004)

Shelter possibilities

Generally, the weather conditions in river flooding are less severe than for coastal flooding. One can assume that it is easier to find shelter with mild weather conditions. Besides, it depends on the area how many shelters are available and if the people know where to find these.

Some people decide to go to a public shelter. For example, the 'Superdome' during Hurricane Katrina. Pleijter and Kolen (2016) assumed a fixed mortality of 0.05% in their model for shelters, based on data of New Orleans.

In this study, the people in a public shelter are assumed safe and are therefore not counted in the number of exposed people. People who decide to shelter at home are taken into account in the number of exposed people.

Age

Age is also of relevance as one believes that children and the elderly are extra vulnerable. The number of fatalities in Canvey Island (1953), New Orleans (2005), and France due to Xynthia (2010) have shown that the elderly form a large part of the fatalities. It should be compared to the age distribution to check if the conclusion can be drawn that the elderly are more vulnerable. For the 1953 event, the European Floods in 2002, and the flood fatalities in Greece between 1970-2010, this comparison has been done in literature and is shown below.

For 1953, the age distribution of the fatalities compared to the age distribution of the population showed that people over the age of 60 years were more vulnerable (Jonkman, 2007), see Figure 3.10.

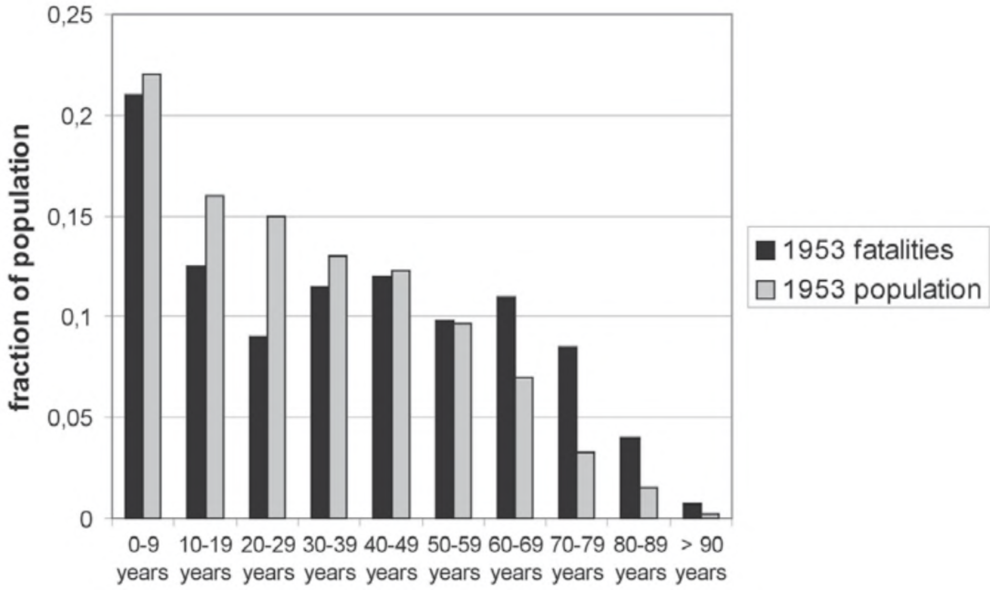


Figure 3.10: Fatalities in 1953 per age category compared to the population (Jonkman, 2007)

Age is also considered for the European floods in 2002 with 74 fatalities. For 60%, the age was known and was analyzed by Priest (2007). The result is shown in Figure 3.11. The graph shows a peak for age ranges 40-49 and 50-59 above the age line, but seems to fit relatively well for the age distribution. The age categories 70-79 and 80+ are also above the age line. Priest (2007) mentions that 7 fatalities were stated as 'older residents' but that the specific age was unknown; this could emphasize the vulnerability of the older age ranges.

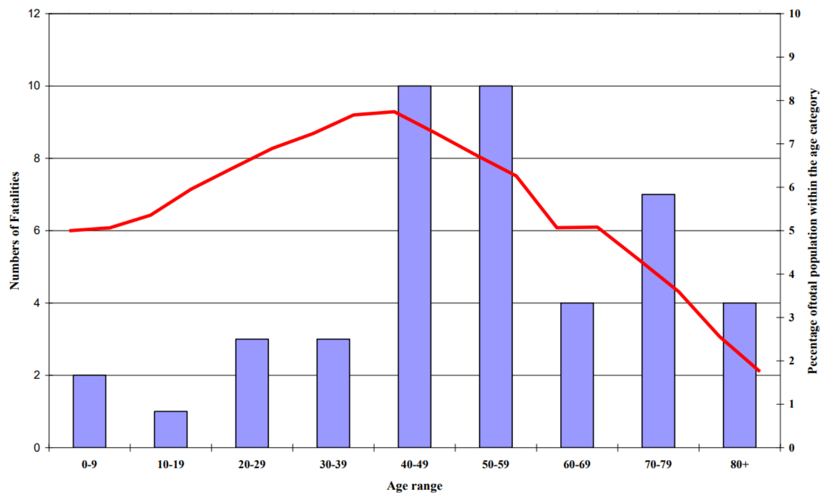


Figure 3.11: Fatalities in European flood events per age category compared to a general age line of the affected countries (Priest, 2007)

The analysis done by Diakakis and Deligiannakis (2017) for flood fatalities in Greece in the period 1970-2010 shows an over-representation of people aged over 70 years and an under-representation of people aged between 10 and 35 years.

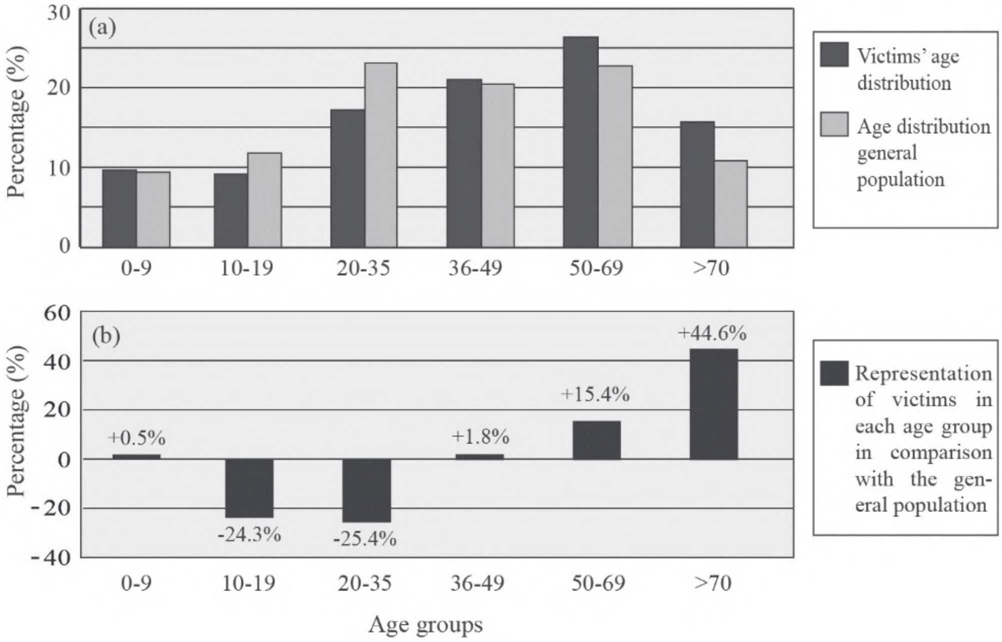


Figure 3.12: a) Fatalities per age category compared to the population for the period 1970-2010 in Greece, and b) representation of victims compared to the population (Diakakis and Deligiannakis, 2017)

Based on the data of CBS ('Centraal Bureau voor de Statisiek' in Dutch), some conclusions can be drawn. The total number of people in the Netherlands increased since 1953 with almost 7 million. Moreover, the age distribution has shifted over time, see Table 3.6. The part of 65+ of the total population has more than doubled. Due to 'ageing', more people are growing older, which means that the elderly are going to play a larger role in society. Approximately 19% of the current population is aged above 65 and this is approximately 11% more than in 1953. Age is now implicitly incorporated in the mortality functions, but it could be necessary to adjust the functions based on this shift in age distribution between 1953 and now.

Table 3.6: Age distribution in 1953 and 2019 (Data from CBS)

	1953	2019	Difference	Unit
Population	10.4	17.3	6.9	million
Age categories:				
<20 years	37.3	21.9	-15.4	%
20 - 40 years	28.7	24.9	-3.8	%
40 - 65 years	25.9	33.9	+8.0	%
65 - 80 years	7.0	14.6	+7.6	%
>80 years	1.1	4.6	+3.5	%

Behaviour and activity
Behaviour plays a large role in mortality, this can be partly reconstructed from the circumstances and the causes of the death, see Section 2.6. Many flood fatalities could have been prevented if people had behaved differently. The behaviour is influenced by many factors, such as flood risk awareness, previous flood experience, and the knowledge of the

area. But also age, gender, and health are presumed to be related. Besides, the way people behave is also influenced by communication means, warnings, and the transport available.

This shows that behaviour and activity is influenced by so many underlying factors, that it can differ significantly per flood event. Therefore, this study does not include this factor in the mortality functions.

3.4. Summary and main focus

The important factors mentioned, substantiated with the points of discussion, can be applied in various ways. Therefore, a new loss of life overview is given to visualize this, see Figure 3.13.

The first block shows the total number of people in the area at risk, this is based on information of the residents in the area. This number can be reduced if there are people evacuating out of the area, then a smaller number of people is left in the area (second block). People left in the area can decide to leave their homes and go to a safe public shelter in the area. These people are assumed to be safe and are excluded from the estimation. Therefore, a new block is formed to make a difference between people left in the area at risk and exposed people in the area at risk. The third block shows the exposed people in the area at risk, thus people who did not evacuate and who did not go to a public shelter.

When the breach occurs, the mortality functions are going to play a role. The earlier used categories (flood hazard, flood exposure, social vulnerability, and other characteristics, Section 3.2) are pointed towards mortality. The mortality functions estimate the potential flood fatalities. Between the exposed people in area at risk and flood fatalities, there is also a dotted line added for the people rescued, people fled, and other survivors. Fleeing is defined as people moving to a safe place during the flood event, thus after the breach. People can also be rescued by rescue teams or by other persons.

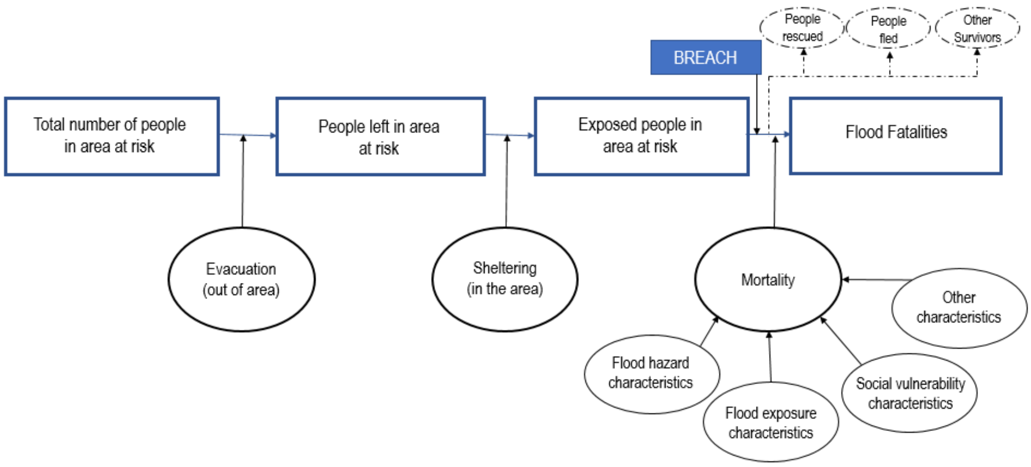


Figure 3.13: Overview of loss of life, based on Jonkman (2007) and De Bruijn and Van Kester (2015)

The main focus is on the implementation of the discussion points in the mortality functions in the loss of life approach. Some of the discussion points are already captured in the loss of life approach. These factors are considered below.

The definition of warning time is of great importance. In this study, warning time is defined as the time between the people are informed until the moment of the levee breach, thus before the flood starts. When using this definition, warning time is not included in the mortality rate, but it is included in the evacuation fraction in the loss of life estimation. A warning time of 1, 2, 3, or 4 days is implemented in the evacuation scenarios and this resulted in evacuation fractions for different areas in the Netherlands (De Bruijn et al., 2011). These evacuation fractions include the aspects infrastructure and transport. For that reason, warning time and effectiveness, infrastructure and transport are captured in the estimation of flood fatalities. It is thus not necessary to adapt the mortality as this would result in double-counting.

Warning time is defined between being informed and the levee breach. However, when breaching occurs, the people can still be warned at locations where the floodwater did not arrive yet. Communication nowadays is expected to be on-going during the disaster. However, the effect of warning in this context is implemented in the water arrival time. Otherwise, the effect of people having more time to prepare and/or leave the area is double-counted. Figure 3.14 shows a simple overview.

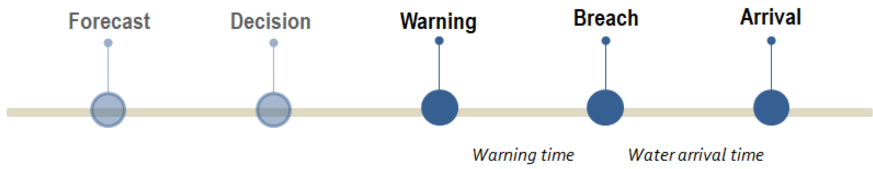


Figure 3.14: Overview of the different terms: this study defines warning time between warning and the breach. The time available after the occurrence of the breach is captured in water arrival time.

3.5. Potential (preliminary) alternative functions

Potential alternative functions are proposed to further investigate the sensitivity of the important factors on the simulated mortality. These are preliminary functions as these functions can be further developed based on the case study.

General adaptations:

- Fixed mortality for river flooding (e.g. 0.3 % or 0.5%). Homogeneous over the area or a fixed mortality per zone.
- Mortality in ranges (upper and lower mortality).

Per aspect:

- Building characteristics
  Correction for μ_N and σ_N equal to 1.68 and 0.37 for the rapidly rising water zone as proposed by (Jonkman, 2007).
- Water level rise rate
  a) Leave it out of consideration, only take into account the water depth and flow velocity;
  b) Leave it out of consideration for areas with large arrival times.
- Water arrival time
  a) Adding a flee fraction, as done by (De Bruijn and Slager, 2014);
  b) Adding a threshold after a period of time and assume that areas with longer arrival times than this threshold fall under the remaining zone.
- Shelter possibilities
  Exclude assigned public shelters from the people exposed by adding a shelter fraction in the loss of life calculation.
- Age
  a) Take into account people aged above a threshold (e.g. 65 or 70 years). Add an extra factor for this or change the distribution parameters;
  b) Implement it in the shelter possibilities by assuming that people aged above 65 can only reach the highest habitable level and can not reach attics and roofs as done by USACE (2006).

Part II: Case Study - Bommelerwaard

4

Case study set-up

In order to test the sensitivity of the mortality functions to the proposed changes, a case study is carried out. This chapter shows all relevant aspects concerning the case study set-up. Section 4.1 describes the Bommelerwaard area, Section 4.2 presents the input of the hydrodynamic model and Section 4.3 introduces the mortality model with its required input. The approach for the case study is summarised in Section 4.4.

4.1. Location and characteristics of the area

Dike ring 38 protects the Bommelerwaard, a river area located in Gelderland with around 50,000 inhabitants. The Bommelerwaard is enclosed by three rivers: the Waal, the Meuse and a distributary of the Meuse ('Afgedamde Maas' in Dutch). The river area is protected by a levee system with two types of levee, A and C. Type A protects the area directly from the water and type C indirectly. An overview of the dike ring is shown in Figure 4.1 and 4.2.

Dike ring 38 has two dike trajectories: 38-1 and 38-2. Dike trajectory 38-1 is located next to the Waal and dike trajectory 38-2 is located next to the Meuse. The river Waal has a significantly larger average discharge (1,500 m^3/s) than the river Meuse (230 m^3/s) and also much higher peak discharges and hence is assumed to be more relevant in case of flooding. The safety standard for dike trajectory 38-1 is determined by the individual risk ('Lokaal Individueel Risico' (LIR) in Dutch, see Section 2.1) which makes this dike ring extra relevant for this study on mortality; dike trajectory 38-2 is determined by the economic risk (Slootjes and Van der Most, 2016b). For these reasons, this case study concerns breach scenarios from the river Waal and thus focuses on the northern part of the Bommelerwaard.

The Bommelerwaard has a surface of around 11,000 ha and the levee system has a total length of 49 km for type A. The Bommelerwaard is a flat polder and in case of flooding, it behaves as a bathtub: the whole inner dike area is filled up with water in case of a flood, for dike trajectory 38-1 this is irrespective of the exact breach location. The eastern part has a higher elevation than the western part, which means that the floodwater will flow towards the west. Obstacles that can retain water, such as compartment dikes or elevated landscape elements, have an influence on the flood pattern and must be taken into account. In the Bommelerwaard, a highway (A2) and railway (Utrecht - Den Bosch) are crossing the area and also the regional dike 'Meidijk' has an influence on the flood pattern.

Zaltbommel is the largest municipality in the Bommelerwaard with around 28,000 inhabitants and is located directly next to the Waal river. Between Zaltbommel and Rossum, a nature reserve is located, the 'Kil of Hurwenen'. It originates from a cut-off of a meander of the Waal. The nature reserve is part of the floodplain of this river and is flooded at high water levels.

The embankments protecting Zaltbommel consist roughly of three parts. The first part is called ‘Waalbandijk’, which is a green traditional river dike. Adjacent to this section, one can find a part that protects the old city center and has a length of about 1 km. Around 400 m is designed as a flexible flood defence: in case of high water levels in the river Waal, the embankment is raised with beams of aluminum. The next section is a traditional river dike again and is called ‘Gamerschedijk’. Moreover, Zaltbommel has coupures on several locations which can be closed during high water events. The embankments are operated by Water Board ‘Rivierenland’.

Figure 4.1: Overview of the Bommelerwaard in the Netherlands.

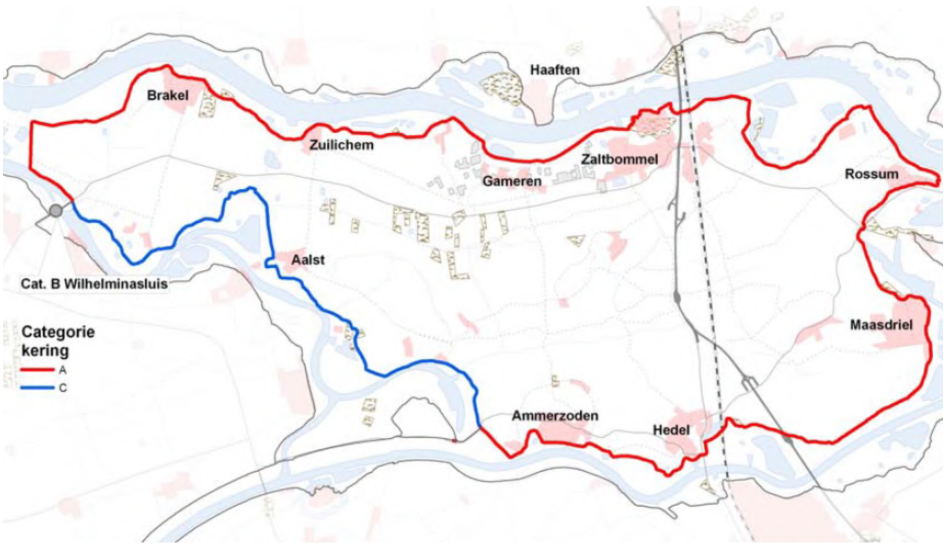


Figure 4.2: Overview of the Bommelerwaard (Vergrouwe and Bossenbroek, 2010). The red lines indicate flood defences of type A and the blue lines indicate flood defences of type C.

4.2. Hydrodynamic model

A hydrodynamic model is developed to simulate the flood characteristics which will be the input for the mortality calculations. This section introduces the software and the first expectations of the results and considers all input parameters and underlying assumptions.

Software

Flood simulations can be produced by several software packages. De Bruijn and Slager (2018) made an overview of the model types and their strengths and weaknesses. They concluded that flood simulations for large areas require 1D2D or 2D models, such as Sobek-1D2D, 3Di, and D-Flow Flexible Mesh.

The software used in this study for the flood simulations is D-Flow Flexible Mesh (D-Flow FM) which is part of the Delft3D Flexible Mesh Suite, developed by Deltares. D-Flow FM is the intended successor of Delft3D-Flow and SOBEK. It allows the user to apply finer resolutions with much more freedom at locations that require more detail, for example, the breach location, around obstacles, and other areas with local topographical variations. The program allows flexible combinations of unstructured grids: the grid can consist of triangles, pentagons, hexagons, or any other polygon in either Cartesian or spherical coordinates, and 1D and 2D grids can be combined (Deltares, 2019). Therefore, D-Flow FM can improve the accuracy, especially in complex areas of interest, while it takes into account the computation efficiency. Moreover, it can carry out flood simulations using parallelization for models that do not fit on a single machine or to make computations faster (Deltares, 2020).

The unsteady shallow water equations are solved by D-Flow FM in two (averaged over depth) or three dimensions, derived from the incompressible free surface flow Navier-Stokes equations, and can be used for non-steady flow and transport phenomena resulting from meteorological and tidal forcing (Deltares, 2019).

The software is under development by Deltares. The user interface is already usable, but it is not suitable yet for the goals of this study as it needs specific outcomes (such as maximum water depths and maximum flow velocities) in order to make mortality calculations. For that reason, the core of the program is used: the 'interacter'. Section 4.2.6 elaborates on the use of the interacter. The D-Flow FM version used in this study is 1.2.91.65784M.

Expected results

Water Board 'Rivierenland' did a pilot on flood simulations in the Bommelerwaard with the new software. On the one hand, the pilot was used to test new functionalities of the new software (breach growth, grid generation, and refinement, etc.) and on the other hand to create a consistent approach for modelling choices in flood simulations of dike rings in the Netherlands. In the future, the water board would like to use this hydrodynamic model for emergency response management and risk communication in general (HydroLogic, 2019). In August 2019, a first (concept) report was prepared with conclusions of the sensitivity of the input. One of the main conclusions was that the model resolution has a large effect on the discharges flowing through the underpasses which influences the size of the flood area and the arrival time. The pilot study used a breach scenario in the Meuse. This study aims to investigate what the impact of the level of detail of flood simulations is on the outcomes of mortality calculations, therefore, a breach is modelled directly for Zaltbommel next to the river Waal.

4.2.1. Model resolution

The model resolution is the tool to control the level of detail of the flood simulations. The model resolution is linked to the cell size: the smaller the cell size, the higher the number of cells per unit area and hence more detail can be captured in the model. However, the calculation time can significantly increase when using fine resolutions on (relatively large) areas, because small-sized cells result in a larger number of cells, hence a larger matrix needs to be solved by the computational kernel, thus slower processing. Moreover, in smaller cells the Courant condition (used to automatically compute the time step size of the model) is more likely to be limiting than when using larger cells. Depending on the modelling choices, a 100m grid has a calculation time in the order of minutes, while for a 5-10m grid it is in the order of days. In D-Flow FM, homogeneous locations can be modelled with coarse resolutions, while locations of interest, such as the breach location and around obstacles, can be modelled with finer resolutions. This advantage is used in this case study.

As mentioned in the previous section, based on the modelling choices, the model resolution must be fine enough to make sure there is a difference between building and street level. This applies to elevated elements as well. If a heightened element has a small width, this could be wrongly modelled. This suggests that the width of such an element must be larger than the grid size.

In this study, the sensitivity of mortality is investigated when using flood simulations with a coarse and a fine model resolution. The standard mortality model (see Section 4.3) is able to work with model resolutions of 5, 25, 50 and 100m. Therefore, a model resolution of 5 and 100m will be tested. To check also an intermediate scenario, a model resolution of 25m can be used.

The 5m resolution model is not going to be used for the whole Bommelerwaard as this would make the calculation time too large. The main focus is on the largest municipality Zaltbommel which is close to the river Waal and the breach location. Only Zaltbommel will be refined till 5m grid cell sizes. Section 4.2.4 considers the 5m resolution model in more detail.

4.2.2. Digital elevation model

The elevation pattern determines to a large extent where the water is flowing and what the water level will be. The eastern part has a higher elevation than the western part of the Bommelerwaard which results in a water flow from the east to the west.

The Digital Elevation Model (DEM) is based on data of AHN3 ('Actueel Hoogtebestand Nederland 3' in Dutch). The AHN3 data is gathered in the period 2013-2019 by laser altimetry in the Netherlands. The pilot study for flood simulations in the Bommelerwaard had a DEM with a 5m resolution which was aggregated from a 0.5m resolution. Vegetation and buildings were filtered out and only the terrain elevation remains. The 5m resolution DEM was made available by Deltares and is used in this study.

For the 25m and 100m resolution, the 5m resolution DEM is aggregated by using the median value.

Obstacles

In the digital elevation model, obstacles such as heightened roads or regional dikes, need to be taken into account, as they can (temporarily) retain water and therefore, influence the inundation pattern. The digital elevation models with a model resolution of 25m and 100m, are based on the median values, and this has as a consequence that obstacles are schematized with a lower elevation than they have in reality.

For obstacles, it is, therefore, relevant to take into account their maximum value. The obstacles in the 100m and 25m resolution DEMs are corrected by hand to this maximum value. This is done for the following obstacles:

- Highway A2 (noise barrier not included)
- Railway (Utrecht - Den Bosch)
- Provincial road N322, only from Zaltbommel to the eastern boundary of the Bommelerwaard
- Meidijk (regional dike)
- Elevation next to the Steenweg in Zaltbommel until road N322

The obstacles are assumed to retain the floodwater up til its maximum elevation ('standzeker' in Dutch).

Underpasses

The underpasses of the highway or railway also have to be included in the model, because this enables the water to flow through obstacles. Consequently, this will influence the inundation pattern. Some underpasses are relatively small and are therefore chosen to be only included in the 25m resolution model and not in the 100m resolution model.

The overview of the obstacles and underpasses is added in Figure 4.3 with the relative size of the underpasses shown in different colours to indicate inclusion in the 25 and/or 100m model.

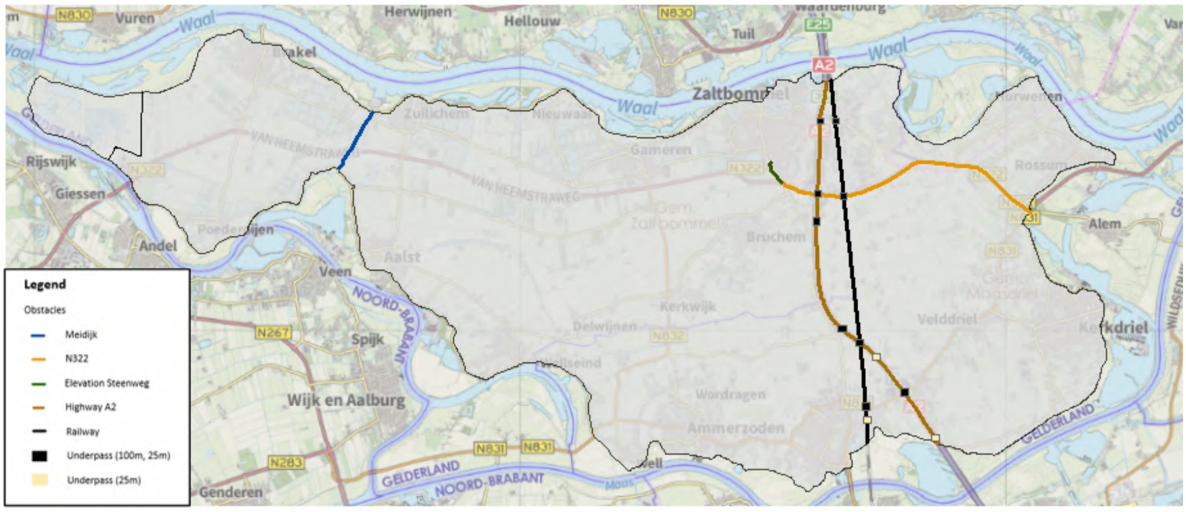


Figure 4.3: Overview of the relevant obstacles and underpasses

Utilizing these model assumptions, figures that show the digital elevation in the three different resolutions can be created. The results of the 100m, 25m, and 5m resolution models are shown in Figures 4.4, 4.5, and 4.6 respectively.

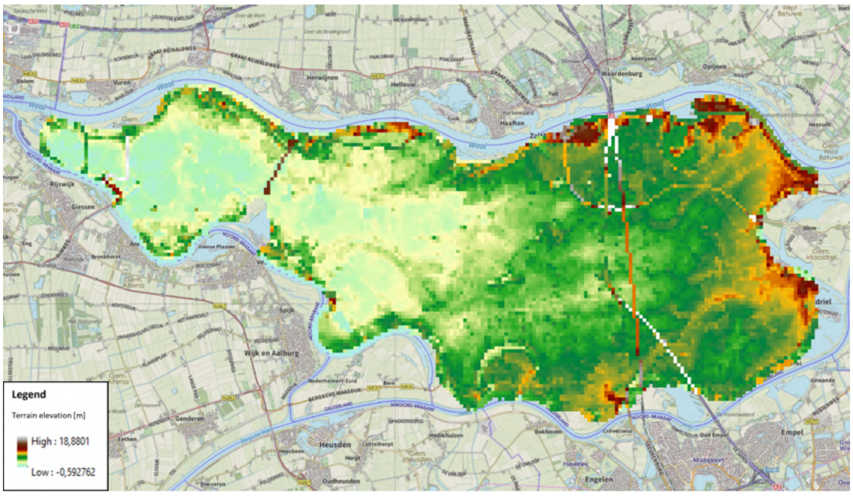


Figure 4.4: Digital elevation model with 100m resolution

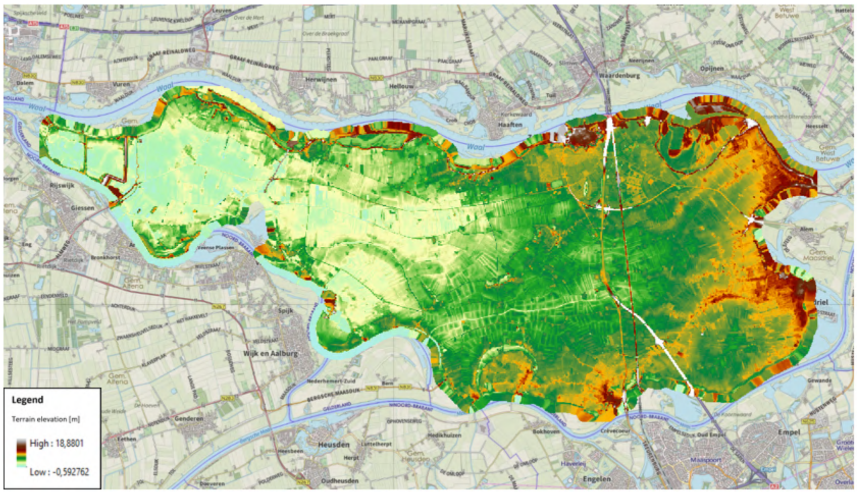


Figure 4.5: Digital elevation model with 25m resolution

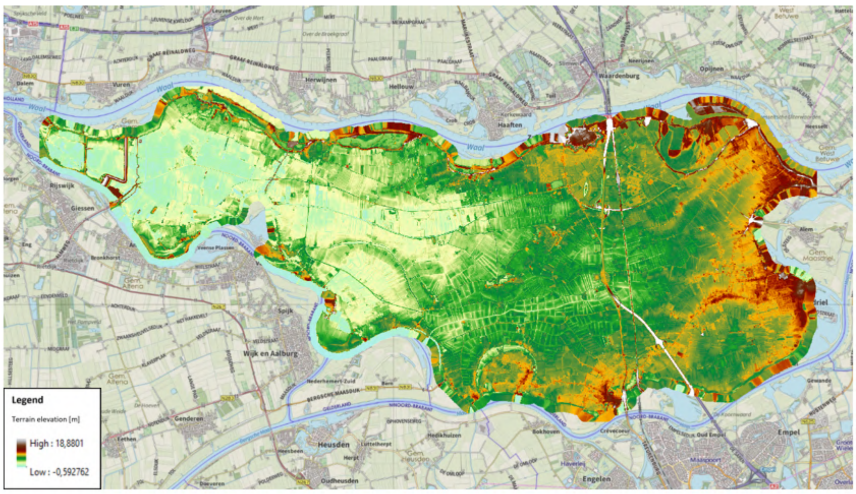


Figure 4.6: Digital elevation model with 5m resolution

4.2.3. Roughness

The roughness affects the inundation pattern through the area as very rough areas have a slower flood propagation than very smooth areas. It can also influence the water depths. Hydraulic roughness is the term that includes multiple effects as skin friction, form drag, and the acceleration and deceleration of the flow (Woodhead, 2007). There are different roughness coefficients which can be used, such as Manning, Chézy, and White-Colebrook. Studies have been done to allow a direct conversion of remote sensing data to friction coefficients (Woodhead, 2007). This study takes into account the roughness coefficient from the guidelines for flood simulations of De Bruijn and Slager (2018), this is the White-Colebrook coefficient. Appendix B describes the White-Colebrook roughness formulation and also presents a brief literature review on roughness.

The roughness coefficient can be applied to the model uniformly or per grid cell. As the roughness is spatially varying in the Bommelerwaard, the White-Colebrook roughness is applied per grid cell. It can be linked to different land use classes. The land use LGN6 ('Landgebruik Nederland' in Dutch) is utilized which is based on data of 2007/2008 and is divided into 39 land use classes. The land use classes are translated into White-Colebrook roughness values for the winter season. An overview of the conversion of the relevant classes into roughness values in this study is shown in Appendix B. The table is based on the available conversion table of De Bruijn and Slager (2018). Some classes concern land use in coastal areas and are for that reason excluded in the legend and table.

The land use of LGN6 has a model resolution of 25m. For the 100m resolution model, the 25m resolution is aggregated by using the mean value. The 25m resolution model is also converted to a 5m resolution grid, but this does not give extra information in the smaller grid cells. The grids are shown in Figures 4.7 and 4.8.

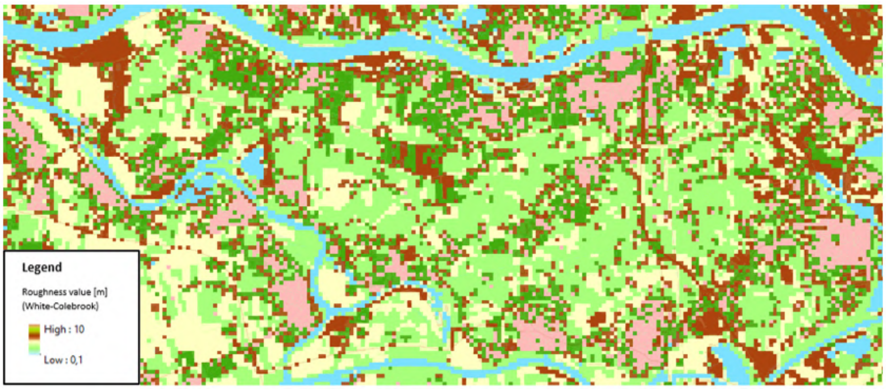


Figure 4.7: Overview of the White-Colebrook roughness values for the 100m resolution model (aggregated from the 25m resolution model)

Figure 4.8: Overview of the White-Colebrook roughness values for the 25m resolution model

4.2.4. 5m resolution model

Zaltbommel is the largest municipality of the Bommelerwaard and is going to be modelled in greater detail with a model resolution of 5m. To provide more detail in the flood characteristics of obstacles as well, the refined area is extended with an area between the highway and the railway, as shown in Figure 4.9.

Figure 4.9: Overview of refined area (in light blue) for the 5m resolution. It covers the municipality of Zaltbommel and a part of the area between the highway and railway.

The roughness of the refined area can be implemented in different ways. The first option is by making a difference in the built environment between buildings and streets. Only the buildings will receive a higher roughness. This is similar to the 25m resolution roughness grid, but the 25m resolution model is not refined enough to make a distinction between buildings. Another option is to take into account the actual height (or by adding some height) of the buildings in the elevation model. In this option, the streets receive a lower roughness and no water can flow through or stand in the buildings.

Both approaches are applied to test the potential different outcomes in flood characteristics as this could be relevant later on for the mortality calculations.

In both approaches, information on the buildings are necessary. The geodatabase of BAG 2017 ('Basisregistratie Adressen en Gebouwen' in Dutch) is used for this. This database is more recent than the roughness data of LGN6 (2007/2008), which means that there are now more buildings in Zaltbommel than taken into account in the roughness grid. Because the outcomes of the 100m, 25m, and 5m resolution models are compared to each other, only buildings which correspond with the LGN6 data are used to keep the comparison between the 5m and the 100m and 25m fair. Buildings after 2007/2008 are thus left out of consideration for the comparison of these two approaches.

The details of the two approaches are further explained below.

Approach 1: higher roughness to buildings and lower roughness to streets

The roughness grid for the 5m resolution contains the same information as the 25m resolution model, but in the 5m model it is possible to make a difference in building and street level. The buildings receive a higher roughness value than the streets. Since streets in this case include everything which is not building (streets itself, but also gardens, parked cars, bushes, bins, fences and so on) a White-Colebrook roughness value of 1.00 m was selected which is larger than the roughness of grass (0.25 m) but much smaller than 10.00 m which was used for urban areas, see Appendix B.

The result for this approach is shown in Figures 4.10 and 4.11.

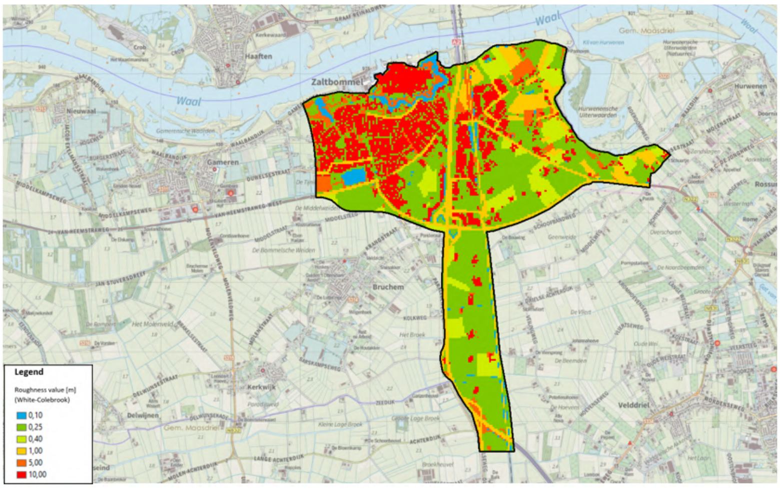


Figure 4.10: Roughness grid for the refined area with 25m resolution

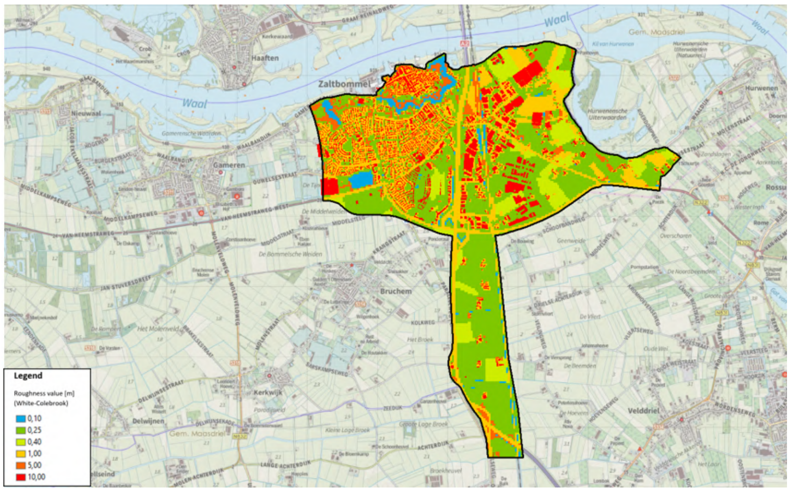


Figure 4.11: Roughness grid for the refined area with 5m resolution when only the buildings have a higher roughness

Approach 2: roughness buildings making use of solid objects

In this approach, the buildings are implemented as solid objects with a fixed height, so no water can flow through the buildings. The White-Colebrook roughness for the area between the buildings is assumed to be 1.00 m, similar to approach 1. By the use of solid objects, the floodwater is not flowing over the buildings but through the streets and the flood characteristics of narrow streets are captured. The actual heights of the buildings may vary since some buildings have one building floor while others contain multiple floors, but this is not included in this comparison study. All buildings receive a fixed height of 10 meters, so the terrain elevation data points of these grid cells receive an additional height of 10 meters. Therefore, the water level is not flowing over the buildings during the simulation. The results are shown in Figures 4.12 and 4.13.

Note that in this approach the water is not flowing through or standing in the buildings and thus no water depth is assigned to the locations of the buildings. When no water is assigned, no damage or mortality can be estimated. Since the aim of this study is to evaluate mortality, approach 1 is favored over approach 2 and will be used for the mortality calculations in the next phase. To investigate the influence of approach 2 on mortality, the flood characteristics (water depth and rise rate) or the mortality map can be interpolated to fill the gaps at the locations of the buildings. This is done in Chapter 5.

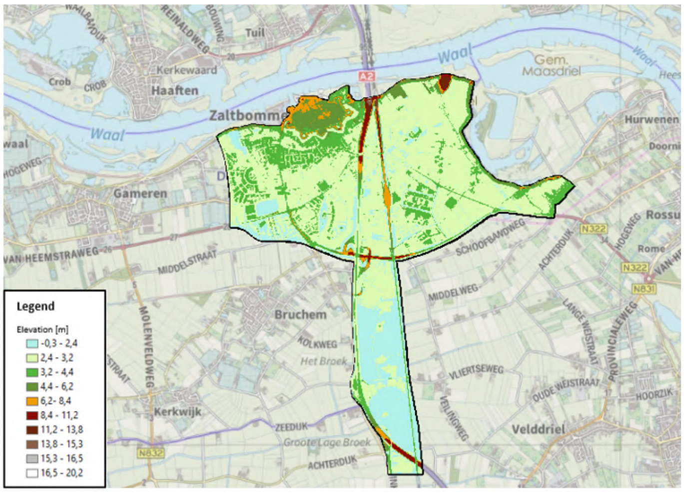


Figure 4.12: Digital elevation model for the refined area with 5m resolution

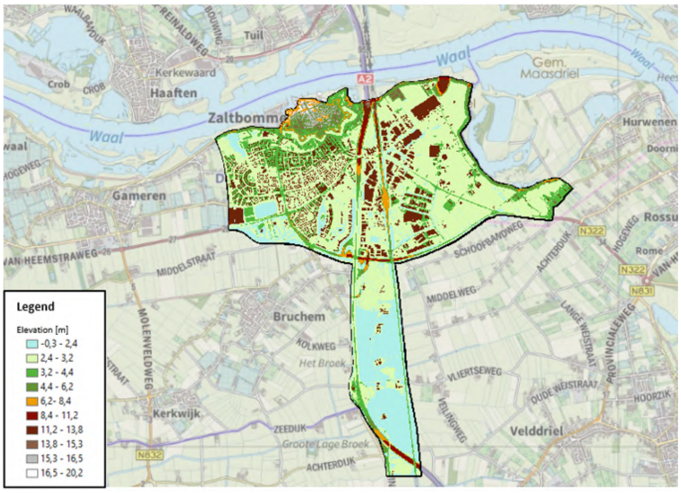


Figure 4.13: Digital elevation model for the refined area with 5m resolution where buildings received an additional height of 10 meters

4.2.5. Breach characteristics

A breach can occur due to several reasons. The VNK2 scenarios showed that the probability of failure is fairly uniform for dike ring 38 and the failure mechanisms overflow and wave overtopping, and up-burst and piping are most important (Vergrouwe and Bossenbroek, 2010).

VNK2 analyzed different scenarios, such as the location of the breach, the moment of the breach and the type of wave. The breach in the case study is based on the breach scenario at Hurwenen of VNK2. The breach is schematized as a horizontal boundary condition with a breach discharge depending on time. The standard wave ('maatgolf' in Dutch) is used, which corresponds to a maximum breach discharge of 2754 m^3/s and a maximum width of 210 m according to VNK2. The breach location is shown in Figure 4.14 and the breach discharge is shown in Figure 4.15.

Figure 4.14: Left: overview of the area where the red X presents the breach location; Right: overview zoomed in on Zaltbommel with the red X as breach location.

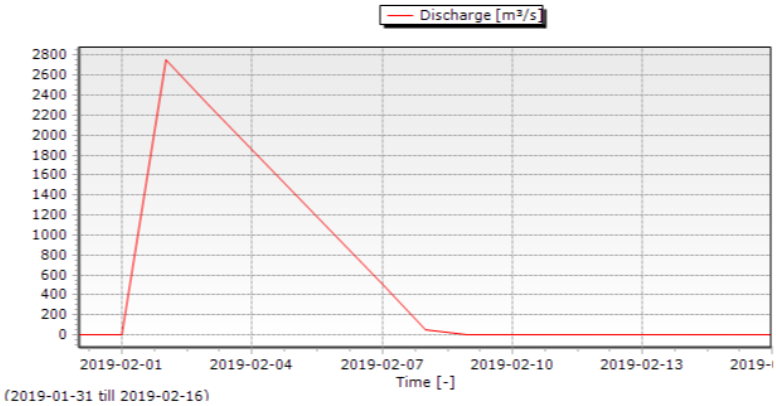


Figure 4.15: Breach discharge depending on time: it goes to the maximum value in one day and goes back to zero after one week (based on assumptions). Figure is created in D-Flow FM.

This is the simplest method to include a breach. This pragmatic approach is chosen in order to keep the model simple and the results interpretable as the main focus of this study is the applicability of the current mortality functions for finer model resolutions, thus more detailed estimates of the breach characteristics are of less relevance. For future studies, the breach schematizing can be improved by including the river model. When connecting the river model to the dike ring area, the interplay between the flooded area and the water level of the river is taken into account. The river model was not available for this study.

4.2.6. Model set-up and grid generation

The core of the D-Flow FM software is called the 'interacter'. As D-Flow FM is still in development and not everything is yet included in the interface at the time of this study, the interacter is used to perform simulations.

The flood simulations will be done with a simulation time of 12 days. The model requires a start time and stop time, in this study it is taken from February 1, 2019 till February 13, 2019.

Grid generation

This study uses D-Flow FM models with a 100m, 25m, and 5m resolution. These grids are made within the interacter. The grids for 100m and 80m resolution were made available by Deltares. As the grid refinement can only be applied with the factor 2, the 100m resolution is used to make the 25m resolution grid (100->50->25). The 80m resolution grid is used to make the 5m resolution grid (80->40->20->10->5). This means that the 5m resolution refined area can only be made from a multiplication factor. Due to the large computation time, not the whole of the Bommelerwaard is modelled with a 5m resolution. Therefore, the 20m resolution grid is used for the rest of the Bommelerwaard, as this is close to the 25m resolution grid and eases comparisons.

Only the inner dike area is used for this flood simulation, hence the grid is constructed for the inner dike area. The edges of the grid present the dikes. The area outside of the dikes is not taken into account and this means that no water can flow out of the area and that the edges (the dikes) are included in the model with an infinite height. However, the dikes have a limited height and scenarios exist where water is flowing out of this dike ring. For that reason, outside water level boundaries are added to allow for this in case of large water depths in the area higher than the dikes. This is further explained in the next paragraph.

Fixed weirs

The fixed weirs are added to the model to enable overflow. The fixed weir is constructed by making a shapefile in GIS at the middle of the dike and then convert this with a Python script to a point file. The points are located at a maximum distance of 5m from each other. Then these points receive the maximum elevation value from the digital elevation model with 5m resolution. To ensure that this maximum value is indeed the maximum value, the script makes a buffer of 5m around the points and corrects the value if another value within that radius has a higher value. These scripts were made available for this study by Deltares.

The fixed weirs are imposed on two locations. Firstly, at the western boundary of the Bommelerwaard, an extra area (outside of the dike) is added to allow for overflow and prevent unrealistic large water depths in the area. A fixed weir is imposed on top of the dike. As this dike has a height of approximately 8m, the water depths can still be too large in the area as the dikes at the southern edge vary roughly between 5 and 7m. Therefore, also a fixed weir is added at a part of the southern edge of the area to allow for overflow, in this case outflow. The crest heights of the dikes at the southern edge are rounded to half meters. An outside water level boundary is added on the fixed weir that allows the water to flow out when the water depth in the Bommelerwaard is higher than the height of the fixed weir. A water level boundary of 4.5m is added, which is lower than the crests of the dikes. The fixed weirs are shown in Figure 4.16.

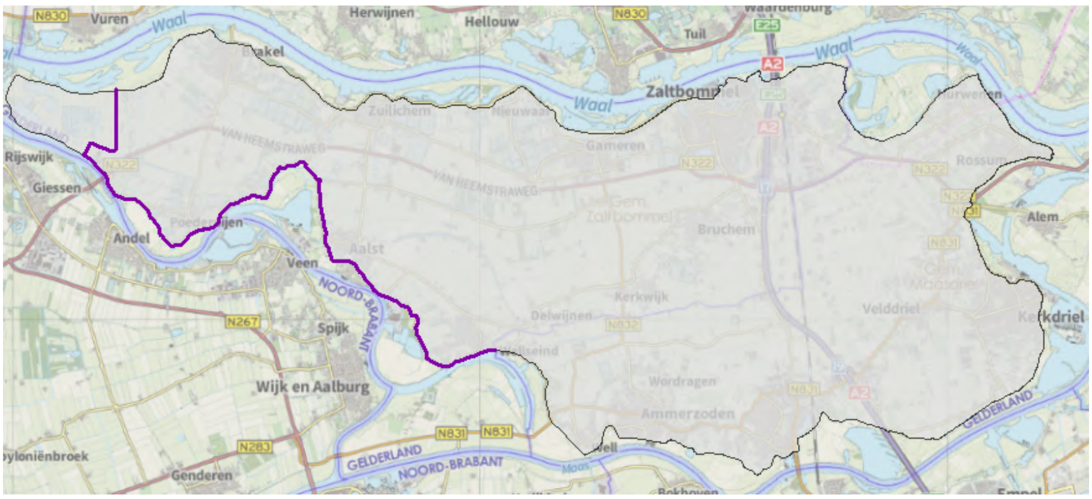


Figure 4.16: Overview of the locations of the fixed weirs at the edge in purple

4.3. Mortality model

The current mortality model used in the Netherlands is called 'SSM2017' ('Schade Slachtoffer Module' in Dutch) and this model also estimates the economic damages. The input and output is briefly discussed below.

Expected results

In the research program VNK2, the question is answered what the probabilities and consequences of flooding are in the Netherlands. It shows per section and dike ring what the potential economic damages and fatalities are. For the Bommelerwaard, the number of fatalities in case of a breach at Hurwenen with a standard wave ('maatgolf' in Dutch) and without evacuation, is estimated to be 504 (Vergrouwe and Bossenbroek, 2010). Figure 4.17 shows the overview of the inundation pattern for a breach at Hurwenen and Figure 4.18 shows the individual risk for dike ring 38. The evacuation fraction to estimate the individual risk in this figure is 0.77.

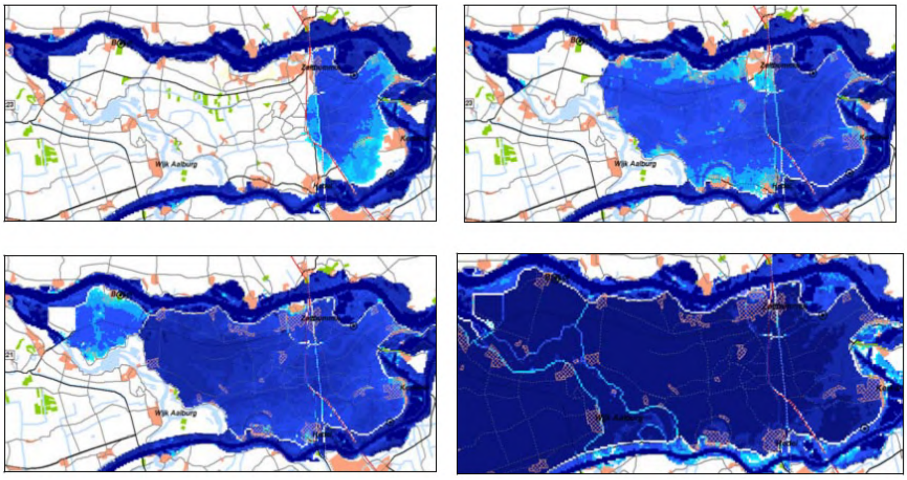


Figure 4.17: Inundation pattern after 6, 16, 24 hours, and 1 week, from VNK2 (Vergrouwe and Bossenbroek, 2010)

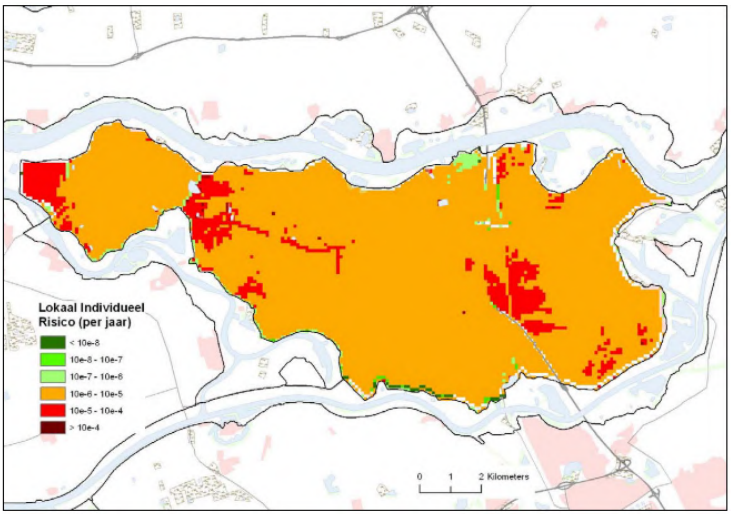


Figure 4.18: Individual risk (LIR), from VNK2 (Vergrouwe and Bossenbroek, 2010)

4.3.1. Input

SSM2017 requires regular input grids with a 5m, 25m, or 100m resolution. The minimum required input file for SSM is the maximum water depth, in .tiff or .asc format. Optionally, the grids for the flow velocity, water level rise rate, and water arrival time can be included. The water arrival time is not included in the mortality calculations, but it is added to the output files to make the arrival times visual.

Conversion D-Flow FM output to SSM input

D-Flow FM generates the output files which are specified by the user. The following output files are specified for this study:

- Map file (NC format)
  The map file stores the information for every cell for every specified time step. Hence, the map file is the largest output file.
- Class map file (NC format)
  The class map stores data (water depth or flow velocity) in specified classes instead of the precise values. This results in a smaller sized file than the map file and this is preferred for visualization purposes. This file is also used to calculate the water level rise rate and water arrival time.
- Fou file (NC format)
  The name of this file originates from 'Fourier' and this file stores amongst others the maximum water levels, maximum water depths, and the maximum flow velocities.
- His file (NC format)
  The name of the his file originates from 'History' and this file is used to investigate certain locations in the modelled dike ring: observation points or cross sections can be added with a specified interval. These are stored in the his file along with the water balance of the model.

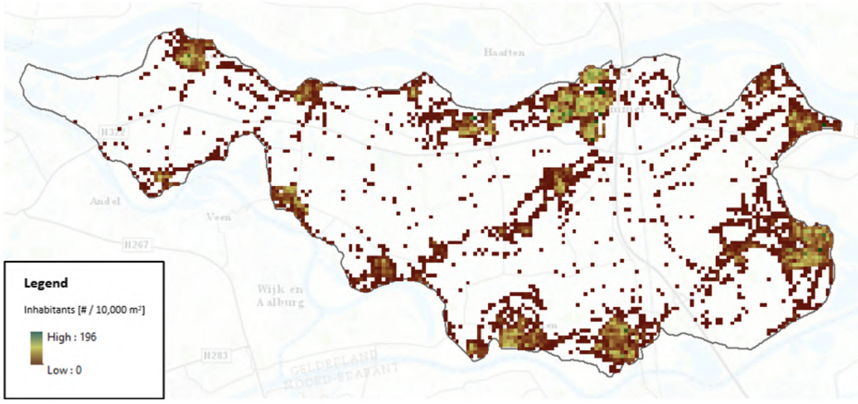
The maximum water depth and maximum flow velocity are thus coming out of the Fou file. The Python scripts converse these files from NC format to .tiff format in order to be readable for SSM2017. Furthermore, the script calculates the water level rise rate according to the definition (see Chapter 3) and the water arrival time by making use of the Class map file. After conversion to .tiff format, these four files are thus imported in SSM2017. The Python scripts were made available by Deltares.

4.3.2. Output

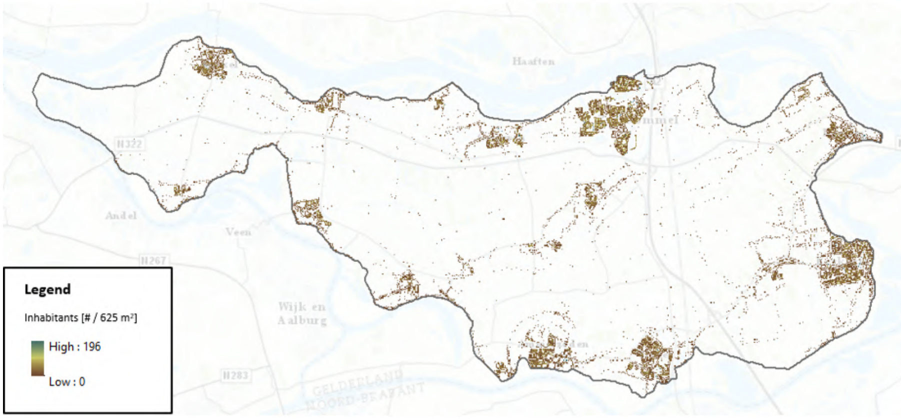
SSM2017 calculates the mortality based on the input files as discussed above, and gives the flood fatalities and people affected in the dike ring area.

The flood fatalities are estimated by multiplying the mortality grid with the inhabitants grid. Therefore, the inhabitants grid must match the model resolution of the mortality grid. In Figure 4.19, the inhabitants grids are shown for the Bommelerwaard.

The 5x5 inhabitants grid is less clear when the whole Bommelerwaard is shown. Therefore, Figure 4.19d zooms in on a part of Zaltbommel where the cells with inhabitants are well displayed.



(a) 100m resolution



(b) 25m resolution

(c) 5m resolution

(d) 5m resolution, zoomed in on a part of Zaltbommel

Figure 4.19: Inhabitants grid with different resolutions (data obtained from SSM2017)

4.4. Summary approach

Figure 4.20 shows the overview of the approach of this case study. Firstly, preparations need to be made in GIS based on data of AHN3 and LGN6: the digital elevation model, the roughness grid, and the refined area are prepared. Secondly, the D-Flow FM model schematization is created. The grids must be generated and the model set-up must be finished by imposing the breach location and timeseries, the water level boundaries, and the fixed weirs. The flood simulations can be carried out now using the interacter. Afterwards, the output of D-Flow FM (NC files) must be conversed to .tiff files, so it can be imported into SSM2017. The SSM2017 block presents the flood fatalities analysis with the four input grids. Finally, the results are mapped and visualized and interpreted for the flood fatalities, people affected, and mortality, and the mortality number of affected persons and the number of fatalities is calculated.

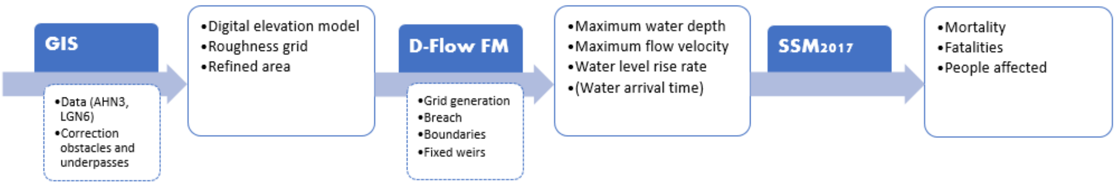


Figure 4.20: Overview of approach

The case study aims to analyse the impact of the level of detail of the hydrodynamic model on the estimated mortality. Therefore, three models are made with a model resolution of 100m, 25m, and 5m. The finest model resolution of 5m is not applied to the whole Bommelerwaard, but limited to the municipality of Zaltbommel, the rest is modelled with a model resolution of 20m. This means that the tasks of Figure 4.20 have to be performed three times.

As the 5m resolution model contains many details, the applied roughness is tested in two different ways: one model with an increased hydraulic roughness for only the locations with buildings and a lower roughness to the streets, and one model using solid obstacles for the buildings by adding 10m height to the digital elevation model for those locations.

5

Results of case study: level of detail flood simulations

This chapter presents the results of the first part of the case study. It considers the output of the D-Flow FM models and the first results of the mortality calculations. Section 5.1 analyzes the flood characteristics for different model resolutions and Section 5.2 presents the mortality outcomes. Section 5.3 focuses on the impact of the different roughness approaches for the refined area with a 5m resolution on the flood characteristics and mortality outcomes. Section 5.4 looks more in-depth into relevant locations and aspects. Section 5.5 summarizes the results and gives the conclusions, discussion and recommendations of this first part of the case study.

5.1. Impact of model resolution on flood characteristics

This section presents the output of the flood simulations for the different model resolutions of 100m, 25m and 5m. The water arrival time, maximum water depth, maximum flow velocity, and water level rise rate are considered. The water arrival times of the 100m, 25m, and 5m resolution are shown in Figures 5.1, 5.2, and 5.3 respectively to give an impression of the inundation pattern.

The water flowing in through the breach spreads both towards Zaltbommel and the east of the Bommelerwaard. The railway is able to stop the water from flowing to the west at first. After 12 hours it is overflown and water continues to flow west. The viaduct forms an underpass which results in a water flow towards the city center of Zaltbommel within 12 hours, especially in the 100m model where the underpass is modelled with one grid cell (width of 100m) where a large volume flows through. Most of Zaltbommel is inundated within 12 hours, while for the 25m and 5m model this takes slightly longer, in the range of 12-24 hours. The higher situated old city center at the northern side, is reached just after 48 hours in the 5m model. Figure 5.4 zooms in on Zaltbommel to make these differences more visual.

At the southern edge, there is also a difference in arrival time between the different model resolutions at the obstacles after the highway and railway have crossed. The 25m and 5m model have an arrival time of 6-12 hours there, while for the 100m model it is longer (12-24 hours). This could be due to the obstacles: the height of the obstacle per cell is based on the maximum elevation stretched out over this cell. For the 100m model, the maximum elevation is thus stretched over a width of 100m, while for the 25m (and 5m) model, the cell size is smaller and thus it is stretched over a shorter length. For that reason, the 25m and 5m model have some locations which are lower than the 100m cell model. These locations are sooner overtopped than those in the 100m model resulting in smaller water arrival times behind the obstacle.

After the railway and highway are submerged on their lowest part, the water is moving further to the west without any significant delay. After approximately 26 hours, the water reaches the Meidijk, the regional dike which cuts the Bommelerwaard polder in two in the flood simulation. The Meidijk has a large influence on the flooding pattern as the water is not able to flow through to the other side. It retains the water while more water is flowing into the area through the breach. The Bommelerwaard (at the eastern side of the Meidijk) is filling up till a water level of approximately 6.2m+NAP. This corresponds to the lowest crest height of the Meidijk at the southern edge and from there the water starts flowing over the dike. When the water level of 6.5 meters is reached, also overflow is taking place at the river embankments which means that water is flowing out of the area. This happens after approximately 52 hours. Due to the outflow, the discharge flowing towards the western side of the Meidijk is not increasing any further. After approximately a week, no water is flowing in anymore through the breach and the water levels are not rising anymore above the 6.5m+NAP.

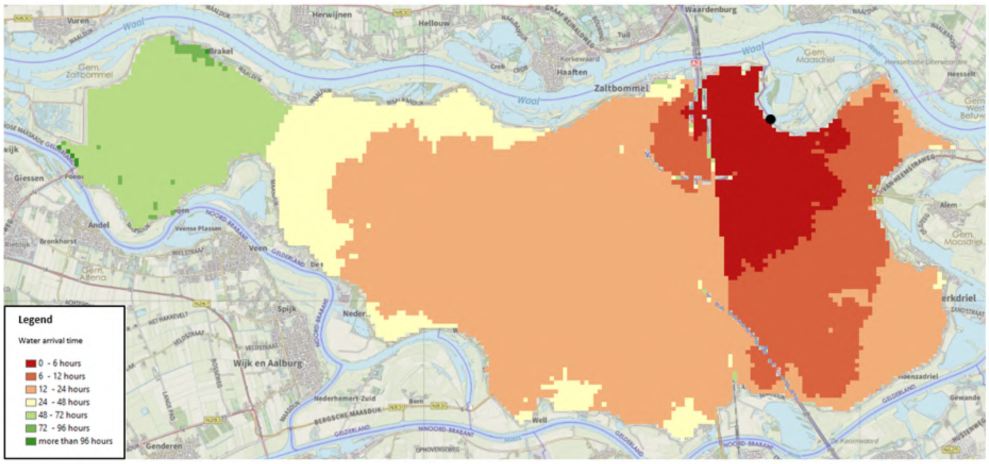


Figure 5.1: Water arrival time map with 100m resolution. The black dot presents the breach location.

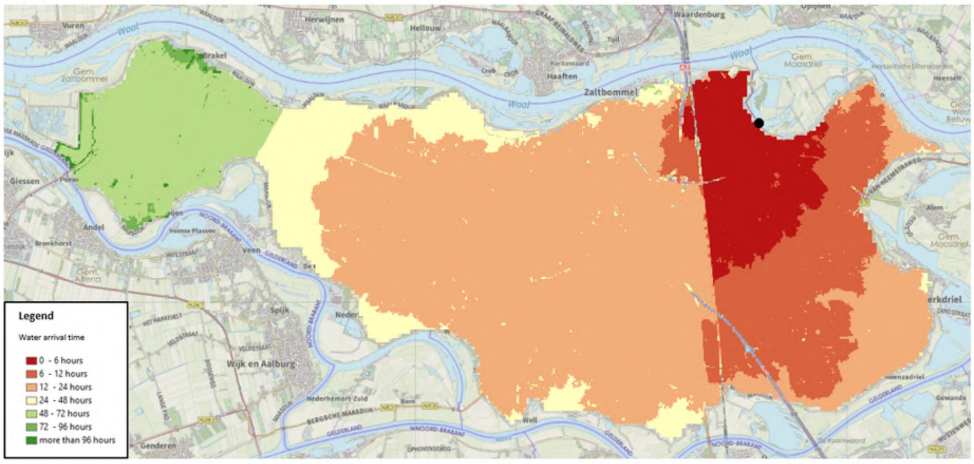


Figure 5.2: Water arrival time map with 25m resolution. The black dot presents the breach location.

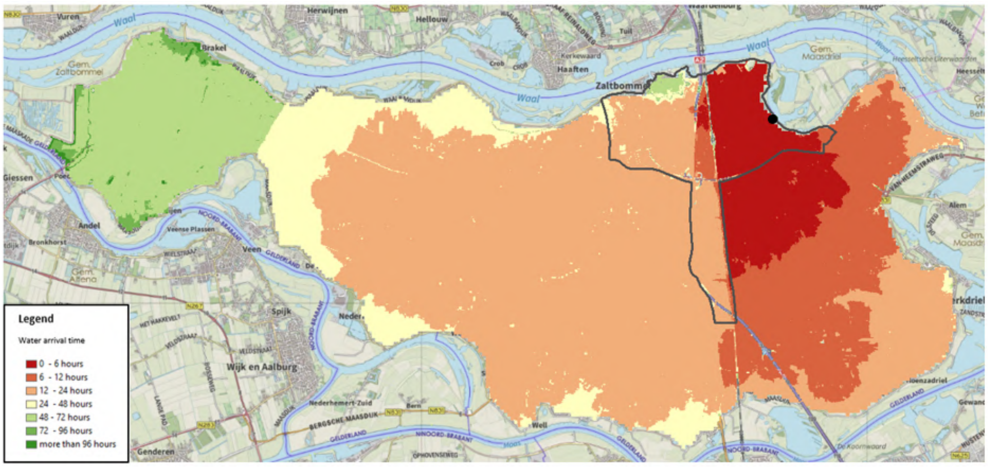
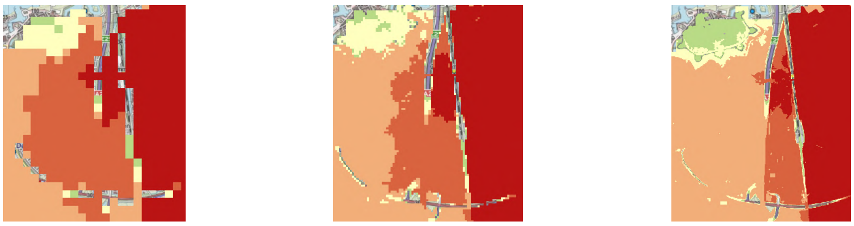


Figure 5.3: Water arrival time map for the 5m resolution model. Only the marked area is modelled with a 5m resolution (the black line in the figure), the rest of the area has a resolution of 20m. The black dot presents the breach location.



(a) 100m resolution (b) 25m resolution (c) 5m resolution

Figure 5.4: Water arrival time zoomed-in on the underpass in Zaltbommel

In short, the water arrival times are very similar, but differences exist around the obstacles and underpasses due to the model resolution. Refinement around obstacles and underpasses is thus of relevance. In the next sections, the findings of the other flood characteristics will be visualized and further analyzed per model.

Maximum water depth

The water depth is the difference between the water level and the bed level. The maximum water depth maps are shown in Figures 5.5 and 5.6. The water level reaches up to 6.5m+NAP as the dikes will overflow at the southern edges if the water level is higher. This happens after approximately 2 days for approximately 5 days.

The water depth is relatively large at most locations, between 3 and 6 meters and on some spots even slightly more than 6 meters. The eastern part of the Bommelerwaard has a somewhat higher bed level which explains the difference in water depths from east to west. The obstacles are clearly visible and on the highest points, the water depth remains zero. The Meidijk retains the water till its maximum elevation and causes the eastern area to fill up like a bathtub. Eventually, the Meidijk is overflowed and the water depths are around 3-5 m as well at the west side of the Meidijk.

The results of the 100m and 25m models are similar, but show some differences. The 25m resolution model contains more detail, variations such as roads are visible with at some locations water depths in the range of 4-5m instead of 5-6m. As the 100m model is coarser, these variations are lacking and therefore it has larger water depths at these locations than in the 25m model. Moreover, the cities and villages in the area, such as Zaltbommel, are coarser modelled. Figure 5.5 shows that Zaltbommel in the 100m model contains more water depths in the range 4-5m than the 25m model in Figure 5.6 (more in the range 3-4m), and as many people live in this area, this could influence the number of fatalities.

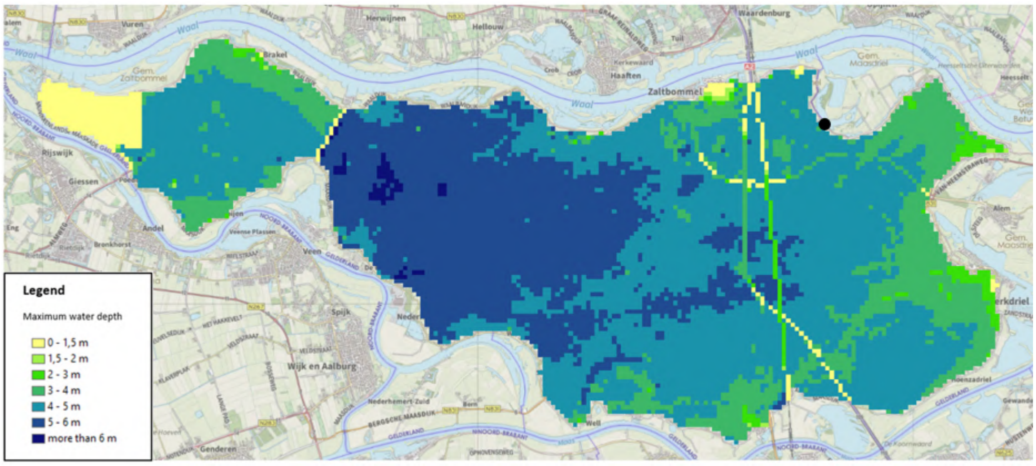


Figure 5.5: Maximum water depth map with 100m resolution. The black dot presents the breach location.

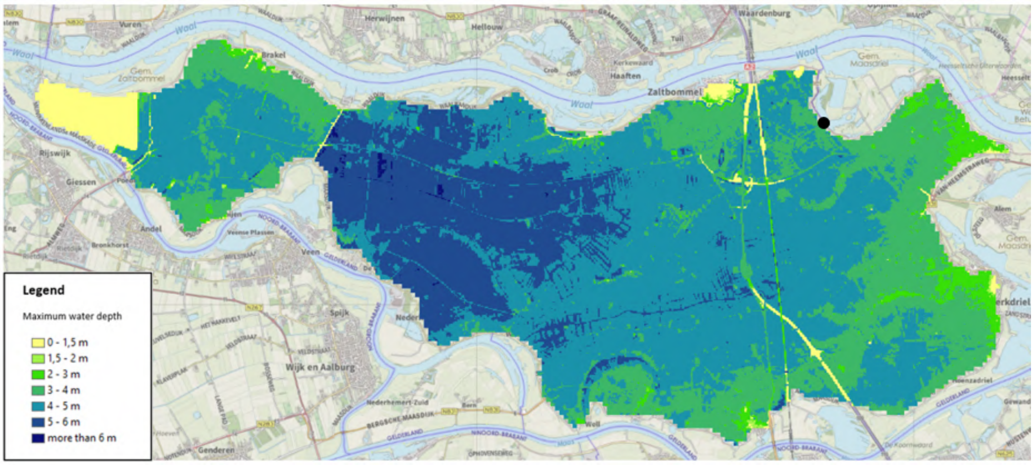


Figure 5.6: Maximum water depth map with 25m resolution. The black dot presents the breach location.

In conclusion, the two models represent the same information. Overall, the locations correspond very well in the two models, but the precise values differ. The water depths in the 100m model seem more conservative with slightly more locations with water depths in a higher range than the 25m model.

Maximum flow velocity

The maximum flow velocities are shown in Figures 5.7 and 5.8. At most locations, the maximum flow velocities are in both models relatively low, between 0 and 0.75 m/s. The flow velocities are the highest at the breach location with flow velocities more than 4 m/s. In addition, the velocities over the railway and highway are relatively high, between 1 and 2 m/s. These velocities are also found at some spots close to the outflow boundaries.

Velocities higher than 2 m/s are of most interest as the flow velocity is only taken into account in mortality calculations if it is higher than 2 m/s (and if the depth-velocity product is higher than 7 m^2/s), and this is the case for the breach location. The breach conditions are further analyzed in Section 5.4.

In the 25m model, velocities higher than 2 m/s are found at more locations than in the 100m model. Velocities between 2 and 3 m/s occur for the underpass at the viaduct before Zaltbommel and an underpass in the railway at the west of the Bommelerwaard. Besides, these velocities occur at some spots next to the Meidijk, where the water overflows the dike, and some spots close to the outflow boundaries. As the 100m model is coarser, the velocities are averaged over a larger cell, so the peak velocities have less effect compared to these in the 25m model, resulting in lower velocities. Besides, the underpasses are wider (coarser grid cells) with lower velocities as result.

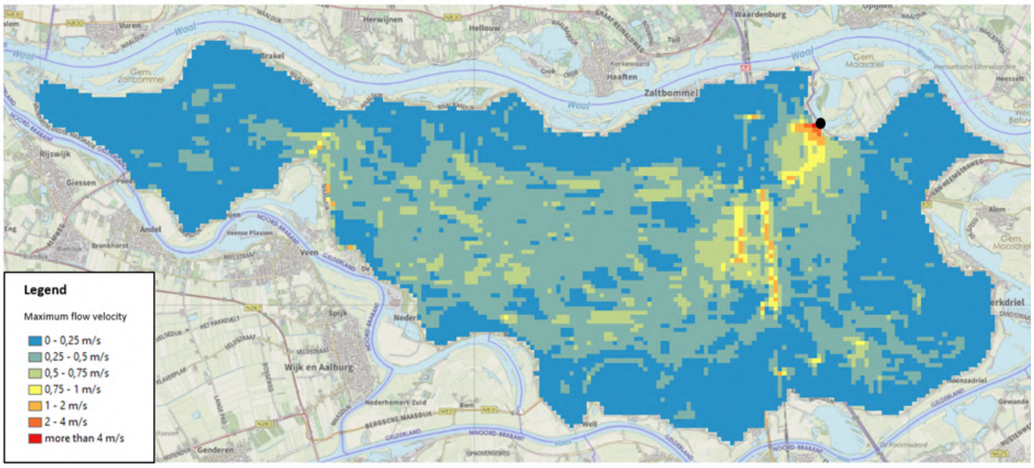


Figure 5.7: Maximum flow velocity map with 100m resolution. The black dot presents the breach location.

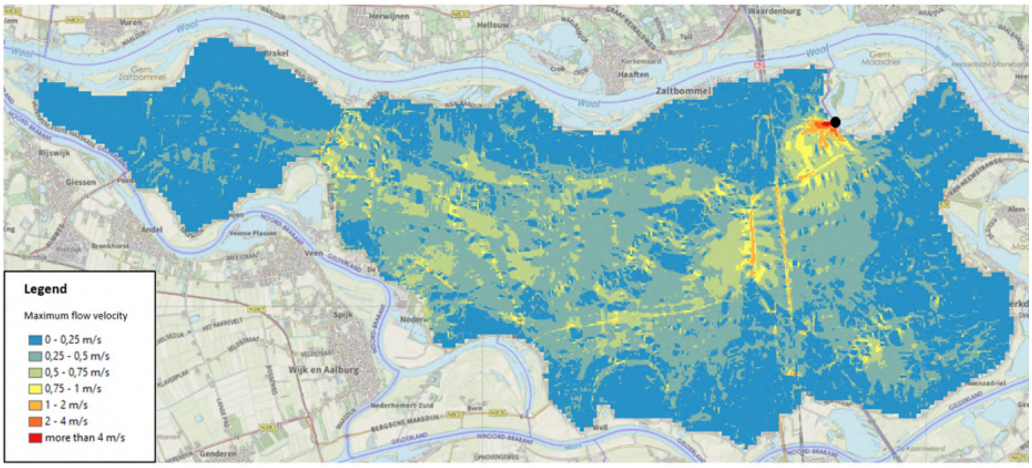


Figure 5.8: Maximum flow velocity map with 25m resolution. The black dot presents the breach location.

Concluding, the model resolution has an impact on the flow velocity. Since the velocity must be higher than 2 m/s to influence the mortality outcomes, the difference in velocities between the 100m and 25m model are mostly of relevance in the breach zone. This is further analyzed in Section 5.4.

Water level rise rate

The water level rise rate is calculated between a water depth of 0.02 and 1.50 m. The maps of the water level rise rates are shown in Figures 5.9 and 5.10. The water level rise rates in both models are similar to each other, but again the difference in the level of detail is clearly visible. The 25m model has more variations in the elevation model which results in higher rise rates than in the 100m model. Also at locations of waterways, the rise rate is higher in these cells. This is not visible in the 100m as this is averaged. This will lead to higher local mortality at some of these spots.

For a large part, the rise rate is below 0.25 m/h, for example, the area west of the Meidijk and the area at the southern and eastern edge of the Bommelerwaard. Also, the part of

Zaltbommel located at the west of the railway has very low rise rates, in the order of 0.05 to 0.10 m/h, as the water is flowing towards the west without delays. Rise rates higher than 0.25 m/h occur mostly due to the obstacles. This is clearly visible next to the highway and railway.

The largest water level rise rates are found next to the Meidijk. The Meidijk retains the water which results in the fast rise. In both models, the rise rate is more than 4 m/h. The influence of the Meidijk on the rise rate reaches relatively far upstream. At some locations next to the Meidijk, the rise rate is so high, that the 1.5m is even reached in 10 minutes in the 25m model.

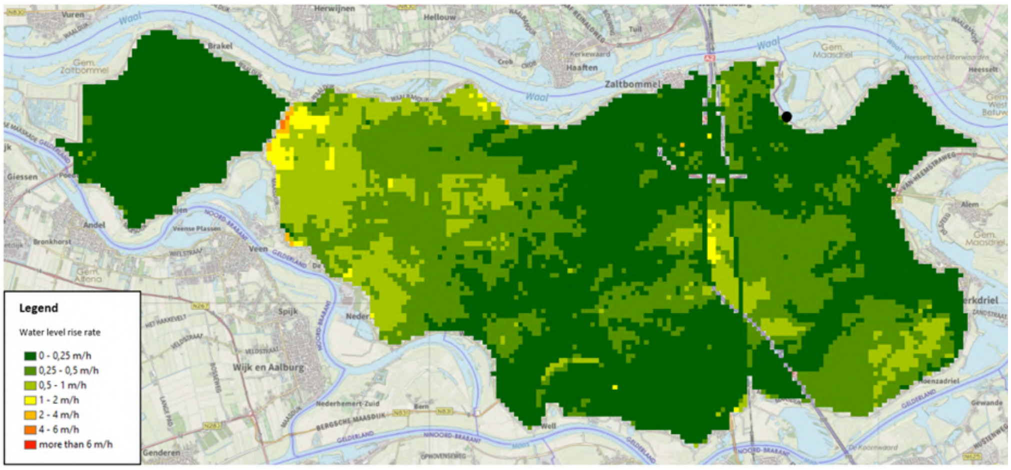


Figure 5.9: Water level rise rate map with 100m resolution. The black dot presents the breach location.

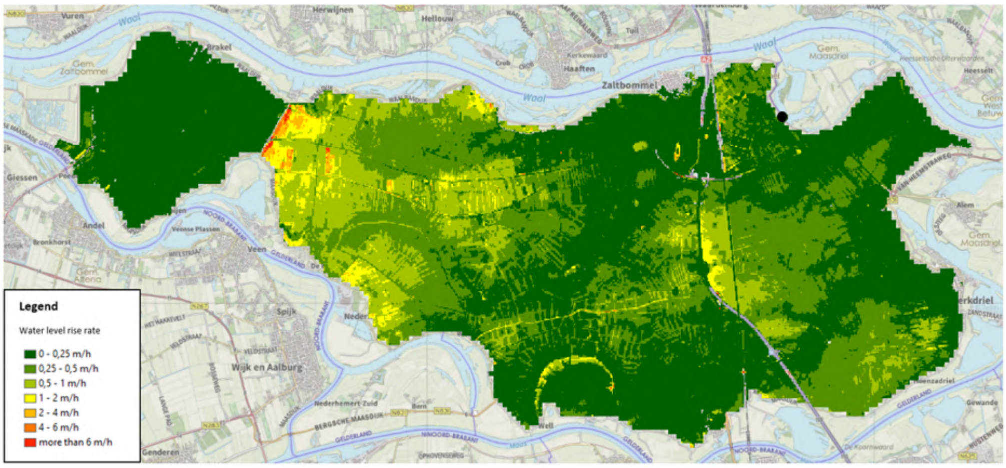


Figure 5.10: Water level rise rate map with 25m resolution. The black dot presents the breach location.

An observation point close to the Meidijk gives an example how fast the water depth increases, see Figure 5.11. It shows that in approximately 20 minutes the water rose to 1.5 m which is a rise rate of around 4 m/h. The water is rising faster in the 25m model than in the 100m model.

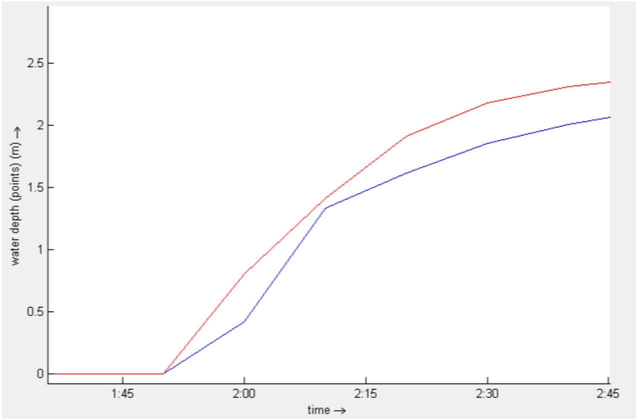


Figure 5.11: Overview of the water depth over time for a location close to the Meidijk. The result of the 100m is given in blue and of the 25m in red.

One can conclude that the model resolution has a significant impact on the rise rate. This will influence the mortality significantly as higher local rise rates could cause higher local mortality.

5.2. Impact outcomes on mortality

The flood characteristics are used to calculate mortality, the functions are explained in Chapter 3. This section presents the mortality outcomes and the number of estimated fatalities for the different model resolutions.

Maximum mortality

Mortality provides the probability of dying for a person present at a certain location due to a flood scenario, hence people affected and evacuation are not taken into account. This is useful to identify hazardous locations. The maximum mortality maps are given in Figures 5.12 and 5.13.

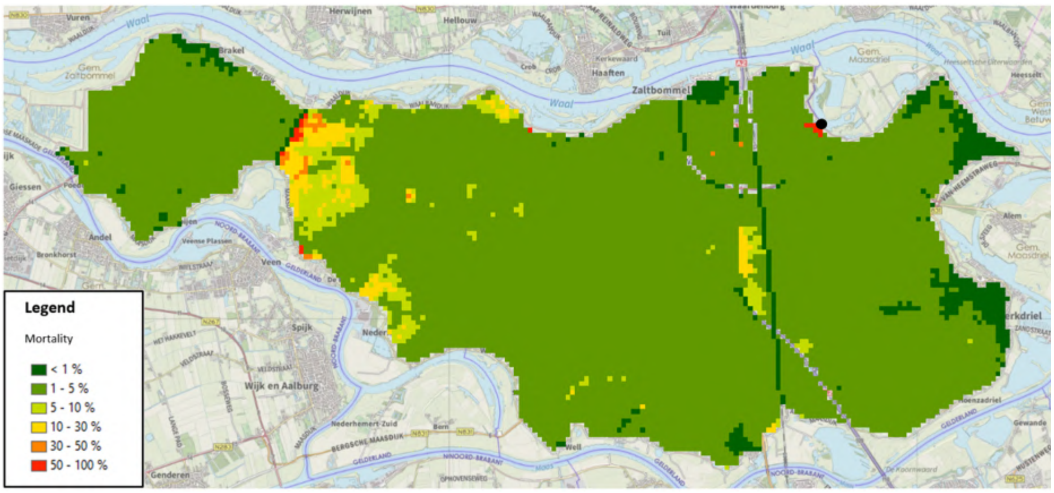


Figure 5.12: Mortality map with 100m resolution. The black dot presents the breach location.

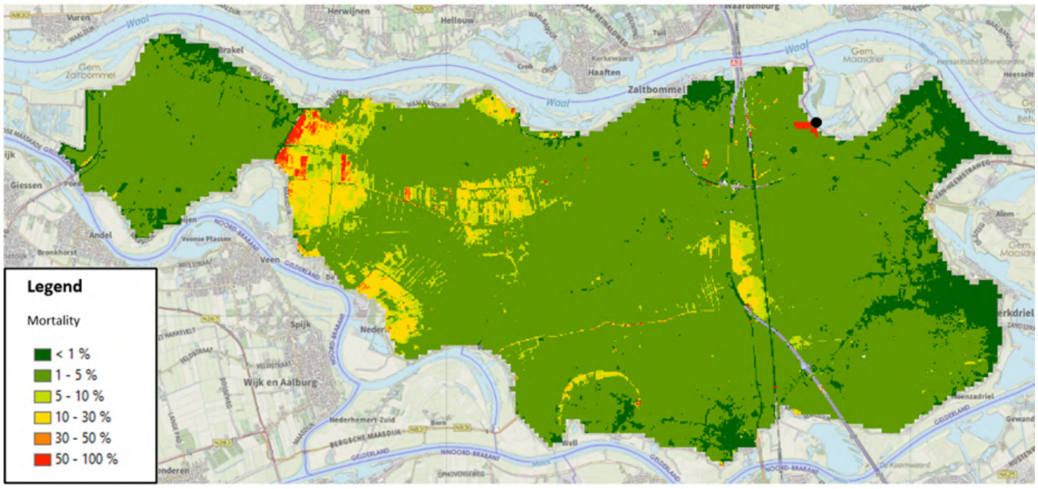


Figure 5.13: Mortality map with 25m resolution.The black dot presents the breach location.

The maximum water depth largely determines the mortality. The maximum water depth is mostly between 4 and 6 meters and this results in mortality between 1.1 and 1.5%, thus in class 1 - 5% in the map. The locations with rise rates higher than 0.5 m/h have an increased mortality, mostly between 10 and 30%, this is due to the obstacles. Close to the Meidijk, the rise rates are very high, the combination of a large water depth and a high rise rate results in mortality between 50 - 100% at these spots. This shows that the locations just upstream of the Meidijk are very dangerous in this scenario. One must point out that the Meidijk is only reached after 26 hours, but the water arrival time is not included in the mortality calculation. In the breach zone, the mortality equals 100%, this is the most dangerous location. The extent of the breach zone is further discussed in Section 5.4.

The histogram in Figure 5.14 shows the division of the mortality categories as fraction of the total area. It shows that in both models, the mortality is mostly between 1 and 5%. The 100m model contains approximately 7% more of the total area in the range 1 to 5% than the 25m model, this can be explained by the slightly larger water depths as explained in Section 5.1. The 25m model has a slightly higher fraction for the categories 10-30% and 50-100%, this can be explained by the higher local rise rates as explained in Section 5.1.

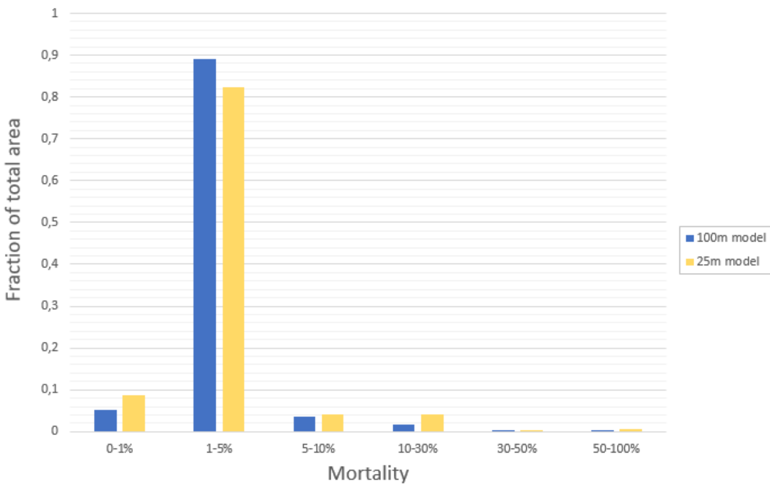


Figure 5.14: Comparison of the mortality categories as part of the total area between the 100m and 25m model

The dangerous locations of the 100m and 25m model correspond very well. As shown in the figures of the flood characteristics in previous paragraphs, the 25m model contains more details than the 100m model. This is also coming back in the mortality map. An example is shown in Figure 5.15: this is a small waterway. The water depths and rise rates are locally higher in the 25m model, resulting in a clearly higher mortality for these set of cells. This is not coming back in the 100m model. One could say that the waterway itself is not a relevant location for a higher mortality as people are never located in water. These spots need to be filtered out or it must be mentioned clearly when showing the map to avoid wrong conclusions based on high mortality at locations of water. These increased local mortality due to a waterway is occurring more often.

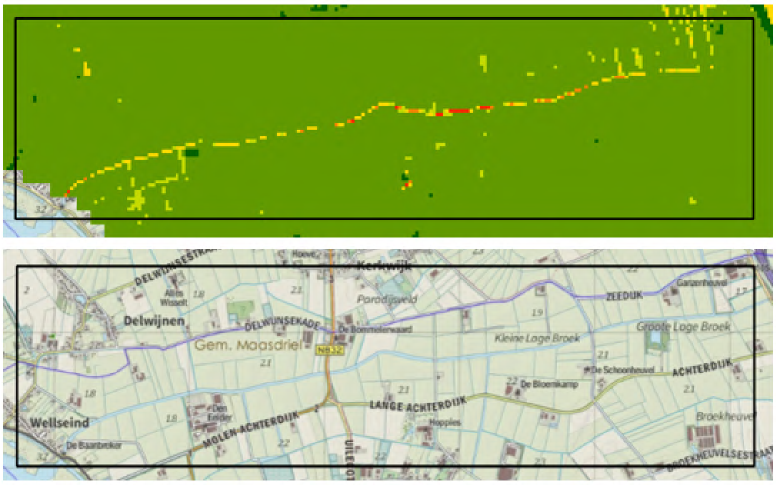


Figure 5.15: Mortality map with 25m resolution, zoomed in on a waterway.

Overall, the mortality maps show the same dangerous locations for the Bommelerwaard. The Meidijk, the obstacles and the breach location are standing out. The 100m model has slightly larger water depths and thus slightly larger mortality rates, but locally, the 25m model contains more details and more higher local mortality spots. Some of these locations are waterways and thus not of relevance.

Number of fatalities

The number of fatalities is calculated by multiplying the number of inhabitants per grid cell with the mortality rate in that grid cell. The mortality model (SSM2017) provides the estimated mortality, number of people affected, and number of fatalities. The outcomes for the 100m, 25m, and 5m models are shown in Table 5.1, these are the results without evacuation.

Table 5.1: Overview of the results of the mortality model without evacuation. Note that the resolution is 5m around Zaltbommel and 20m elsewhere (see Chapter 4).

	Total fatalities	Total people affected	Mortality
100m	598	45,770	1.31%
25m	531	45,856	1.16%
5m	554	46,452	1.19%

The 25m and 5m model have very similar outcomes with around 550 fatalities. The 100m model resulted in around 50 more fatalities and a higher mortality rate than the 25m and 5m model. This could be due to the fact that most people live in the municipalities and that the coarser resolution of the 100m model resulted in slightly larger water depths at these municipalities with larger mortality rates as result. This will be analyzed further in Section 5.4.

The spatial distribution of the fatalities across the Bommelerwaard is shown in Figures 5.16 and 5.17. Most fatalities are shown in the map at the municipalities which is in line with expectations as most people affected are located there. Zaltbommel is the largest municipality and located close to the breach, consequently many fatalities occur at this place.

The fatalities are given per grid cell. To make a fair comparison between the 100m and 25m model, the fatalities grid of the 25m model is aggregated to a 100m grid by summation. The number of fatalities are then for both models given per 100m cell, thus 10,000 m^2. This is only done for mapping purposes.

The previous section considered the dangerous locations and showed that the mortality was very high just before the Meidijk. However, it depends on the location of the inhabitants if fatalities actually occur. There are not many fatalities before the Meidijk, so apparently, not many people live in the area close to the Meidijk, but this could be the case in the future and must be kept in mind.

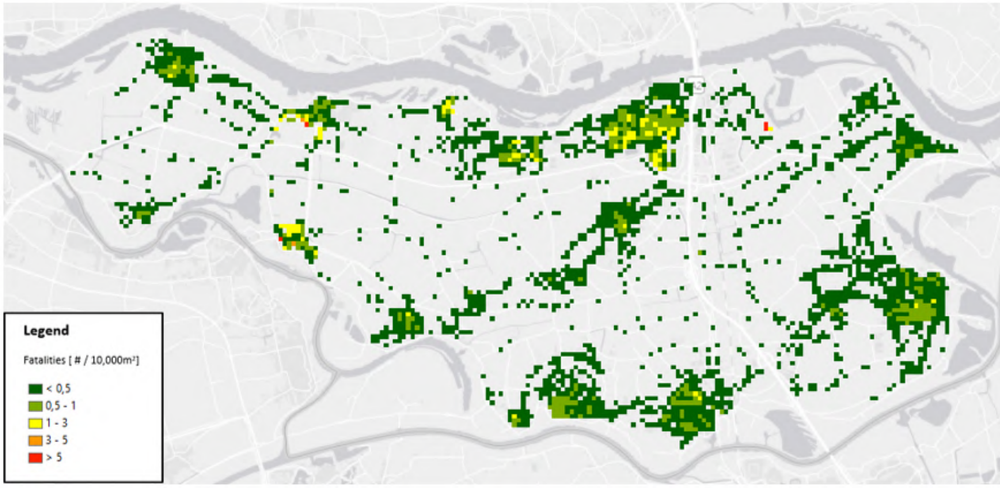


Figure 5.16: Fatalities with 100m resolution

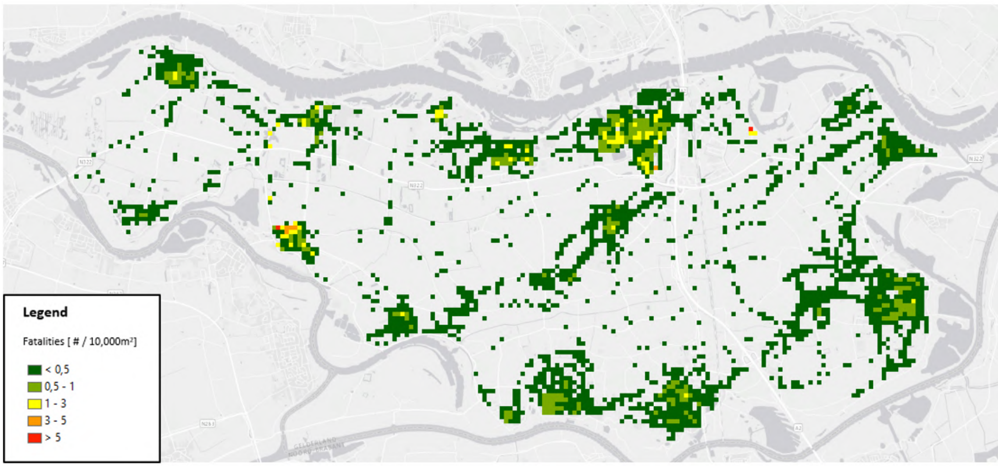


Figure 5.17: Fatalities with 25m resolution (aggregated from 25m resolution to 100m resolution by summation to ease visual comparison)

5.3. Area close to the breach with 5m resolution

For the 5m resolution model, the roughness is implemented in two different ways:

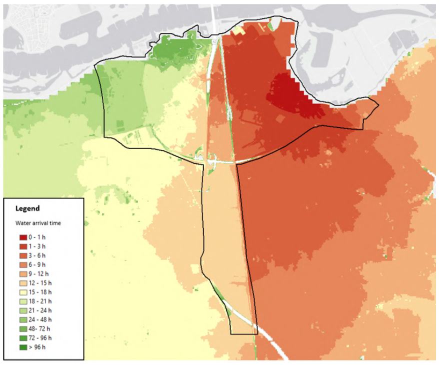
1. Applying a higher hydraulic roughness to only the buildings and a lower roughness to the streets;
2. Adding a height of 10 m to the locations of the buildings in order to take the buildings into account as solid objects.

This section shows the results for the different roughness approaches. Firstly, the impact on the flood characteristics are considered and secondly, the impact on the mortality outcomes. The refined area is also given for the 25m model for comparison.

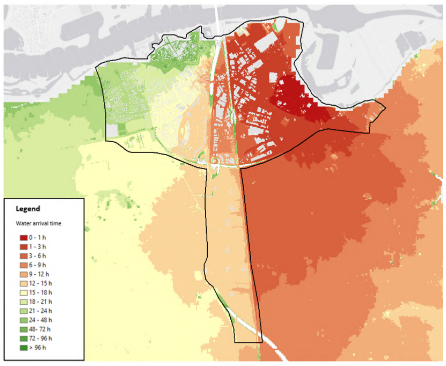
5.3.1. Impact roughness on flood characteristics

Figures 5.18a and 5.18b show the arrival times for the different approaches with 5m resolution. Both models are very similar. The buildings are clearly visible in Figure 5.18b, but the arrival times are nearly unaltered. Figure 5.18c shows the differences, almost whole of the area has no difference or less than 1 hour. As the water flow needs to go around the buildings, the flow velocities are somewhat higher and therefore, the water propagates slightly faster in approach 2.

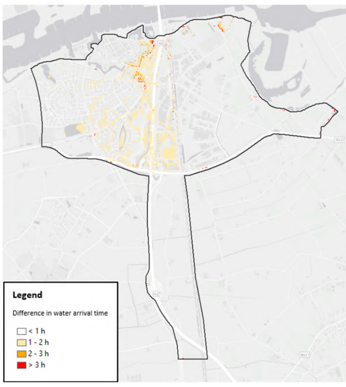
Differences with the 25m model (Figure 5.18d) are larger. The area at the eastern side of the obstacles is very similar, but the differences occur when the underpass of the railway is reached in about 3 hours. From that point, the arrival times become different due to the discharge through the underpass. This also played a role in the difference between the 100m and 25m model. The floodwater passed the underpass of the highway in 7 hours in the 25m model, while the 5m model needs 9 to 12h to pass this underpass. Consequently, Zaltbommel has a 3 to 4 hours difference in water arrival time between the 25m model and the 5m model.



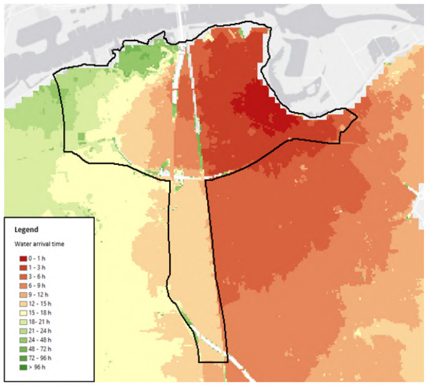
(a) 5m resolution - Approach 1 (higher hydraulic roughness)



(b) 5m resolution - Approach 2 (buildings as solid objects)



(c) Absolute difference between approaches (5m resolution)



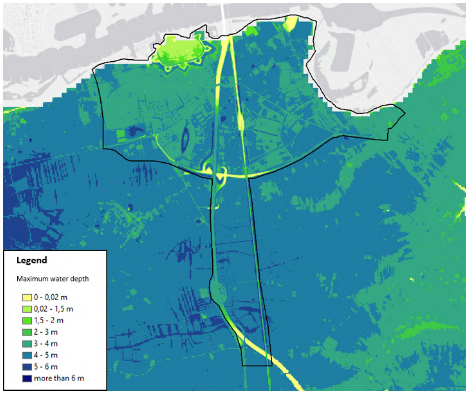
(d) 25m resolution

Figure 5.18: Water arrival time in the refined area

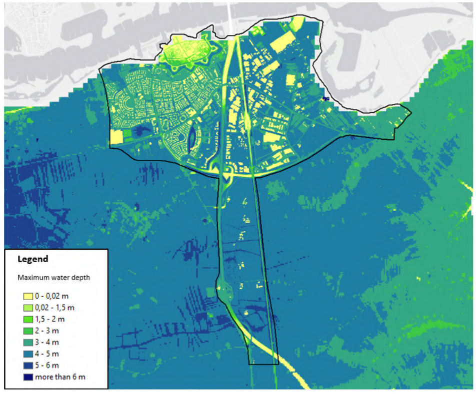
Maximum water depth

Figures 5.19a and 5.19b show the maximum water depths for approach 1 and 2. The largest differences (> 0.5m) are due to the locations of the buildings. As the buildings are implemented as solid objects, no water is standing in or flowing through the buildings. Hence, a water level of zero is assigned to those locations. Another difference is visible at the east side of the highway: the water depths are 0.01 - 0.25m higher in approach 1. However, a closer look has shown that these differences are in the order of 0.01 to 0.05 m. This effect could be attributed to the different flow pattern close to the breach as the water needed to flow around the buildings in the breach zone and that no water can stand in the buildings, pushing more water volume through the streets, resulting in slightly larger maximum water depths.

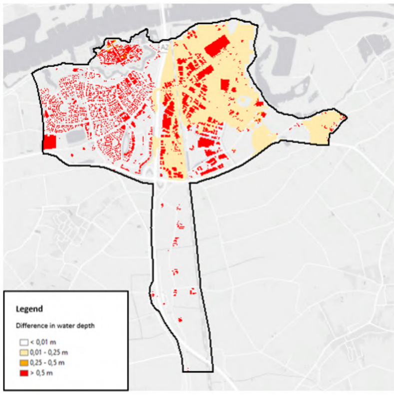
Figure 5.19d presents the water depths for the 25m resolution model. The differences between the 25m and 5m model are very small. The 5m model shows the water depths in the streets between the buildings and contain more continuity (less pixelated). Overall, the differences seem insignificant.



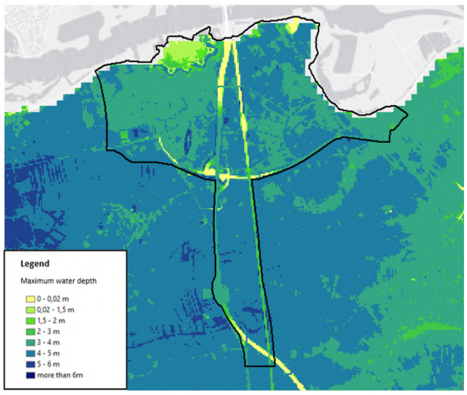
(a) 5m resolution - Approach 1 (higher hydraulic roughness)



(b) 5m resolution - Approach 2 (buildings as solid objects)



(c) Absolute difference between approaches (5m resolution)



(d) 25m resolution

Figure 5.19: Maximum water depth in the refined area

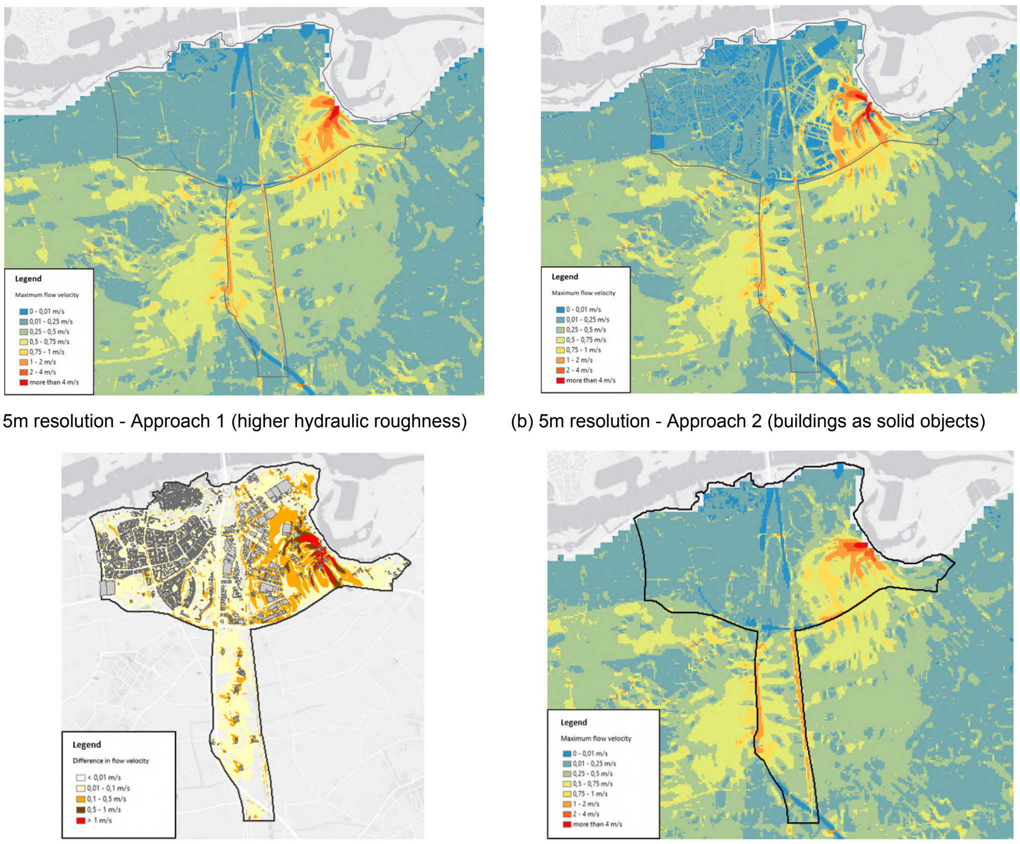
Maximum flow velocity

The flow velocities in Zaltbommel were expected to be higher in approach 2 due to the solid objects forcing the water flow through the narrow streets. However, Figure 5.20 shows that the differences in Zaltbommel are limited to the area close to the breach. The buildings are added in grey for the overview.

There are several buildings located in front of the breach location, influencing the flow pattern and the corresponding flow velocities around the buildings. The differences in flow velocity close to the breach location are over 3 m/s. The effect of this increased velocity is visible until the railway. Figure 5.20d gives the flow velocity for the 25m resolution, the differences between 25m and 5m are also mostly visible in the area upstream of the obstacles. The velocity in the 25m model seems to be between 0.5 and 0.75 m/s for a larger area just upstream of the railway. At this location, the buildings are visible in both 5m models, hence the influence of the roughness is visible here.

Moreover, between the railway and highway, the difference in approach is visible. At the lowest locations, the water flows over the railway and is at some locations blocked by the buildings, sheltering the small areas behind the buildings. These are the orange parts in Figure 5.20c.

As the flow velocity only influences the mortality outcomes if it is higher than 2 m/s (and the depth-velocity product criterion is met), it can only impact the mortality outcomes of (the size of) the breach zone. The influence of the different approaches on the size of the breach zone and the depth-velocity product is further analyzed in Section 5.4 in combination with the 100m and 25m model.



(a) 5m resolution - Approach 1 (higher hydraulic roughness)

(b) 5m resolution - Approach 2 (buildings as solid objects)

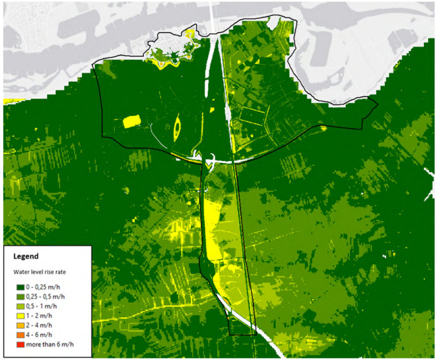
(c) Absolute difference between approaches (5m resolution), the buildings are added in grey.

(d) 25m resolution

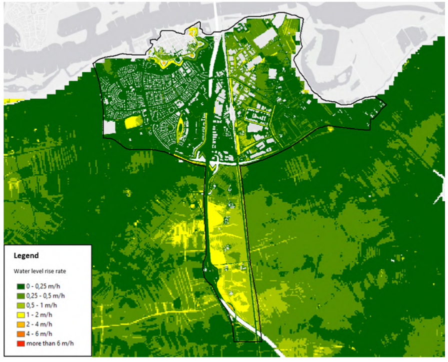
Figure 5.20: Maximum flow velocity in the refined area

Water level rise rate

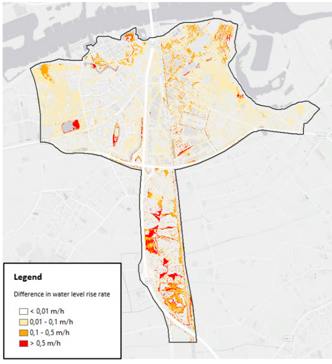
The water level rise rate for approach 1 and 2 and the differences between the approaches are shown in Figure 5.21. The rise rates are generally slightly higher for approach 2 as it has more opportunities to rise fast against the buildings as solid objects. The differences between the approaches are most visible in the area between the highway and railway and east of the railway, this is could be related to the velocity differences from the breach zone.



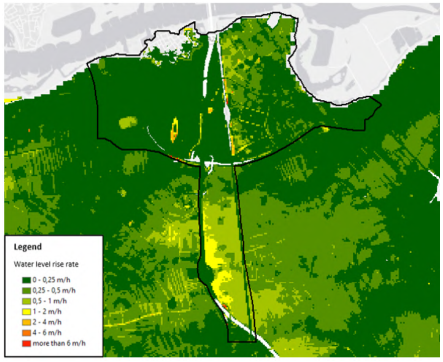
(a) 5m resolution - Approach 1 (higher hydraulic roughness)



(b) 5m resolution - Approach 2 (buildings as solid objects)



(c) Absolute difference between approaches (5m resolution)



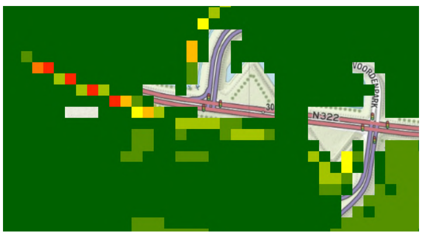
(d) 25m resolution

Figure 5.21: Water level rise rate in the refined area

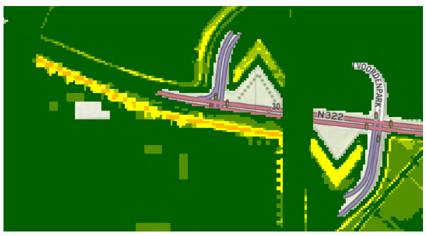
The locations with high rise rates correspond also with the 25m model. However, Figure 5.21d shows that the 25m model has higher values for these spots. Figure 5.22 zooms in on one of these spots where the highway crosses the N322. Figure 5.22 shows that the high rise rates coincide with a small waterway. The high rise rate seems to be more centered into one spot in the 25m model while the 5m smears it over the whole ditch. Also the other spots with rise rates correspond to waterways when zoomed-in. These spots are of less relevance, the same way as explained with Figure 5.15.

(a) Overview of zoomed area within refined area

(b) Zoomed area



(c) 25m resolution



(d) 5m resolution

Figure 5.22: Water level rise rate for a zoomed area with a small waterway

What is also standing out, is the area between the highway and railway. Figure 5.23 shows the water level rise rate in this area for all three model resolutions. The area with high rise rates is much larger for a smaller model resolution. This area between the obstacles illustrate that the model resolution certainly has a significant influence on the water level rise rate.

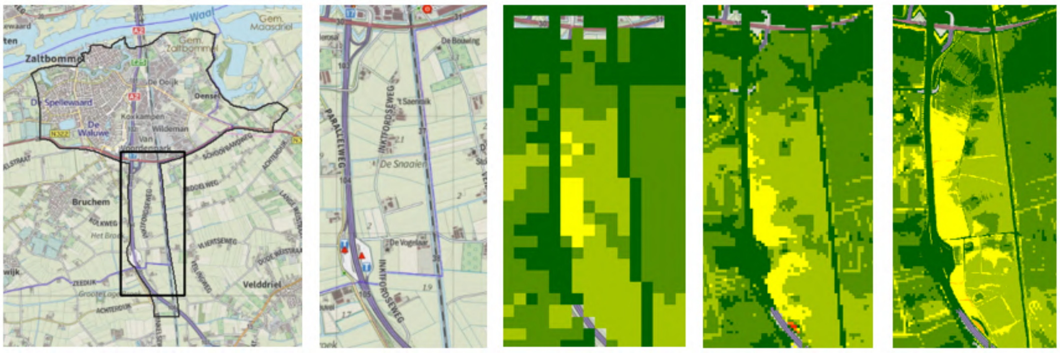
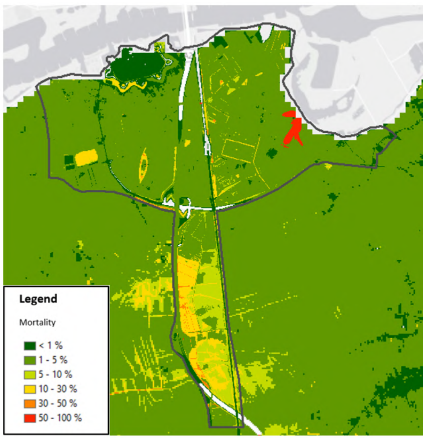


Figure 5.23: From left to right: 1) Overview of zoomed area within refined area, 2) zoomed area, 3) 100m model, 4) 25m model, and 5) 5m model.

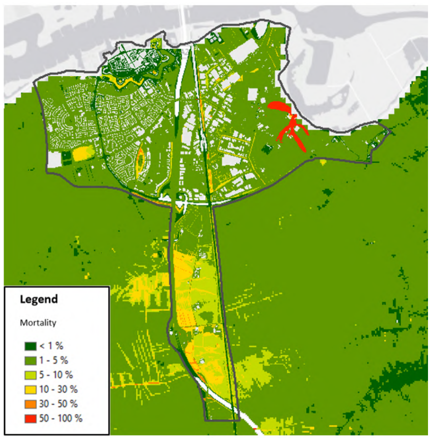
In conclusion, the water level rise rate is similar for both roughness approaches and the different model resolutions, but two significant differences exist between the 100m, 25m, and 5m model. Firstly, the waterways are noticed. The water level rise rate at these waterways is especially high in the 25m model, it is much better visualized in the 5m model. However, waterways are not of relevance as people are not located here and should be filtered out. Secondly, locations between obstacles are a point of concern. The smaller the model resolution, the larger the area with a high rise rate. The impact on the mortality is given in the next section.

5.3.2. Impact roughness on mortality outcomes

The mortality is estimated for both approaches by the mortality model (SSM2017). The mortality outcomes are shown in Figure 5.24. The water depth, and consequently the water level rise rate and mortality, at the locations of the buildings equal zero (or do not exist) for approach 2 since the buildings are solid objects.



(a) Approach 1 (higher hydraulic roughness)



(b) Approach 2 (buildings as solid objects)

Figure 5.24: Maximum mortality map for the refined area

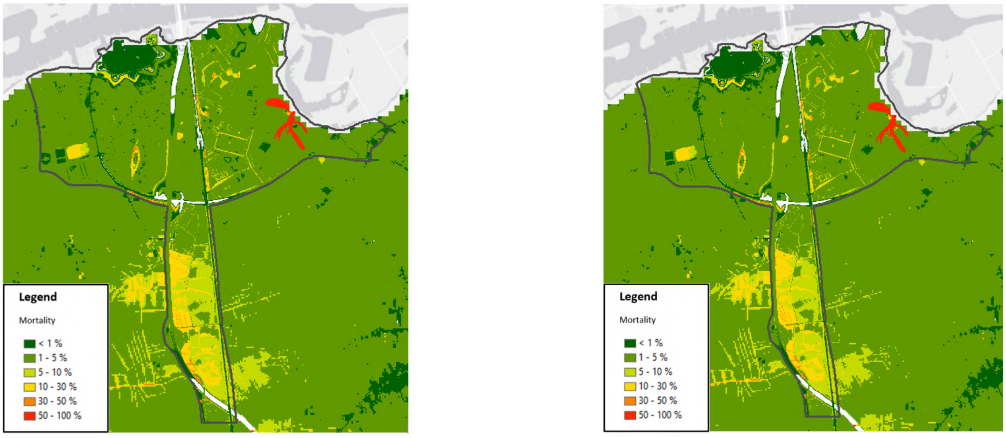
To also compare the mortality outcomes for the two roughness approaches, the mortality needs to be estimated or corrected in the locations of the buildings for approach 2. This can be done in two different ways.

Firstly, the flood characteristics are interpolated at the locations of the buildings. The flow velocity is assumed to be high in the streets, but not in the buildings themselves and is therefore not included in the interpolation, thus the velocities at the locations of the buildings remain zero. Besides, the flow velocity between the buildings is mostly less than 2 m/s and will not be of influence on the mortality outcomes. Hence, only the water depth and water level rise rate are interpolated. Based on these 'new' flood characteristics, the mortality and number of fatalities is estimated again with the mortality model (SSM2017).

Secondly, the mortality is interpolated at the locations of the buildings. With this 'new' mortality grid, the number of fatalities can be estimated by multiplying this mortality grid with the inhabitants grid.

The interpolation of both the flood characteristics and the mortality is carried out with the inverse distance weighting (IDW) interpolation function in ArcGIS. Figure 5.25 shows the mortality outcomes when approach 2 is interpolated at the locations of the buildings. Figure 5.25a shows the mortality when the flood characteristics are interpolated and Figure 5.25b shows the mortality when the previous mortality outcomes are interpolated.

The maximum mortality maps of the interpolations are very similar. The average mortality for approach 2 is for both interpolation methods 4.0%. This is slightly larger than the average mortality of approach 1 (3.7%). Both interpolation methods are thus suitable for comparison with approach 1. The interpolation of the mortality map is used for comparison in the next paragraphs.



(a) Interpolation of flood characteristics, new mortality estimation by mortality model

(b) Interpolation of the mortality map (see Figure 5.24b)

Figure 5.25: Maximum mortality map for approach 2 (buildings as solid objects) using interpolation

Figure 5.26 shows the difference in mortality outcomes for approach 1 and approach 2 (using Figure 5.25b). What stands out, is the difference in mortality at the breach zone. This corresponds to the expectations as the flow velocities differed significantly in size and extent at the breach zone for the different approaches. The fast flowing water from the breach location needs to flow around the buildings in the breach zone resulting in a different breach zone pattern. Besides, the water level rise rate differed for the different approaches between the highway and railway, and this is also visible in the difference in mortality in this area between approach 1 and 2.

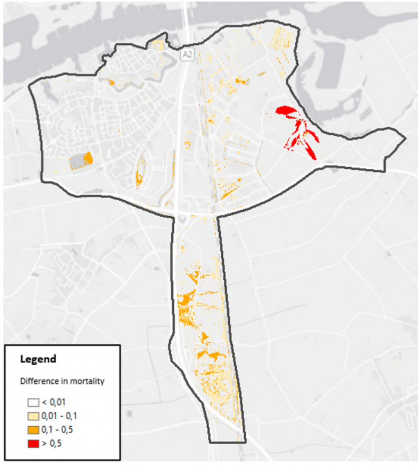
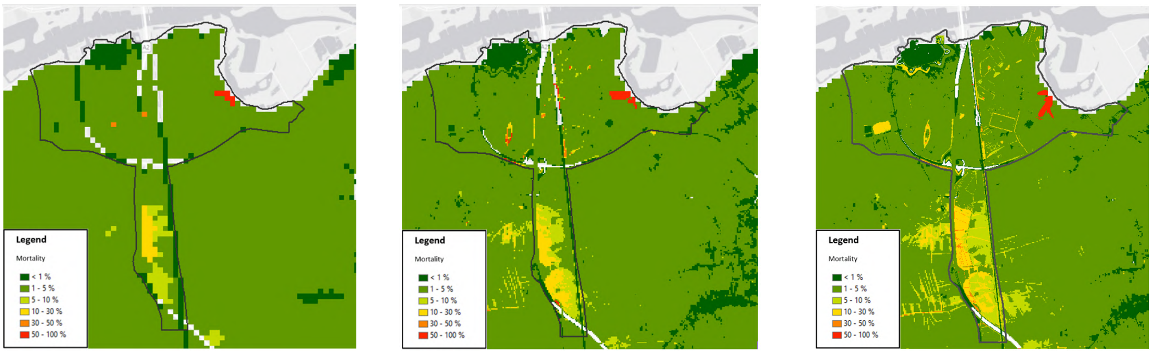


Figure 5.26: Absolute difference of mortality rates between roughness approach 1 and (interpolated mortality of) approach 2

5.3.3. Mortality and fatalities per model resolution in the refined area

Section 5.1 showed and explained the differences between the flood characteristics between the 100m and 25m model resolutions. Figure 5.27 shows the mortality maps for all three models for the refined area. The 25m model contained high rise rates at some spots where water is located and hence these spots come back in Figure 5.27b with high mortality. In the 5m model, more waterways are present since even small ditches are recognized utilizing 5m resolution. These high mortality spots at waterways are of less relevance, because people are not located here. Moreover, there was a difference in water level rise rate in the area between the obstacles. In the 5m model, the water level rise rate is high for a larger extent than in the other models. Consequently, the mortality in the 5m model is higher for a larger extent in this area, especially in the range 5-10% and 10-30%. If many inhabitants are located between the highway and railway, it will result in a larger number of estimated fatalities.

The next paragraph looks into the fatalities, Table 5.2 shows the overview.



(a) 100m resolution (b) 25m resolution (c) 5m resolution

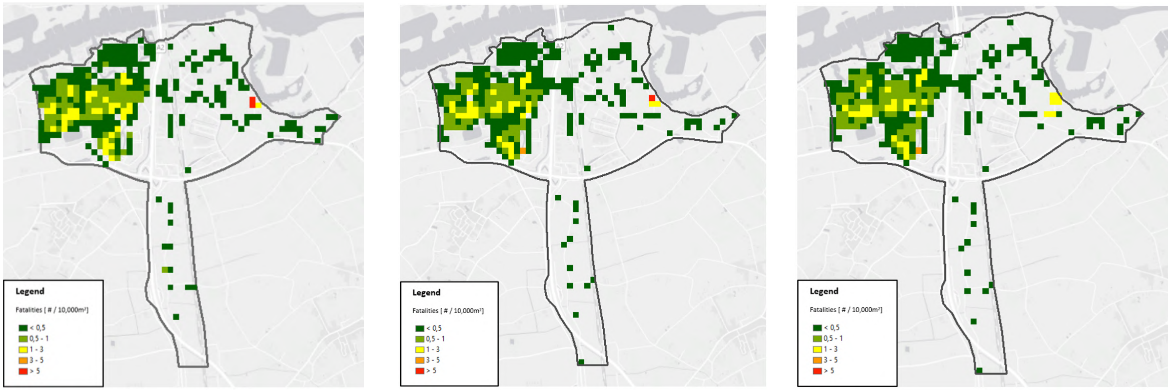
Figure 5.27: Maximum mortality map for the refined area

Table 5.2: Overview of the results of the mortality model in the refined area (without evacuation)

	Fatalities	People affected	Mortality
100m	151	12,475	1.21%
25m	137	12,408	1.10%
5m (Approach 1)	140	12,477	1.12%

For the refined area, the 100m model has 151 fatalities, the 25m model has 137 fatalities, and the 5m model has 140 fatalities. The 100m model has the most fatalities, around 10 more than the very similar 25m and 5m model. This is a difference of less than 10% for the total number of fatalities in the refined area. The benefits of estimating the number of fatalities with a finer model resolution are thus limited for this area.

The spatial distribution of the fatalities in the refined area are shown in Figure 5.28. The 25m and 5m model are aggregated to a 100m resolution for visualization purposes. Figure 5.28 shows that only a few fatalities occur between the highway and railway, so apparently not many inhabitants are located here. This is especially a dangerous area and must be kept in mind for the future.



(a) 100m resolution (b) 25m resolution (c) 5m resolution (approach 1)

Figure 5.28: Fatalities in the refined area (25m and 5m model aggregated to 100m resolution by summation to ease visual comparison)

5.4. Relevant aspects

This section goes more in depth into some relevant aspects. The breach zone, outflow boundaries, water arrival time, and computation times are considered.

Breach zone

Table 5.3 shows the details of the flood characteristics and fatalities in the breach zone area for the different model resolutions and Figure 5.29 shows the visual overview. Both roughness approaches of the 5m model are included as these had different outcomes for the breach zone. Approach 1 corresponds with a higher hydraulic roughness for the buildings (comparable with the approach for the 100m and 25m model) and approach 2 implemented the buildings as solid objects.

The table shows that the velocity criterion is the most stringent criterion of the two, partly because the water depths are relatively high for all the models for this area. The size of the area is approximately the same for the velocity criterion and the breach zone. The velocity is strongly dependent on variations of local elevations, the presence and orientation of objects, and also the roughness. The finer the model resolution, hence the more detailed the input for the DEM and roughness. The size of the breach zone area increases for finer model resolutions. The 25m and 5m model with the same roughness approach are comparable, but there is a larger difference with the 100m model. The 100m model is much coarser than the 25 and 5m model and it could be that the flow velocity is faster averaged over the grid cell to a lower magnitude than in the finer models.

There is also a large difference between approach 1 and 2. When the presence and orientation of the objects are taken into account (approach 2 of the 5m model), the breach zone becomes significantly larger. This is due to the fact that the water flow is blocked by the solid objects and needs to flow around the buildings with greater velocities as result. The velocities stay large for a greater extent and consequently, the velocity criterion is met for a larger area than approach 1.

Table 5.3: Overview of flood characteristics for the breach zone

	h*v ≥ 7 $\mathbf{m^2/s}$		v ≥ 2 $\mathbf{m/s}$		Breach zone (h*v ≥ 7 $\mathbf{m^2/s}$ and v ≥ 2 $\mathbf{m/s}$)	
	number of cells	area	number of cells	area	number of cells	area
100m	8	80,000 m^2	6	60,000 m^2	6	60,000 m^2
25m	155	96,875 m^2	120	75,000 m^2	120	75,000 m^2
5m - approach 1	3788	94,700 m^2	3178	79,450 m^2	3155	78,875 m^2
5m - approach 2	5477	136,925 m^2	4311	107,775 m^2	4298	107,450 m^2

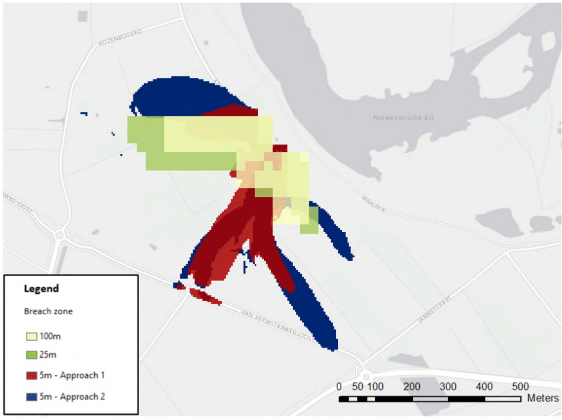


Figure 5.29: Overview of the breach zone per model resolution. Since the layers overlap, some transparency is added to improve the visibility of the breach zone sizes.

Outflow boundaries

Figure 5.30 shows the overview of the fatalities close to the outflow boundaries. The outflow boundaries do not result in many fatalities. Most fatalities are located on the lower right of Figure 5.30, the municipality of Aalst is located here. These fatalities are not related to the outflow boundaries, but only to the high water level rise rate and the large water depth.

(a) 100m resolution

(b) 25m resolution (aggregated by summation till 100m resolution)

Figure 5.30: Overview of fatalities close to outflow boundary. The outflow boundary is shown in blue.

The velocity was higher than 2 m/s at a few spots next to the outflow boundaries in the 25m model resulting in a breach zone condition. However, no inhabitants were located at these spots. The name 'breach zone' is not suitable here, but the conditions correspond to the criteria. The maximum flow velocity occurred after approximately 80 hours. This moment in time makes sense, because the maximum breach discharge is reached after 24 hours after the start of the breach (assumption), and needs 24 hours before it arrives at the outflow boundary, and then needs another day to reach a water level of approximately 6m+NAP before the outflow starts. The maximum flow velocity is expected to be realistic, because the flood water overflows the dike and cascades down to the lower river level of the tributary of the Meuse ('Afgedamde Maas' in Dutch), acting like a weir with free flow. The outflow discharge is similar for the 100m model, but the velocities in the 100m model are averaged to lower values, hence these velocities higher than 2 m/s do not occur in this model.

Water arrival time

The water arrival time is not included in the mortality calculations. This paragraph shows the fatalities linked to the water arrival times. An overview is given in Table 5.4. In this study, nearly all fatalities occur within 2 days.

The 5m resolution is only applied to the area around Zaltbommel, this area is flooded within approximately 24 hours. The number of fatalities within 24 hours is practically the same for the 25m and 5m model. The rest of the Bommelerwaard is modelled with 20m resolution, corresponding to a water arrival time larger than 24 hours. The difference between these models in the category 24-48 hours could be explained by the grid: the 20m grid is based on the 80m grid (see Chapter 4) and the 25m and 100m model on the 100m grid which could result in small differences around the edges.

There are some differences between the 100m and 25m/5m models. The difference in fatalities between categories <12 hours and 12-24 hours can be explained by the underpass in the highway and railway before the city center of Zaltbommel. The water reaches most of Zaltbommel within 12 hours in the 100m model, because the water flows through the viaduct with a width of 100m. In the 25m model, this underpass can be modelled with a width of 25m, resulting in a water arrival time of 12-24 hours for a large part of Zaltbommel. The difference in the total number of fatalities between 100m and 25m/5m occurs mostly within the first 24 hours as the 100m model estimates around 40 fatalities more.

Table 5.4: Overview of fatalities corresponding to the water arrival times

	Water arrival time					
	$\leq 12h$	$12 < w \leq 24h$	$24 < w \leq 48h$	$48 < w \leq 72h$	$> 72h$	Total
100m	103	270	186	34	5	598
25m	42	290	164	27	8	531
5m (and 20m)	40	292	182	33	7	554

Computation time

The flood simulations are carried out with a simulation time of 288 hours (12 days). Table 5.5 shows the overview of the computation times of the models. For every refinement, the computation time increases significantly. It must be emphasized that the software is still in development, but at the time of performing this study, the computation times of the 5m models are rather long. The difference in computation time between the two roughness approaches for the 5m resolution, can be ascribed to the higher flow velocities in the second approach since high velocities on small sized flow links reduce the time step.

Since the computation time differs significantly per model, it could play a role in the selection of the model resolution, including a trade-off between accuracy and computation time. For example, when used for emergency response, it is not (yet) feasible to apply finer model resolutions as this requires quick outcomes.

In this study, it was chosen to keep the time settings for the different models similar as much as possible for comparison reasons. It is possible to reduce the computation time, for example by reducing the number of grid cells, the simulation time, or number of time steps. Also other more advanced solutions are thinkable, such as parallel modelling; for these techniques is referred to the report of Morelissen and Vossen (2009).

Table 5.5: Overview of computation time per model

	Computation time	
	in hours	*in days*
100m	1	0.0
25m	23	1.0
5m - Approach 1 (and 20m)	113	4.7
5m - Approach 2 (and 20m)	170	7.1

5.5. Conclusions, discussion and recommendations

This section presents the conclusions, discussion, and recommendations regarding this part of the case study. Firstly, the flow pattern is summarized, secondly D-Flow FM is evaluated regarding the flood simulation set-up, thirdly the modelling approach with the different model resolutions, and fourthly the mortality and fatality assessment. The latter will reflect on the usefulness of the detailed flood simulations regarding mortality calculations. Finally, the generalization of the results to other river areas is discussed.

5.5.1. The flow pattern

The Bommelerwaard is a low-lying area (polder) with deep water as a result. Due to the breach, first Zaltbommel and the east part of the Bommelerwaard are flooded within approximately 12 hours. The floodwater reaches the Meidijk after approximately 24 hours and overflowed after approximately 52 hours with flooding at the west part of the Bommelerwaard as a consequence.

The flood simulations have shown that the water depths are as large as 4 to 6 meters, which is extremely dangerous as higher elevated areas could also become unsafe. The water depths at the west are somewhat larger due to sloping of the bed level from east to west. The Meidijk plays a large role in the Bommelerwaard. This dike retains the water to until a maximum elevation of around 6m+NAP with high rise rates and large water depths as a consequence. The mortality just upstream of the Meidijk is very high accordingly.

Also other obstacles cause high rise rates, hence forming risky places. The highway and railway retain water temporarily. The area between these obstacles have increased mortality due to the high rise rates.

The most dangerous place is the breach zone. Fortunately, this is only a small area, around 60,000 – 80,000 m^2 in the different models. The breach zone has such severe conditions that the mortality in the Dutch models is assumed to be 100%.

All models give a good indication of these dangerous locations. If there are inhabitants located at these dangerous locations, the number of fatalities can be large. The high mortality spots do not always correspond with high fatalities, because no inhabitants are allocated in these cells.

5.5.2. D-Flow Flexible Mesh

The software that is used in this study is called D-Flow Flexible Mesh, this software is still under development. Firstly, the software itself is discussed and secondly, the modelling approach using this software.

Software

The quality of the software D-Flow FM compared to other software programs for inundations modelling was analyzed by Henckens and Engel (2017) and they showed that D-Flow FM resulted in similar, accurate results as for 3Di and InfoWorks ICM. The main difference with other software programs for inundation modelling is that D-Flow FM does not utilize the sub-grid approach (such as 3Di and HEC-RAS), but utilizes optimal modelling flexibility by refining areas of interest with much more freedom than in other programs (SOBEK, 3Di, HEC-RAS, InfoWorks ICM, etc.). Examples of areas of interest are the breach zone, areas around obstacles, and areas with local topographic variations. This means that one grid can be created with different cell shapes and sizes, and 1D and 2D grids can be combined. In this study, the usage of different model resolutions has been analyzed since large differences can exist between 100m and 5m grid cells due to local variations within a cell. For homogeneous areas this is expected to be of less relevance. More details of the software are given in Section 4.2.

Modelling approach

The Bommelerwaard has an area of around 11,000 ha and refining the whole area would result in too large computation times. Hence, to compare the results of the usage of different model resolutions, the 5m resolution is only applied for the area close to the breach next to the municipality of Zaltbommel.

Some recommendations are described below on the modelling approach with the software D-Flow FM.

- Breach modelling
  The exact breach characteristics are not of interest for this study and were included in this study by a horizontal boundary condition with a Q-t relation. The schematizing of the breach can be improved by including a breach model and the river model as this incorporates the interplay between the water level of the river and flooded area.

- Boundaries
  The outline of the area presents the outer dike ring and the model does not allow propagation of the water out of this dike ring. Consequently, the water levels became unreasonably large at first. Outflow boundaries needed to be added to allow for overflow to another dike ring. The outflow boundaries were added at the lowest dike sections of the dike ring where overflow is to be expected. They were applied to the grid cells next to the edge. The overflow could result in high velocities and the combination of a high velocity and large water depth could classify the mortality in the breach zone. This happened for two cells in the 25m model, but these cells did not correspond with inhabitants.

- Obstacles
  Obstacles were included following the guidelines of De Bruijn and Slager (2018) by correcting elevations at obstacle locations (from median) to the maximum values. Firstly, this case study has shown that this affects the overflowing discharge. The maximum for a 100m cell is stretched over 100x100m while in the 25m it is only stretched over 25x25m. This could result in a faster overflow at obstacles for the 25m model compared to the 100m model. The case study showed that this influenced the arrival time slightly. A possibility to prevent this from happening is to include obstacles by fixed weirs. Secondly, in this study, the obstacles were assumed to retain water till its maximum elevation (‘standzeker’ in Dutch). However, the overflowing water could result in (local) failure of the obstacle with a possible second breach zone as a consequence. This is not taken into account. The impact of this assumption

differs per situation. In this study, the Meidijk caused large water depths in the east part of the Bommelerwaard where most people are exposed, hence a conservative result. At the west of the Meidijk, only around 35 fatalities occurred.

- Underpasses
  Obstacles, such as the highway, could have underpasses in it. An underpass is a gap in the obstacle that gives water an opening to flow through. The underpasses can be modelled using the grid cells, as it is done in this study, within the 100m model thus an underpass of also 100m. This allows more discharge through the underpass than in the 25m model with an underpass width of 25m. The underpass in the Bommelerwaard resulted in slightly different arrival times. This has to be kept in mind, especially if an obstacle has multiple small underpasses. In that case, the underpasses could be modelled differently, for example by adding 1D elements (independent of model resolution).

- Grid generation
  Refinement of the grid is done in the interacter using a multiplication factor. Therefore, the 5m model is based on an 80m resolution model. Therefore, the edges could differ slightly from the 100m and 25m model, resulting in a small difference in the number of people exposed.

- Time settings
  The time steps are set as uniform as possible in the different models. At the first runs, the outflow boundaries gave very unstable behaviour around the outflow boundaries for the 100m model and also slightly for the 25m model. The DtUser time step needed to be reduced to ensure stable behaviour around the outflow boundaries. This time step specifies the interval for external forcing update and also for the 'his' and 'map' output files (see Section 4.3.1). For the 5m resolution model, this was not necessary, because the average time step was lower. In the last runs, the DtUser was reduced to 5 seconds in the 100m and 25m model.

5.5.3. Modelling approach

As flood simulation software is becoming more and more advanced, this study investigated the outcomes for different model resolutions. The flood characteristics were modelled with a 100m, 25m and partly with a 5m resolution. For the 5m resolution model, two different roughness approaches were tested.

Model resolution

The larger the model resolution, the more pixelated the outcomes. The 25m and 5m model contained clearly more details than the 100m model, but overall, the different models represent the same information but with different precise values.

The maximum water depths and flow velocities correspond very well for the three different models. The 100m model is the coarsest and resulted in slightly larger water depths in Zaltbommel and some other places. Overall, the velocities are similar, but are actually only of relevance in the breach zone. In addition, the model resolution has an influence on the discharge through the underpasses. Since Zaltbommel has two underpasses in the obstacles just upstream of the city, the water arrival time were slightly different in Zaltbommel. It is thus recommended to use finer model resolutions around obstacles and underpasses or to apply 1D objects or fixed weirs. This is especially of relevance when an obstacle has many small underpasses.

The largest differences came into sight in the water level rise rate. These differences are related to two aspects. Firstly, the water level rise rate differed significantly at locations of waterways. The 5m model is very detailed, hence the high rise rate spots coincide well with the waterways. In the 25m model, the waterways are less continuous than in the 5m model and this could be the reason that the rise rates were significantly larger at these spots. In the 100m model, these small waterways were not visible. However, these spots are not relevant as people are not located at these spots, it is recommended to filter these locations out to avoid misinterpretations. Secondly, the water level rise rate differed in the area between the obstacles. Obstacles retain water and therefore, they make high water level rise rates possible. The effect of the obstacle on the rise rate reached more upstream when the model resolution was smaller. This illustrates that finer model resolutions are relevant around obstacles and can have a significant impact on the water level rise rate, depending on the area.

Roughness approach 5m resolution
In case of fine model resolutions, the roughness can be implemented in two different ways: by increasing the roughness of the buildings and lower the roughness of the streets, or by implementing buildings as solid objects using increased elevations. Both approaches give approximately the same results for the water arrival time and maximum water depth.

The velocity was expected to be much higher in the solid objects approach as the velocity is forced to flow through the narrow streets. However, this was not the case for the whole of Zaltbommel. Apparently, the buildings are not close enough together to cause velocities high enough to reach the 2 m/s criterion and influence the mortality map. This shows, that for this study, the roughness approach has limited influence on the flood characteristics and mortality for a large part of Zaltbommel.

The velocities did differ around the breach. For the breach zone, the velocities are so high, and if the water is blocked by buildings, the velocity becomes even higher and remains high for a longer extent. The modelling of the roughness by solid objects increased the breach zone area with around 36% in this study. As the breach zone is strongly dependent on variations in local bed levels and the presence and orientation of objects, this effect differs per area. It is recommended to investigate the influence of this modelling approach further, especially for floods with high velocities or areas with many obstacles. The breach zone area is still limited, but it is an important area, especially if people live there.

5.5.4. Mortality and fatality assessment

For mortality calculations, it is particularly important that the outcomes give a representative view of the hazardous locations. Overall, all three models satisfy this and present a good overview of dangerous locations for the Bommelerwaard.

The number of fatalities between 100m and 25m were similar. In addition, the number of fatalities for the 25m and 5m model resolution in the refined area were very similar. The total number of estimated fatalities for the 100m model equals 598 and in the 25m model it is 531, thus a decrease of 11% for using a finer model resolution. Therefore, the benefits of estimating flood fatalities with finer model resolutions seem to be limited for this area.

One must point out that the mortality functions are based on a coarse level of detail. The data from 1953 are based on village-level and amongst others on eye-witnesses. This must be kept in mind when applying the mortality functions on a fine resolution as this could give errors in mortality estimations. For that reason, the official guidelines calculate the individual risk (LIR) with a resolution of 100m and take the median mortality value per neighbourhood.

The combination of similar outcomes of dangerous locations, the limited impact of the finer resolutions on the estimated number of fatalities, the large increase in computation times when using finer resolutions, and the fact that the mortality functions are based on village-level, the 100m model resolution is still recommended for the development of mortality maps. Only areas around obstacles and underpasses are recommended to be modelled with finer resolutions or by using 1D objects of fixed weirs.

However, the criteria of the breach zone are based on a physical basis regarding building collapse and human instability. Therefore, the village-level does not apply for the breach zone. In this study and area, the finer model resolutions increased the size of the breach zone. In combination with the roughness approach, it is recommended to investigate the modelling of the breach zone further.

5.5.5. Generalization of results to other river areas

The conclusions of the Bommelerwaard area can be compared to other river areas to discuss the possible transferability of knowledge gained in this case study. The generalization of the results depends on the characteristics of the case study area.

The main difference between the Bommelerwaard and other river areas, is that the Bommelerwaard behaves as a bathtub and fills up with water independent of the exact breach location in dike trajectory 38-1, resulting in large water depths (4-6m). Most river dike ring areas are sloped areas resulting in a water flow from high to low elevation. As a result, the water depths upstream are not so large, but the water depths and water level rise rates can become very large in the downstream deeper part of the area. The Alblasserwaard, Betuwe, and Land van Maas en Waal are examples of sloped areas with water depths larger than 5 meters in the downstream parts.

The Meidijk played a large role in the flood pattern in the Bommelerwaard and caused high rise rates upstream of this dike. Some of the other dike rings also have such an obstacle in the dike ring area influencing the pattern, for example the Diefdijk in the Betuwe. Besides, infrastructure such as the highway and railway caused high rise rates in the Bommelerwaard, and these infrastructures are also crossing other dike rings. Therefore, the recommendation to model obstacles with finer model resolutions or with fixed weirs or 1D objects is also recommended for other river areas.

Regarding the water arrival time, arrival times in other river areas are, overall, larger than the arrival times in the Bommelerwaard, especially in elongated river areas such as the Betuwe. The water arrival times slightly differ for the different model resolutions in the Bommelerwaard around obstacles with underpasses and this effect is also expected in the other dike ring areas.

6

Results of case study: possibilities for alternative mortality functions

This chapter forms part two of the case study of the Bommelerwaard and explores the possibilities for alternative mortality functions. Section 6.1 introduces the approach and focus, Section 6.2 presents the motivation and results obtained by applying these alternative functions in the case study and discusses them, and Section 6.3 provides the conclusions and derives recommendations for improvement of the standard functions. Appendix C shows the mortality maps per sensitivity analysis.

6.1. Introduction

In Chapter 3, the mortality functions are introduced. Important factors are derived based on literature, knowledge of past events, and mortality worldwide. The points of discussions are further analyzed, resulting in preliminary alternative functions. This section introduces the approach and focus of the sensitivity analysis.

Advantages current approach

Before introducing the preliminary alternative functions, the advantages of the current approach that may be desirable to preserve are summarized:

- Based on historical data
  The functions are mainly based on data of the flood event in the Netherlands in 1953 and contain also some data from Japan and the UK. It is desirable to stay in (or close to) the confidence interval of these data. However, one needs to keep in mind that many factors changed since 1953 (see Chapter 3). Besides, it has a physical basis as well as it is partly based on physical processes, such as the depth-velocity product regarding human instability and building collapse in the breach zone (Jonkman, 2007).
- Indication of dangerous locations
  The aim of the mortality functions is to make a good estimation of the dangerous locations and number of fatalities, and it is not recommended to use it to assess the exact number of fatalities (Jonkman, 2007). As the functions are based on the flood characteristics only, high mortality spots correspond to severe flood conditions and hence give an indication of dangerous locations.
- Simple application
  The current Dutch approach is easy and fast in use, and it aims to be not too complex regarding the input parameters. Since the input parameters are based on the flood characteristics only, the results are understandable and interpretable. The functions are applicable on large scale, such as dike rings.

Adaptations to the current Dutch approach are introduced and analyzed to seek for possibilities for improvement, since many implicit factors in the approach have changed since 1953. The aim of the sensitivity analysis is to analyze the impact of the different parameters in mortality and fatality assessment. This gives an indication about how well or poor the preliminary alternative functions perform and which parameters or functions have the potential to be further analyzed to improve flood fatality risk in the future.

Approach

The current guidelines for the determination of the individual risk (LIR) make use of flood simulations with 100m resolution. For that reason, the results of the flood characteristics of the 100m model are used as base case for the sensitivity analysis. The mortality functions are coded in Python to enable changes in the functions since this is not possible in SSM2017.

The number of fatalities and the mortality rate are considered per sensitivity analysis, these give a first indication about the performance of the preliminary mortality functions. The mortality rate will be the measure in the sensitivity analysis: when the mortality deviates more than 0.25 percentage point (p.p.), thus the absolute difference, it will be further analyzed regarding the individual risk in Chapter 7.

Zone of interest

The rapidly rising water zone and remaining zone are mostly based on data from 1953 and also on some data from Japan and the United Kingdom. The data points are shown in a large table in the appendices of Jonkman (2007). The remaining zone has very low mortality (in the range 0-2%), based on 93 data points, while the rapidly rising water zone has very high mortality (approaching 100%), based on 15 data points. For that reason, the main focus of possibilities for alternative mortality functions is on the rapidly rising water zone. As the transition zone interpolates between the rapidly rising water zone and the remaining zone, this zone is also influenced. The breach zone is only applied to a limited extent close to the breach (around 100m). Because of the small size of the breach zone, the number of estimated fatalities is relatively small. Moreover, the breach zone is very dangerous, so there is less discussion on the outcomes. Therefore, the focus of the alternative mortality functions is not on the breach zone.

Table 6.1 gives insight into the fatalities per zone and also per water arrival time for the base case of the 100m model. Figure 6.1 shows the size and location of the zones. The breach zone has 100% mortality, thus all 18 inhabitants located in this zone are denoted as fatalities. The first 24 hours, the rise rate is very low. The water can flow without any significant delay and fatalities occur mainly in the remaining zone. After 26 hours, the Meidijk is reached where rise rates are high. In the 100m model, only 3 fatalities occur in the rapidly rising water zone, but also 86 fatalities occur in the transition zone. After 48 hours, all fatalities occur in the remaining zone.

Table 6.1: Overview of the fatalities related to water arrival time and zone for the case study of the Bommelerwaard with 100m resolution

Water arrival time	Breach zone	Rapidly rising water zone	Transition zone	Remaining zone	Total
0 - 12h	18	0	0	85	103
12 - 24h	0	0	8	262	270
24 - 48h	0	3	86	97	186
>48h	0	0	0	39	39
Total	**18**	**3**	**94**	**483**	**598**

It must be emphasized that the categorizing of the zones follow from the flood characteristics and are thus dependent on the local conditions and landscape. Intuitively, the zones are divided following the categories: breach zone - rapidly rising water zone - transition zone - remaining zone, but Figure 6.1 shows that the rapidly rising water zone conditions are located relatively far away from the breach. In the Bommelerwaard, the Meidijk causes high rise rates just upstream as this dike blocks the water, and therefore the rapidly rising water zone is located before this obstacle. In addition, a large area before the dike corresponds to transition zone conditions. The conditions for the transition zone are also visible between the highway and railway obstacles. Apparently, the rise rate is not high enough to cause a rapidly rising water zone here. For more details about the flood characteristics in the Bommelerwaard is referred to Chapter 5.

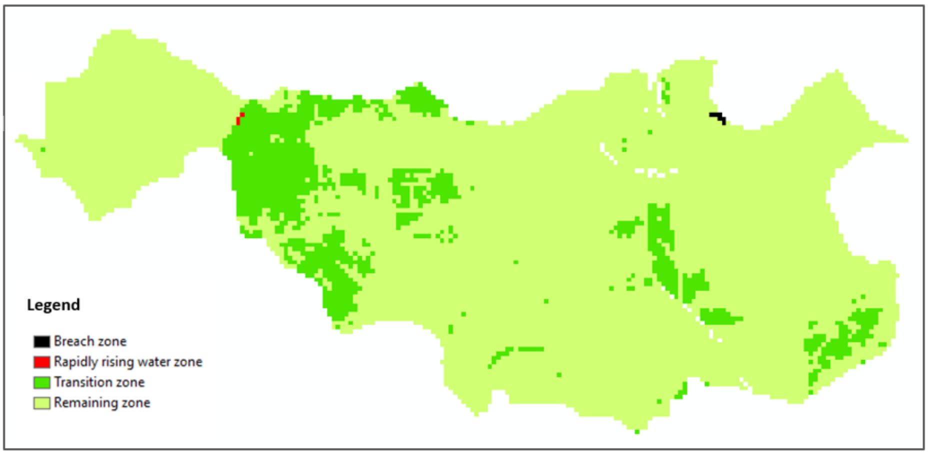


Figure 6.1: Overview of the size of the different zones in the base case of the Bommelerwaard with 100m resolution

6.2. Sensitivity preliminary alternative functions

In Section 3.5, preliminary alternative functions are proposed which will be tested on sensitivity in this section for the case study of the Bommelerwaard. Section 6.2.1 explains briefly the motivation of the preliminary alternative functions to be tested, Section 6.2.2 briefly elaborates on the confidence interval, and Section 6.2.3 presents the results.

The mortality functions are presented and explained in Chapter 3. For convenience, the functions are also given in Figure 6.2 including the values of the parameters for the lognormal distributions for the rapidly rising water zone and remaining zone. The transition zone is the interpolation between these two zones and depends on the water level rise rate. The breach zone is also shown, which is 100%.

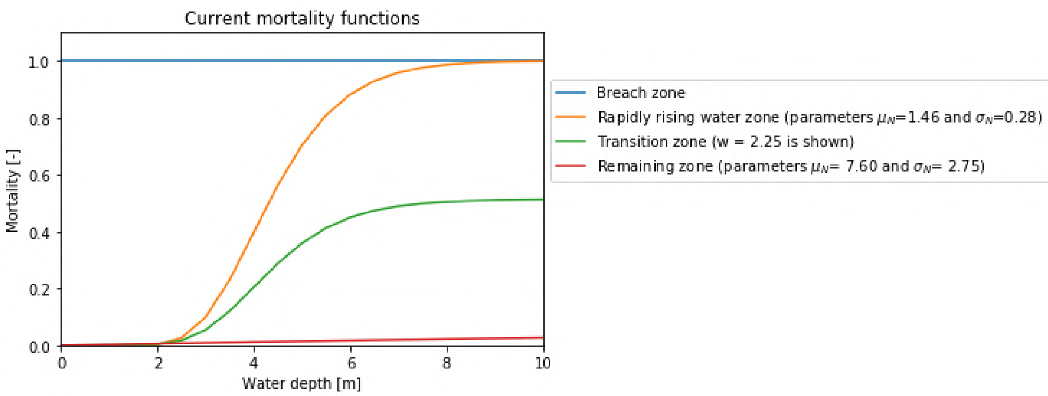


Figure 6.2: Overview of the mortality functions. The distribution parameters for the rapidly rising water zone and remaining zone are shown in the legend.

Overview of sensitivity analyses:

1. Water level rise rate and water arrival time
   (a) Water level rise rate left out. Mortality is based on water depth only (Lognormal distribution with parameters μ_N = 1.89 and σ_N = 0.46, based on the fitted line through the whole available data set (Jonkman, 2007))
   (b) Water level rise rate is taken into account only for specified water arrival times (6, 12, or 24 hours). If it is longer than the specified water arrival time, the relation water depth-mortality is used again (see 1a).
   (c) After a specified water arrival time (e.g. 6, 12, or 24 hours), the mortality functions of the remaining zone are applied, independent of the criteria of the zones. Before this arrival time, the current mortality functions are applied.
2. Water arrival time
   (a) Inclusion of water arrival time in preparedness at home by using upper and lower boundary of mortality function as proposed in Pleijter and Kolen (2016)
   (b) Inclusion of the water arrival time in a flee fraction as proposed in De Bruijn and Slager (2014). After a specified arrival time, the mortality is reduced with this flee fraction.
   (c) Inclusion of the water arrival time in an adapted flee fraction from 2b for the Bommelerwaard
3. Building characteristics
   (a) Improved building characteristics applied to the rapidly rising water zone: 50-50 distribution cavity walls and concrete (parameters μ_N = 1.68 and σ_N = 0.37, as given in Jonkman (2007))
   (b) Inclusion of improved building characteristics for the rapidly rising water zone by a reduction factor per construction year
4. Age
   (a) Increased overall mortality due to more people aged over 65 in society since 1953
   (b) Increased mortality per neighbourhood due to more people aged over 65 in society since 1953
   (c) Increased mortality per neighbourhood per fraction of people 65+ (+0.1% per fraction 65+, counted from 10%)
   (d) Increased mortality (factor 2) when no dry floor is available during maximum water depth and the people are aged over 65 (per neighbourhood)
5. Fixed mortality
   (a) 1% applied to the whole area (mortality in 1953)
   (b) 1.16% applied to the whole area (mortality in 25m model)
   (c) 1.19% applied to the whole area (mortality in 5m (and 20m) model)

6.2.1. Motivation

The preliminary alternative functions are briefly motivated, for a more detailed explanation, see Chapter 3.

1. Water level rise rate and water arrival time

Jonkman (2007) showed that the best fit to the available data is when the water level rise rate is included. This gives a better fit (R^2 = 0.76 for rapidly rising water zone) than when the water depth is the only parameter (R^2 = 0.28). The fit for the remaining zone is very low (R^2 =

0.09). Even though the fit is better when including the water level rise rate, it is important to look at the essence of the water level rise rate. The water level rise rate is dangerous because of the rapidly rising water and hence the surprise effect for people who could suddenly end up in a dangerous situation. However, if the water arrival time is long, and the people are informed about the coming water, the surprise effect is gone and people can be prepared. This was one of the offered explanations in literature why the water level rise rate did not play a role in New Orleans in 2005 since the people were warned (Jonkman, 2007).

Therefore, sensitivity analyses are carried out to implement the water arrival time in the mortality functions regarding the water level rise rate. Firstly, the water level rise rate is left out (even when the goodness-of-fit is lower). Secondly, the rise rate is left out after a specified water arrival time. And thirdly, the remaining zone is applied after a specified water arrival time. This is done because the remaining zone has lower mortality due to the more slow-onset character of this zone. Here, fatalities mostly occur due to the lack of shelter or a failed attempt to find shelter in time.

The mortality function based on water depth is shown in Figure 6.3.

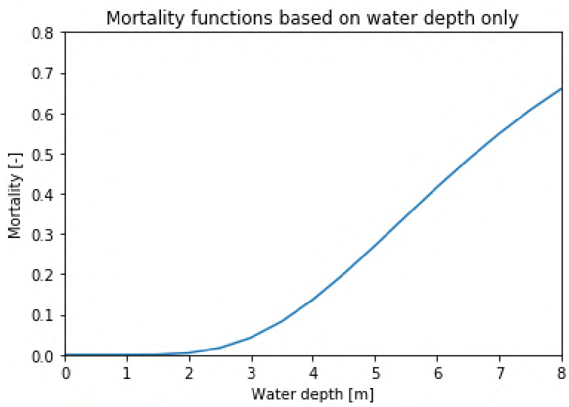


Figure 6.3: Overview of the mortality function based on water depth only (parameters μ_N = 1.89 and σ_N = 0.46, based on the fitted line through the whole available data set (Jonkman, 2007))

2. Water arrival time

Water arrival time can also be implemented apart from the water level rise rate parameter. The water arrival time influences the probability that the people are being exposed to the flood and could also influence the preparedness of the people. Both aspects are considered below.

Firstly, the preparedness of the people can be influenced by longer arrival times. The 'PBL' method ('Planbureau voor de Leefomgeving' in Dutch) takes into account the locations of the people being exposed during the flood and makes a division in people at home being prepared or not prepared (Pleijter and Kolen, 2016). When people are prepared, the PBL method applies the lower boundary of the confidence interval of the mortality function, and in case of non-preparedness, it applies the upper boundary. The upper and lower boundary are applied for the rapidly rising water zone and remaining zone. The transition zone interpolates between these 'corrected' zones and the breach zone remains 100%. This way, the water arrival time can be connected to people being prepared. This study explores the sensitivity if the people are assumed to be prepared after 6 or 12 hours and unprepared before 6 or 12 hours.

Table 6.2 shows the distribution parameters used. Note that the threshold for the water depth differs between the three criteria. This threshold refers to the water depth for which the mortality for the rapidly rising water zone and remaining zone are equal.

Table 6.2: Overview parameters. Parameters are provided in Pleijter and Kolen (2016), based on Jonkman (2007). The visual overview of the upper and lower boundaries are shown in Figure 6.10.

	Rapidly rising water zone	**Remaining zone**	**Threshold**
Average (used as current parameters)	μ_N = 1.46 and σ_N = 0.28	μ_N = 7.60 and σ_N = 2.75	2.1 m
Upper boundary (used as unprepared)	μ_N = 1.34 and σ_N = 0.23	μ_N = 6.45 and σ_N = 2.55	2.3 m
Lower boundary (used as prepared)	μ_N = 1.69 and σ_N = 0.36	μ_N = 8.76 and σ_N = 2.94	2.0 m

One could say that being prepared is already implicitly included in the mortality functions. The rapidly rising water zone includes the 'surprise effect' which is strongly related with being unprepared. Moreover, the remaining zone has a low mortality because preparedness is presumably implicitly included.

Secondly, the focus is on the influence of the water arrival time on the probability that people are still in the area or that the long water arrival time resulted in people fled to other safe areas. De Bruijn and Slager (2014) introduced a flee fraction to include water arrival time in mortality calculations, see Table 6.3. Their case study of the Betuwe area turned out to be very sensitive to this flee fraction. The effect of fleeing is in addition to the preventive evacuation, Table 6.3 shows an example of the people present when evacuation is also taken into account. The inclusion of flee fractions can also be checked for the Bommelerwaard area.

Table 6.3: Overview flee fractions, as proposed in De Bruijn and Slager (2014)

Water arrival time	**Flee fraction**	**(1 - Flee fraction)**
0 - 3 hours	0%	100%
3 - 6 hours	10%	90%
6 - 12 hours	20%	80%
12 - 24 hours	50%	50%
24 - 48 hours	80%	20%
>48 hours	90%	10%

Example of people present with evacuation and fleeing (with evacuation fraction = 0.56)
44%
40%
35%
22%
9%
4%

The approach of the flee fraction is assumed to be very relevant, because people nowadays have improved communication tools and infrastructure compared to 1953. Especially with the rise of social media. A quote from Maaskant et al. (2009) is given to illustrate this (quote is translated from Dutch): *"From the fire in the Armande museum, footage was earlier on Youtube than 112 had been called. When the airplane crashed of Turkish Airlines at Schiphol, information was earlier available on Twitter than via the official channels of rescue services."*

The flee fractions of De Bruijn and Slager (2014) are further substantiated for the Bommelerwaard. Therefore, it is important to take into account the exits of this dike ring area. Figure 6.4 shows the overview with six exits.

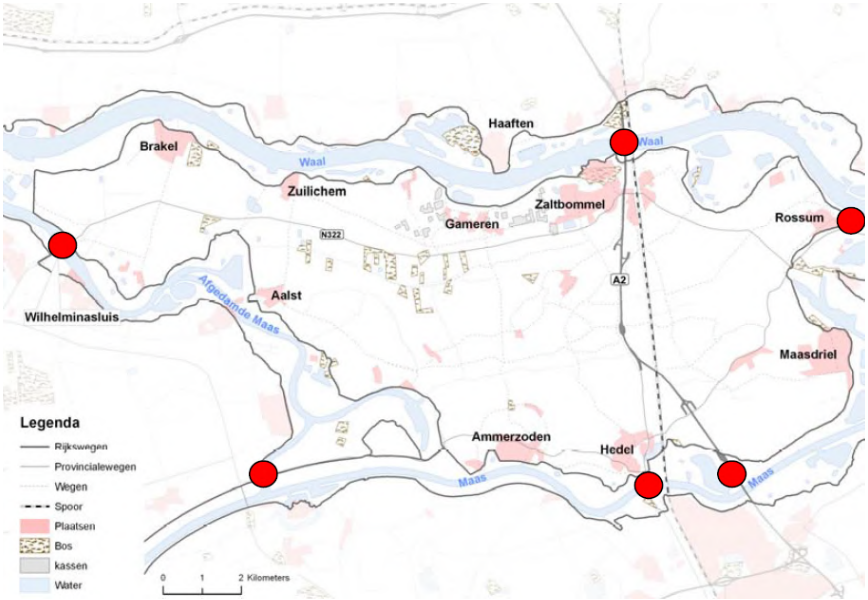


Figure 6.4: Overview of the exits of the Bommelerwaard (Vergrouwe and Bossenbroek, 2010)

The exit at Zaltbommel will not be usable due to flooding of Zaltbommel. The exit at Rossum is flooded in approximately 12 hours, so it can be used if people are warned in time. Inhabitants of Ammerzoden and Hedel have an exit within a reach of 10 km. These municipalities have arrival times in the order of 20 hours, so could be able to flee if they have been made aware of the coming danger in time. People living more upstream of Ammerzoden can take the exist between Aalst and Ammerzoden. The rest of the inhabitants of the Bommelerwaard need to go to the western exist. To illustrate the maximum distance: from Rossum to the most western exist is about 22 km. If the average vehicle travel velocity during evacuation of 20 km/h is maintained (often applied in evacuation studies), people in the Bommelerwaard are able to flee within one hour travel time.

This study adapts the flee fractions of De Bruijn and Slager (2014) to new fractions more specific for the case study of the Bommelerwaard. De Bruijn and Slager (2014) include a free fraction of 10% for 3-6 hours. As the breach can occur at night, including a flee fraction for this range might be too optimistic. Therefore, 4 hours is applied as ‘initiation time’, this is similar to the assumption made in the study of Asselman and Jonkman (2003) in which also 4 hours is used for decision making and initialization in case of a ‘non-organized evacuation’ after occurrence of a breach. The previous paragraph showed that the travel time is relatively short in the Bommelerwaard. For that reason, a total unorganized evacuation time of 24 hours is assumed. For river areas, the assumption is that 90% of the people would leave if they are asked to and 10% will stay in the area (Maaskant, Jonkman, and Kok, 2009). The flee fraction of 90% thus represents the upper boundary, this is reached when more than 24 hours are available.

In short: assuming that 10% will stay in the area, 24 hours are needed for evacuation and categories of 4 hours are applied, the flee fractions become as shown in Table 6.4. This is an example of possible flee fractions for the Bommelerwaard. An example of people present is added to this table if also evacuation is taken into account, because the flee fractions are in an addition to evacuation.

Table 6.4: Proposed flee fractions for the Bommelerwaard based on Table 6.3

Water arrival time	**Flee fraction**	**(1 - Flee fraction)**
0 - 4 hours	0%	100%
4 - 8 hours	15%	85%
8 - 12 hours	30%	70%
12 - 16 hours	45%	55%
16 - 20 hours	60%	40%
20 - 24 hours	75%	25%
>24 hours	90%	10%

Example of people present with evacuation and fleeing (with evacuation fraction = 0.56)
44%
37%
31%
24%
18%
11%
4%

One can point out that the flee fraction depends on the communication and human behaviour. If the government would send a message (e.g. 'NL alert') that everybody needs to stay home, the flee fraction would be much lower. But the opposite is also possible: if the government sends an urgent message that the dike has failed and that people (e.g. if they are living at a distance of more than 3 km from Zaltbommel) need to leave immediately, the flee fraction can be much higher at an earlier arrival time. Crisis managers must further analyze the areas with possibilities to flee and the routes to the exits combined with the flood scenarios for an appropriate advice and hence, avoid people having a higher risk of drowning during their escape.

3. Building characteristics

The building quality in 1953 in Zeeland differs significantly from nowadays. The buildings of today are stronger and thus less vulnerable to collapse and the expectation is that this would lead to less fatalities present-day than in 1953. This is mainly relevant for the rapidly rising water zone. Hence, the mortality function for this zone needs to be corrected. The building characteristics are discussed in Section 3.3.

If the building distribution in the Netherlands is assumed to be 50-50 for brick cavity walls and concrete, the distribution parameters of the lognormal distribution are μ_N = 1.68 and σ_N = 0.37 (Jonkman, 2007). The impact on mortality in the Bommelerwaard is tested using these parameters. Figure 6.5 shows the overview of the current function and improved function for the rapidly rising water zone.

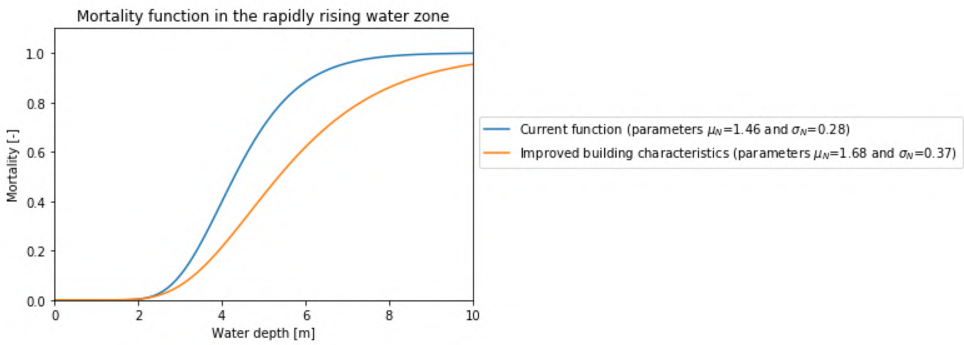


Figure 6.5: Overview of the mortality functions for sensitivity analysis 3a

This study also explores the impact of another measure: the construction years. Data of construction years are easy accessible, for example by using BAG ('Basisregistratie Adressen en Gebouwen' in Dutch). The average construction years of the buildings in the Bommelerwaard are shown per neighbourhood in Figure 6.6.

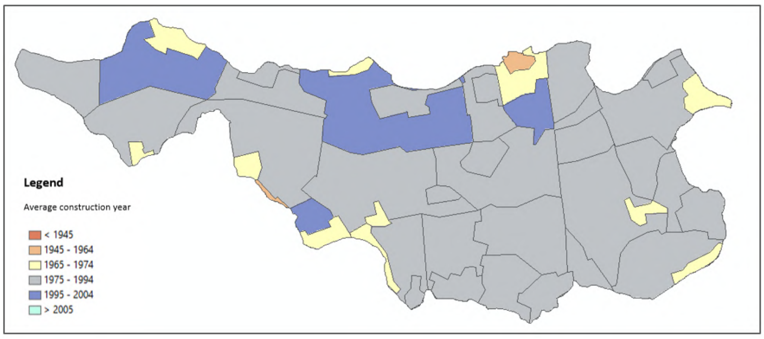


Figure 6.6: Overview of the average construction years of the buildings per neighbourhood (Data from BAG)

This study introduces reduction factors for construction years. Table 6.5 shows an example of these reduction factors. In the period 1965-1974, the focus was on quick construction due to housing shortage, and therefore there is a risk of quality (Jansen, 2019). For that reason, the reduction factor is relatively close to the residences category before. After 1975, the building quality improved, especially with the introduction of the 'Bouwbesluit'. Since the residences after 2005 are characterised by renovation, the reduction factor is the average of the three categories before. The adapted mortality functions for the rapidly rising water zone are shown in Figure 6.7.

Table 6.5: Example of reduction factors per construction year. Type of residences and characteristics are based on Jansen (2019).

Construction year	Type of residence	Key characteristics	Reduction factor
<1945	'Pre-war residences'	Single stone walls, timber floors	0%
1945 - 1964	'Early-post-war residences'	Brick cavity walls, timber floors	10%
1965 – 1974	'Housing shortage residences'	In-situ concrete, precast concrete panels floors	15%
1975 – 1994	'Energy crisis residences'	Cavity walls (CaSi or concrete)	30%
1995 – 2005	'Bouwbesluit residences'	New standards, high quality buildings	50%
>2005	'Renovation'	Existing residences are renovated	30%

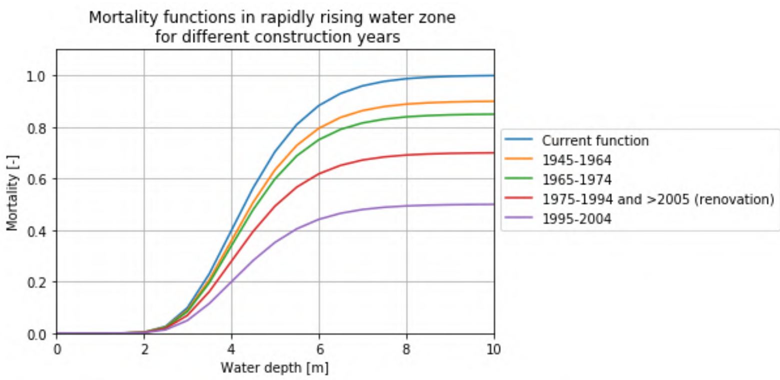


Figure 6.7: Overview of the mortality functions for sensitivity analysis 3b

4. Age

The literature study and points of discussion have shown that age played a role in loss of life in past flood events, because elderly are more vulnerable. Floods entail severe conditions, so the physical condition of the exposed people is important as it says something about the ability to cope with these severe conditions.

The research of Jonkman (2007) showed that in the 1953 event, the people aged above 60 years were more vulnerable because the fraction of the fatalities for the people 60+ was larger than the fraction of the population, see Figure 6.8. Since the distribution of age changed since 1953 due to 'ageing', a correction for age is introduced. Data from CBS show that 8% of the population was aged over 65 years in 1953, while nowadays it is 19%. Based on Figure 6.8 and the data of CBS, the assumption is made that approximately 20% of the fatalities in the 1953 event were aged above 65, while approximately 10% of the population was aged over 65 in 1953 and this has increased to 19% in 2019. One could say that the mortality functions implicitly take into account around 10% vulnerability for elderly while it should be higher nowadays since the population distribution has shifted. Four possibilities to include age are explored in this sensitivity analysis.

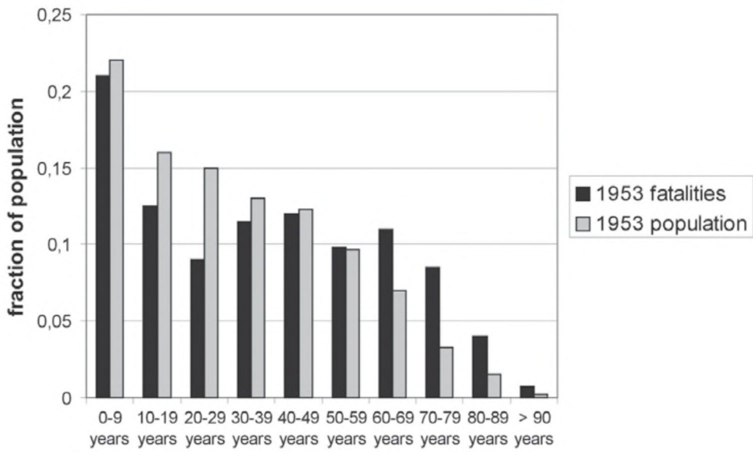


Figure 6.8: Comparison of fractions for the fatalities and population per age category in 1953 (Jonkman, 2007). This figure is also shown in Chapter 3.

Firstly, a correction factor is included for the overall mortality based on this shift in the age distribution. The base case has 598 fatalities and 48,110 inhabitants. In 1953, 10% of the inhabitants is assumed to be 65+, in the base case thus 4,811 inhabitants. 20% of the fatalities is assumed to be 65+, hence 120 fatalities of the 598 are expected to be 65+. This gives a mortality of 2.5% among the elderly in the base case.
Nowadays, 19% of the inhabitants is expected to be 65+, that gives 9,141 inhabitants in the base case. When a mortality of 2.5% is also assumed among the elderly in 2019, it results in 229 fatalities instead of 120. In short, using these assumptions based on the shift in age distribution, 109 more fatalities are expected with an overall mortality rate of 1.47% as a consequence. This is 0.23 percentage point higher than in the base case (1.24%).

An overall increased mortality influences the number of fatalities, but is not applied per grid cell and thus does not give additional insight into the required increase of (median) mortality per neighbourhood. Therefore, the second sensitivity analysis explores the possibility for a correction factor per neighbourhood. The mortality is increased when a neighbourhood contains more than 10% of the people aged above 65 in the same manner as in sensitivity analysis 4a. It calculates the mortality among the elderly per neighbourhood by taking into account the number of inhabitants, the expected number of people aged over 65 years among the inhabitants for 1953 and for the current situation, the fatalities, and the assumption that 20% of the fatalities is expected 65+. The mortality rate among the elderly per neighbourhood for the 1953 situation is then applied to the number of inhabitants above 65+ nowadays (varying per neighbourhood, with a maximum of 23%). The mortality cannot become higher than 100% and the neighbourhoods with lower fractions of elderly in the population than 10% have the same mortality as in the base case.

Sensitivity 4b thus also depends on the number of inhabitants per neighbourhood. In the third sensitivity analysis (4c), the mortality is increased when a neighbourhood contains more than 10% of the people aged above 65 with 0.1% per percentage of people 65+ (above 10%). For example, if 15% of the people is aged over 65, the mortality for this neighbourhood is increased with 0.5%. This is only done when the mortality in the base case is larger than 1% and it cannot exceed 100%.

Fourthly, the mortality is increased for the age fraction above 65 years in neighbourhoods that do not have a dry floor in the building anymore during the flood. This is inspired by the IPET report for New Orleans where people aged over 65 are assumed to reach the highest habitable level and no roofs or attics (USACE, 2006). LIWO ('Landelijk Informatiesysteem Water en Overstromingen' in Dutch) has an available map which shows per neighbourhood the percentage of the buildings that have a dry floor available when the maximum water depth takes place, see Figure 6.9. When this has the category 0-20%, this study assumes that elderly have a mortality twice as large as in the base case.

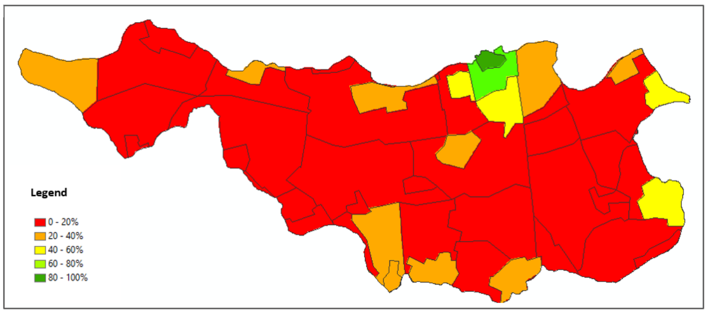


Figure 6.9: Percentage of buildings per neighbourhood that have a dry floor when the maximum water depth takes place (Data from LIWO)

5. Fixed mortality
At last, the sensitivity is tested when a fixed mortality is used. This means that one mortality rate is applied to all the cells and the flood characteristics are thus not taken into account. The mortality rate for the 1953 event was around 1%. Therefore, 1% mortality is applied to the whole area. Also the mortality rates of the 25m and 5m model are applied from the flood simulations in Chapter 5.

6.2.2. Confidence interval current functions and uncertainty

This section briefly elaborates on the confidence interval of the current mortality functions and the position of the alternative functions compared to this interval. The confidence interval is a measure for how uncertain the fitted line is through the data. Generally, the more data, the smaller the width, and hence the more certain the fit. The confidence intervals for the mortality functions are given in Figure 6.10 with a confidence level of 95%. The parameters for the confidence intervals are based on Table 6.2.

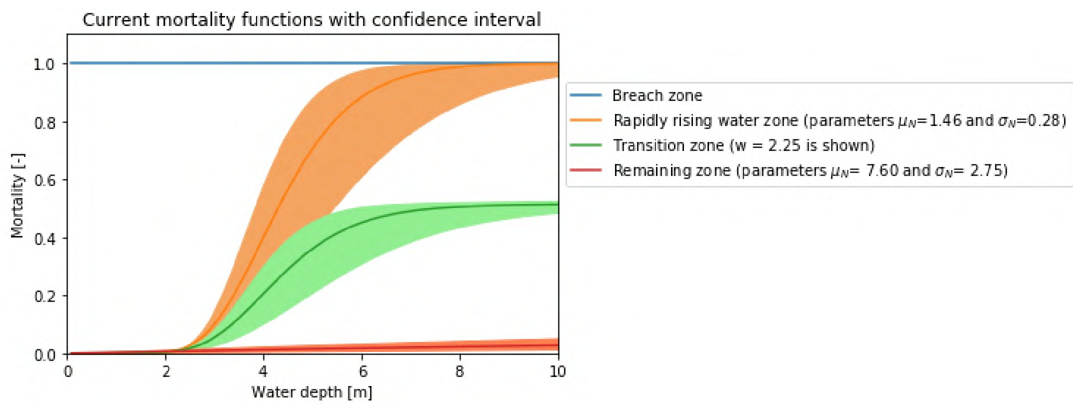


Figure 6.10: The current mortality functions with confidence interval. The parameters for the confidence intervals are based on Table 6.2.

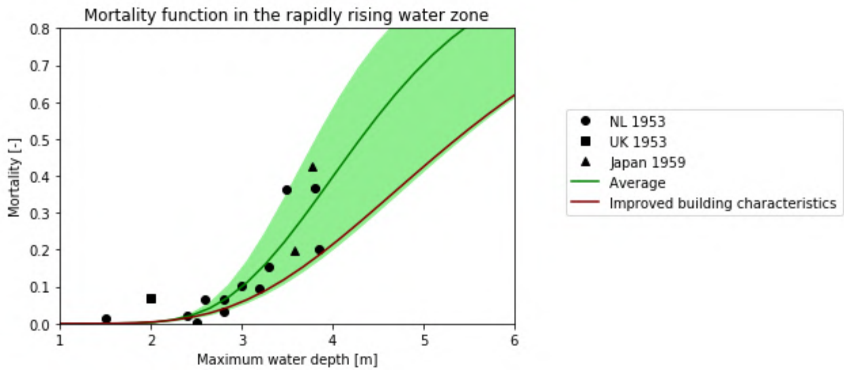
The breach zone is assumed to have 100%, but contains some uncertainty as well. As mentioned in the literature review in Chapter 2, the assumption of 100% might be too conservative. For example, much lower percentages were found in New Orleans, in the order of 5-10% (Jonkman et al., 2009). Moreover, the size of the breach zone contains some uncertainty, the assumption of the dv-product (>7m^2/s) could also be slightly different (e.g. >5m^2/s as in New Orleans). The size of the breach zone is also related to the modelling approach, as discussed in Chapter 5. However, if the breach zone conditions would be adapted in this study, the number of fatalities would barely be affected because of the small size and small number of fatalities compared to the total number of fatalities. Therefore, the focus is not on the breach zone in this sensitivity analysis, but the uncertainty in this zone must also be kept in mind.

The position of the alternative functions compared to the confidence interval gives a visual sense of how the functions perform compared to the data of 1953. Some of the sensitivity analyses are based on improvements of the functions themselves, and some introduce an extra factor. In case of a shifted lognormal distribution, it can be checked if the functions are still within the confidence interval. This is only the case for sensitivity analysis 3a and 3b. The other sensitivity analyses are also briefly discussed according to the data of 1953 and about their uncertainty, because it is important that no 'noise' is added as this can lead to false conclusions.

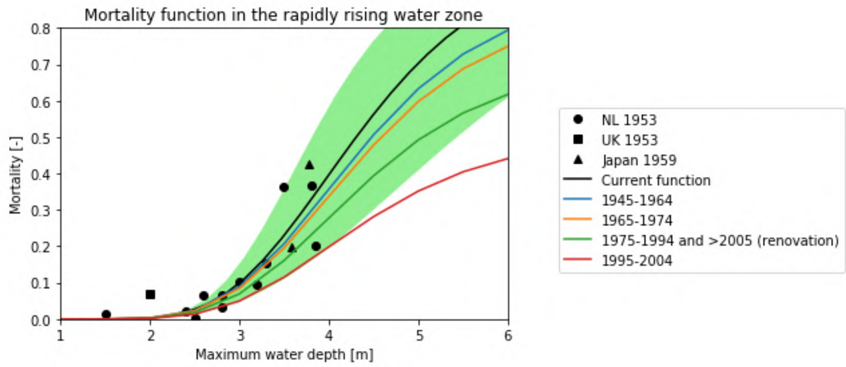
1. Water level rise rate and water arrival time
   When leaving the parameter water level rise rate out, either leaving it out completely or after a specified water arrival time, the mortality is based on the relation water depth - mortality only. The goodness-of-fit differs, but both approaches are based on data of 1953.

2. Water arrival time
   The inclusion of the water arrival time by a flee fraction reduces the presence of people in the area. This means that the mortality is still based on the same flood characteristics and on the same data, but the number of fatalities reduces. This is comparable to the applied evacuation fraction which is also based on expert judgment to lower the number of people present. It is reasonable to say that also the flee fractions need upper and lower bounds, just as the evacuation fractions have, to include uncertainty (e.g. due to human behaviour) in the estimated fractions.

3. Building characteristics
   The improved building characteristics are included by shifting the lognormal distributions, so their positions can be compared to the confidence interval, see Figure 6.11. The adapted mortality for improved building characteristics with a 50-50 distribution of cavity walls and concrete buildings is based on research of Asselman (2005), and this is based on the 1953 event and on a damage model. Figure 6.11a shows that the adapted function for the rapidly rising water zone falls just within the 95% confidence interval of the current function. One must point out that this alternative function is based on underlying assumptions for the damage curves, and this contains some uncertainty as well. Figure 6.11b shows that the reduction factors per construction year fall well within the confidence interval, except for the construction years between 1995-2004 for water depths larger than 4 m. Sensitivity analysis 3b is not based on extensive research and damage models as sensitivity analysis 3a is, and is therefore more uncertain.



(a) 50-50 distribution (sensitivity analysis 3a)



(b) Construction years (sensitivity analysis 3b)

Figure 6.11: The mortality function for improved building characteristics compared to the current mortality function in the rapidly rising water zone

4. Age
   Because more elderly are present in society nowadays, the possibility to correct the mortality for age is explored. The mortality per neighbourhood is only increased in the order of one percent or less and does not result in exceedance of the confidence intervals. The next section will show if this could result in significantly more fatalities. The correction factors are thus close to the current mortality functions, but they contain some uncertainty. Firstly, demographic developments must be taken into account if corrections are made for age, hence predictions are needed which contain some uncertainty. Secondly, this study worked on the assumption that 20% of the fatalities is 65+ as this was approximately the case in 1953. In future events this could be different. The latter is assumed to be of more relevance for uncertainty than the first. For example, in New Orleans the fraction of fatalities for people over 65 was nearly 60%.

5. Fixed mortality
   The fixed mortality is based on the event mortality of 1953, but the case study outcomes showed that the mortality is higher than 1% for the Bommelerwaard. When a fixed mortality is applied, it is also possible to include upper and lower bounds to account for deep polders.

This shows that not every adaptation can be linked to the 1953 data, for example the flee fractions. Improvements of the mortality functions need to be substantiated and defendable, but since the last flood is almost 70 years ago, it is not possible to improve the functions based on new Dutch data. However, improvements can also be substantiated in other ways, such as Maaskant, Jonkman, and Kok (2009). They introduced an improvement of the functions based on: a) the effects on the existing mortality and fatality estimations; b) the relevance of the effect in practice; c) the level of substantiation in the current approach and in the proposed adapted approach; and d) the feasibility of implementation and recalculations in the short term.

The first three criteria are all considered in this report. The effects on the existing mortality and fatality estimations are shown in the next section, the relevance in practice is described in Chapter 7 by evaluating the impact on the individual risk by following the official guidelines, and the level of substantiation is dealt with in detail in the previous chapters.

6.2.3. Results

The results of the sensitivity analysis are shown in Table 6.6. The mortality maps are only given for several cases, all the other maps are given in Appendix C. The results are discussed and compared with those of the base case below.

Table 6.6: Overview of the results of the sensitivity analysis. The mortality is calculated by dividing the number of fatalities by the number of inhabitants. Evacuation is not taken into account.

		Fatalities	Inhabitants*	Mortality**
Current 100m model (base case)		598	48,110	1.24%
1. Water level rise rate and water arrival time				
a. Water level rise rate left out		5575 (~factor 9)	48,110	11.59% (+10.35 p.p.)
b. Water level rise rate left out after:	*6 hours*	5494 (~factor 9)	48,110	11.42% (+10.18 p.p.)
	12 hours	4744 (~factor 8)	48,110	9.86% (+8.62 p.p.)
	24 hours	2187 (~factor 4)	48,110	4.55% (+3.31 p.p.)
c. Remaining zone applied after:	*6 hours*	526 (-12%)	48,110	1.09% (-0.15 p.p.)
	12 hours	526 (-12%)	48,110	1.09% (-0.15 p.p.)
	24 hours	531 (-11%)	48,110	1.10% (-0.14 p.p.)
2. Water arrival time				
a. Preparedness	*6 hours*	331 (-45%)	48,110	0.69% (-0.55 p.p.)
	12 hours	445 (-26%)	48,110	0.92% (-0.32 p.p.)
b. Flee fraction from De Bruijn and Slager (2014)		263 (-56%)	48,110	0.55% (-0.69 p.p.)
c. Flee fraction for the Bommelerwaard, adapted from 2b		208 (-65%)	48,110	0.43% (-0.81 p.p.)
3. Improved building characteristics				
a. Based on a 50-50 distribution of buildings of masonry and concrete		571 (-5%)	48,110	1.19% (-0.05 p.p.)
b. Based on construction year		580 (-3%)	48,110	1.21% (-0.03 p.p.)
4. Age				
a. Increased overall mortality for people aged over 65		707 (+18%)	48,110	1.47% (+0.23 p.p.)
b. Increased mortality per neighbourhood for people aged over 65		640 (+7%)	48,110	1.33% (+0.09 p.p.)
c. Increased mortality per neighbourhood per fraction of people aged over 65		727 (+22%)	48,110	1.51% (+0.27 p.p.)
d. Increased mortality when no dry floors are available and the people are aged over 65 (per neighbourhood)		623 (+4%)	48,110	1.29% (+0.05 p.p.)
5. Fixed mortality				
a. 1% applied to whole area (mortality in 1953)		482 (-19%)	48,110	1.00% (-0.24 p.p.)
b. 1.16% applied to whole area (mortality in 25m model)		558 (-7%)	48,110	1.16% (-0.08 p.p.)
c. 1.19% applied to whole area (mortality in 5m model)		573 (-4%)	48,110	1.19% (-0.05 p.p.)

* For comparison reasons, the number of inhabitants is used to estimate the mortality. The mortality map is multiplied with the inhabitants map to estimate the number of fatalities. In SSM2017, the number of people exposed is also estimated, which is slightly lower than the number of inhabitants. The mortality percentage for the base case is therefore now equal to 1.24% instead of 1.31%.
** The difference in mortality in comparison with the base case is expressed in percentage point (p.p.), thus the absolute difference.

1. Water level rise rate and water arrival time

When the water level rise rate is left out, the mortality is based solely on water depth. Figure 6.12 presents the mortality map when mortality is only dependent on water depth. The figure shows that the mortality is generally in the range 10-30% or 30-50% and only on a few spots lower than 10%. Accordingly, the number of estimated fatalities becomes very large, around a factor 9 larger than in the base case. This is also the case when the water level rise rate is left out after an arrival time of for example 6, 12 or 24 hours.

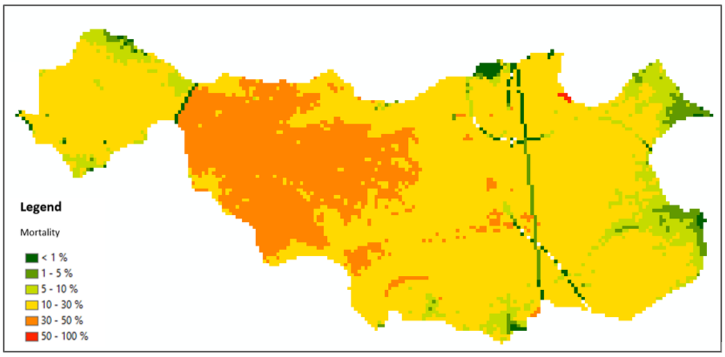


Figure 6.12: The mortality function Mortality map when water level rise rate is left out and the mortality is only based on water depth (sensitivity analysis 1a)

The high mortality rates can be explained by the large water depths. The water depths for this case study are in the range 4 to 6 meters. The mortality function is very steep in this range and becomes very high for large water depths, resulting in mortality values in the range 15 to 40% when only water depth is taken into account, see Figure 6.13. The total mortality is in the order 10%, and when the mortality-water depth relation is applied after a water arrival time of 24 hours, it is still about 5%, which is not plausible compared to past events. This shows that even when a small part of the Bommelerwaard has this mortality function (area for arrival times larger than 24 hours), it has a large effect. For deep, low-lying polders, where water depths can become very large, it is thus not recommended to leave out the water level rise rate.

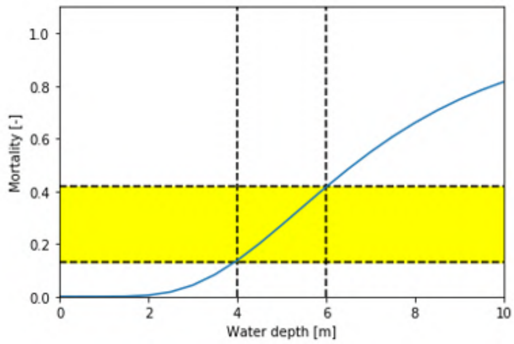


Figure 6.13: The mortality function based on water depth only, highlighting the mortality for water depths between 4 to 6 meters (sensitivity analysis 1a)

When the mortality functions of the remaining zone are applied after a specified water arrival time, the mortality (with water depths between 4-6 m) becomes around 1 to 2% at maximum. Figure 6.14 shows the result using a water arrival time of 12 hours. The mortality map is almost uniform. This might give a better estimation of the number of fatalities, but the indication of dangerous locations has been lost.

The numbers of fatalities became lower in the order of 10%. Table 6.1 showed that in the base case only 16% (97 of the 598) of the total fatalities occurred in the rapidly rising water zone and transition zone, hence the impact on this number is relatively large, but is not clearly visible in the total number of fatalities. The impact on the individual risk (LIR) could show a larger impact of this alternative approach.

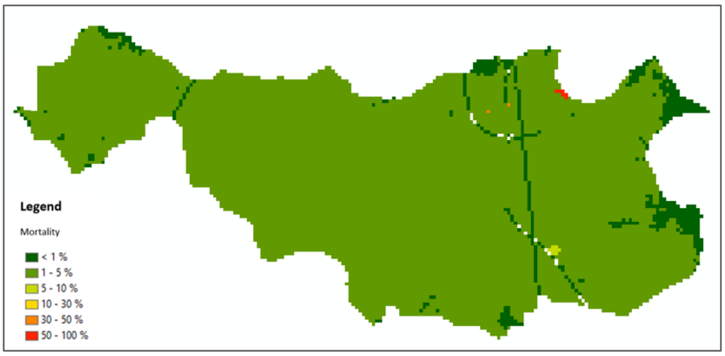


Figure 6.14: Mortality map when the remaining zone applies after 12 hours (sensitivity analysis 1c)

2. Water arrival time

The use of the upper or lower boundary from the rapidly rising water zone and the remaining zone has a significant impact on the number of fatalities. When people are assumed to be prepared after 6 hours, the number reduces with 45% and after 12 hours with 26%. This shows that the distribution parameters are sensitive to changes, especially in areas with large water depths.

The number of estimated fatalities is also very sensitive to the flee fractions, it has been more than halved. The flee fractions are similar, and this is also observed in the results for analyses 2b and 2c. In the base case, the mortality map showed that a large area of the Bommelerwaard has a mortality of around 1 to 2% and an average of 1.24%. The flee fractions reduce the mortality in many locations to below 1% and have an average mortality of 0.55% and 0.43%. Figure 6.15 shows the mortality map for the flee fractions of De Bruijn and Slager (2014). The mortality for water arrival times within 6 hours is visible as this is in the range 1 - 5% while the rest of the Bommelerwaard has for a large part a mortality below 1% due to the flee fractions. After 12 hours, the flee fractions reduce the mortality with 50% and for larger arrival times even more. The mortality before the Meidijk has reduced to a value of around 20%. The deeper parts and parts with a high rise rate are to some degree still visible, but do not stand out anymore.

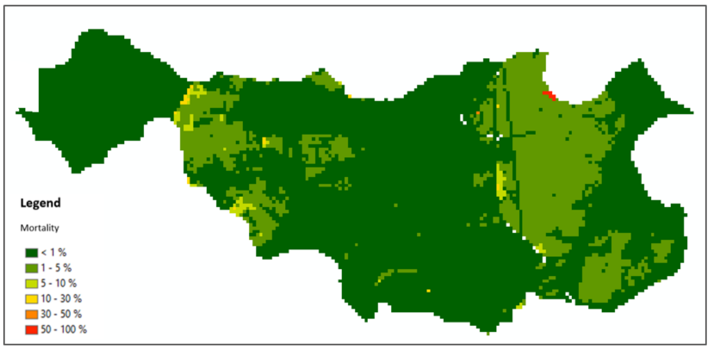


Figure 6.15: Mortality map including a flee fraction (sensitivity analysis 2b)

The flee fractions have a significant impact on the outcomes because the Bommelerwaard has areas with large arrival times and short travel distances to the exits. The effect would be lower for other dike rings if they do not have large arrival times, but are flooded much faster. In that case, only people in areas close to exits (and with enough warning time) are likely to flee the area.

3. Building characteristics

The improved building characteristics resulted in lower mortality in the rapidly rising water zone. The mortality map for the 50-50 distribution cavity walls and concrete (sensitivity analysis 3a) is shown in Figure 6.16. It is visible that the mortality is reduced close to the Meidijk and around the highway, the rest of the area is similar to the base case. The number of fatalities is reduced with only 5% to a number of 571 and hence, the total mortality rate is very close to the value of the base case. For the approach of using the construction years, it is even closer with only an increased number of fatalities of 3%.

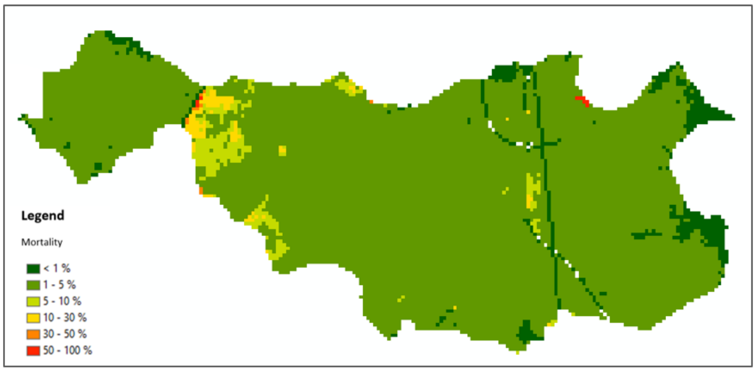


Figure 6.16: Mortality map for improved building characteristics (sensitivity analysis 3a)

The limited impact of these two sensitivity analyses on the number of fatalities is understandable when looking at the distribution of fatalities in the base case in Table 6.1. From the 598 fatalities, only 3 fatalities were located in the rapidly rising water zone and only 94 in the transition zone, thus 97 fatalities are located in the zone affected by the building characteristics. The reduction from 598 to 571 fatalities means that the improved building characteristics for the 50-50 distribution reduced the fatalities with 27, and compared to 97, this is almost 30%. In conclusion, the impact on the total fatalities for this sensitivity analysis is limited, but it would be interesting to see what the impact is on the individual risk (LIR), see Chapter 7.

4. Age

Sensitivity analysis 4a introduced a correction for the overall mortality of the base case. The overall mortality became 1.47%, which is 0.23 p.p. higher than the base case and increased the number of fatalities significantly with 18%. This is very similar to the findings of sensitivity analysis 4c in which mortality corrections were applied per fraction of elderly aged over 65 years. This resulted in 1.51% mortality with an increase of 22% of the number of estimated fatalities.

Sensitivity analysis 4b introduced a correction factor for age in the same manner as for 4a, but then per neighbourhood. This approach increased the number of fatalities only slightly with 7%. The increase in overall mortality has thus more impact on the number of fatalities than applying the assumptions per neighbourhood.

In sensitivity analysis 4d, the one with increased mortality if no dry floors are available in a neighbourhood and elderly are present, the influence is limited with an increased number of fatalities of 4%. This is most likely due to the distribution of the dry floors: the neighbourhoods with most inhabitants are the neighbourhoods that have more than 20% of the buildings with a dry floor available during the flood. This limits the increase of the number of fatalities.

The impact of the inclusion of age is relatively large on the number of estimated fatalities when correcting for the overall mortality. This effect is also expected in other areas when the same approach is used. When applying this approach per neighbourhood (sensitivity 4b), the effect is limited. In sensitivity analysis 4c, the inhabitants were not taken into account when correcting per neighbourhood, and this result was close to sensitivity analysis 4a.

Apparently, many neighbourhoods contain more than 10% elderly in their population which increases the mortality in the neighbourhoods.

In the Bommelerwaard, the average percentage of people aged over 65 is 12% per neighbourhood, the largest value is 23%. If (already dangerous) neighbourhoods exist in other dike rings with high concentrations of elderly, the estimated mortality and number of fatalities would increase significantly when age is taken into account.

5. Fixed mortality
When a fixed mortality is used, the mortality map has no added value as the same value applies to every single location. Consequently, the insight into dangerous locations have been lost. As the mortality of the base case is relatively high, around 1.24%, the fixed mortality rates of 1%, 1.16%, and 1.19% give fewer fatalities. The mortality rates of the 25m and 5m model are very close to the base case as shown in Chapter 5.

6.3. Conclusions and discussion

The sensitivity outcomes have given additional insight into the preliminary alternative mortality functions. This section presents the conclusions, discussion, and potential generalization of the results to other river areas.

6.3.1. Conclusions

The conclusions from the sensitivity analysis are:

- The water depth-mortality relation, applied to a large low-lying area with large water depths, results in a number of fatalities that is unrealistically high. The water level rise rate must, therefore, be remained in the model. This also applies after a specified water arrival time.
- If the mortality function of the remaining zone comes into force after a specified water arrival time, the risky places are not visible anymore in the map. The knowledge of locations with dangerous flood characteristics is very valuable, thus taking into account the water arrival time is preferred in another way.
- The number of fatalities and mortality are very sensitive to the flee fractions. The introduction of the flee fraction is very relevant, but the exact number of the flee fractions themselves could be further substantiated and is thus recommended to look further into.
- The parameters of the lognormal distributions for the rapidly rising water and remaining zone are sensitive to changes, this was illustrated by the introduction of preparedness. Including water arrival time by flee fractions instead of preparedness has a greater impact and thus more potential.
- When only the distribution parameters are changed for the rapidly rising water zone for the improved building characteristics, it resulted in around 5% lower number of fatalities. However, the base case only contained 3 fatalities in the rapidly rising zone and 94 in the transition zone. Therefore, the impact could be further analyzed when looking at the individual risk (Chapter 7).
- The outcomes are also sensitive to the correction factor for the elderly. It is recommended to look into a more substantiated correction factor for age as well, especially when applied per neighbourhood.

Based on these conclusions and the defined criterion if the mortality deviates more than 0.25 percentage point of the base case, the following mortality functions have potential and are further analyzed on their impact on the individual risk in the next chapter: water arrival time (2b, 2c), building characteristics (3a), and age (4c).

6.3.2. Discussion

Hazardous locations (e.g. close to breach, obstacles, before Meidijk) are identified with the current mortality functions as these functions give a direct insight into the relation of mortality and the flood characteristics. In some of these sensitivity analyses, it became clear that the indication of hazardous locations had been lost. To avoid losing this valuable insight, it is a possibility to make two mortality maps:

1. The current mortality map based on the current mortality functions to show the risky places due to the dangerous flood characteristics.
2. The second (new) map includes water arrival time and shows how the mortality could be if people can flee the endangered area. The analyses show that if this effect of fleeing is included, the mortality reduces significantly, hence many lives can be saved.

With two maps, spatial planners, decision makers, and emergency responders are aware of the dangerous locations, but the number of estimated fatalities and the individual risk could be based on the corrected mortality map. After all, dangerous locations are still dangerous locations after a certain amount of time, but if the people are not there anymore, it could reduce the local mortality rate significantly.

Since the Bommelerwaard is a deep, low-lying polder with very deep water depths, many people do not have a dry floor left during the maximum water depth. Fleeing the area is therefore, of major interest. However, crisis managers must determine which areas are recommended to flee given a flood scenario and which areas are not. The latter to avoid people having a higher risk of drowning because they are overwhelmed by the floodwater when on the road.

In conclusion, if crisis management focuses on the possibilities of fleeing (e.g. advanced warning system), it is possible to reduce flood fatality risk. This gives opportunities in the future, because it is expected that flood risk will increase due to climate change and socio-economic development when no additional measures are taken (IPCC, 2012).

6.3.3. Generalization of results to other river areas

This section discusses the generalization of the results and the transferability of the conclusions and knowledge gained to other river areas in the Netherlands.

This chapter shows that water arrival time included in flee fractions is preferred since the flee fractions have a significant impact on the number of estimated fatalities. It is mentioned that the effect of the flee fractions is only large if the arrival times are large and the travel distances to safe areas or the exits are not too long. However, the Bommelerwaard has short arrival times compared to the other river areas, for example, compared to the elongated river area the Betuwe, or the dikes along the Lek river in dike ring 44, or dike ring 45 when the water only reaches Amersfoort after approximately 2 days if a breach occurs in the Grebbedijk. Moreover, dike ring 36, 37, 39, 40, 50 and 51 are mentioned in Kolen, Maaskant, and Terpstra (2013) as dike rings where the evacuation fraction might be higher than the average value because of the proximity of safe places and the number of people present in the area. In other words, the flee fractions are also applicable to the other river areas, and have especially large impact in dike rings where the arrival times are large.

The distribution of the elderly is not dependent on the characteristics of the river area, hence the comparison is less relevant. The impact is especially expected to be large when many people above 65 years are living in an already dangerous area.

The improved building characteristics are relevant for the rapidly rising water zone and partly for the transition zone. The water depths have to be larger than 2.1 m and the rise rates higher than 0.5 m/h before the impact of the improved building characteristics is visible. For areas with shallower water depths, for example, upstream of a sloped dike ring area, this effect will not be visible. As mentioned in Chapter 5, obstacles are in every dike ring expected to be present, hence high rise rates can occur locally and therefore, the impact is expected to also be relevant for other dike ring areas, such as the Betuwe with the Diefijk.

7

Impact on individual risk

The number of fatalities is not the determining factor for the safety standard of dike trajectory 38-1, but the individual risk is ('Lokaal Individueel Risico' (LIR) in Dutch). The individual risk does not take into account the inhabitants, but looks at the probability that a person dies at a location due to flooding. To ensure basic safety for every citizen in the Netherlands, the individual risk is not allowed to exceed 10^{-5} per year.

This chapter is structured as follows. Section 7.1 explains how the individual risk is determined and Sections 7.2 and 7.3 give the results for the individual risk for the different model resolutions and alternative mortality functions and discusses them. Section 7.4 analyzes the individual risk when other neighbourhoods are applied and Section 7.5 explains how flood risk can be reduced in the future. Finally, the conclusions are given in Section 7.6.

7.1. Calculation of the individual risk

The calculation of the individual risk consists roughly of four steps:

1. Create and correct mortality map
2. Weighing of mortality for different scenarios
3. Median mortality per neighbourhood
4. Calculate the individual risk

These steps are briefly explained below.

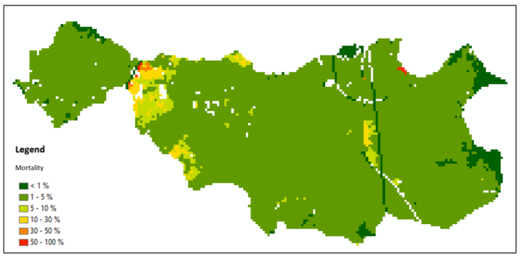
1. Create and correct mortality map

Firstly, the mortality maps need to be developed. The mortality maps are already created in the previous chapters based on the flood characteristics from the flood simulations, but some corrections need to be made.

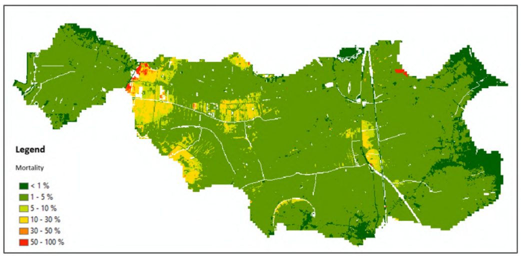
In Chapter 5, flood simulations were carried out for three model resolutions. The waterways were several times mentioned since the water level rise rate differed for these locations for the different model resolutions. However, it was explained that this was not of relevance because people do not live here. Since the individual risk does not consider inhabitants, it could wrongfully increase the mortality per neighbourhood if this is taken into account. The waterways, and if present, also swamps, thus need to be corrected. This is done mainly using LGN6, but this does not cover everything (especially in the 5m model) since LGN6 has a model resolution of 25m (see Chapter 4), and therefore, the mortality maps are visually corrected as well using ArcGIS.

Flood scenarios exist where parts of a dike ring are not flooded and remain dry. The water depth is then zero and thus the mortality is zero for these parts. If these parts are taken into account for the calculation of the individual risk, the median mortality for the total area becomes lower due to the dry areas. This could result in a possible underestimation of the individual risk. Therefore, all areas with a mortality of zero or 'nodata' are excluded in the determination of the median mortality.

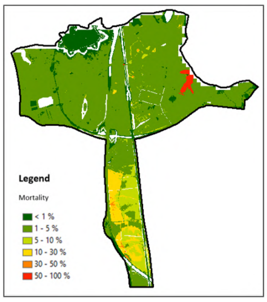
Figure 7.1 shows the corrected mortality maps for the 100m and 25m resolution and the refined area with 5m resolution. It is visible that the 100m model contained fewer waterways than the 25m model. The 5m model contains many details, even small ditches were present in the model and needed to be corrected.



(a) 100m resolution



(b) 25m resolution



(c) 5m resolution

Figure 7.1: Mortality map corrected for waterways and dry locations

2. Weighing of mortality for different scenarios

This study looked into one flood scenario for dike trajectory 38-1, namely the breach scenario based on Hurwenen, located before Zaltbommel. However, dike trajectory 38-1 has two breach scenarios: Hurwenen and Brakel. The worst case scenario is the breach at Hurwenen. For river dike ring areas, the worst case scenario receives a weight of 0.4 and the other scenarios together receive a weight of 0.6 (De Bruijn et al., 2011).

To calculate the individual risk for the whole dike ring area, both dike trajectories 38-1 and 38-2 need to be considered. Dike trajectory 38-1 protects the Bommelerwaard from the Waal and dike trajectory 38-2 protects the Bommelerwaard from the Meuse. The individual risk contributions of these dike trajectories are summed and must not exceed 10^{-5} per year. Since flooding from the Waal is worse than the Meuse (higher peak discharges, hence more water), the breach scenario at Hurwenen is dominant for the individual risk in the dike ring area. This is the only scenario that is taken into account in this study.

3. Median mortality per neighbourhood

To match the level of detail of the mortality functions, the median mortality is used per neighbourhood to estimate the individual risk. Possible outliers in the mortality map are not taken into account when the median is used. Based on the (weighted) mortality (excluding waterways, dry areas), the median can be calculated per neighbourhood.

The data of the neighbourhoods that were used in VNK2 originates from CBS in 2008. For that reason, the neighbourhoods of 2008 are also used in this study. According to the CBS, the defined neighbourhoods are based on the built-up area or socio-economic structure. The overview of neighbourhoods is given in Appendix D.

4. Calculate the individual risk
The general individual risk formula for a neighbourhood is (De Bruijn et al., 2011):

$$IR(N) = (1 - f_e) * P_f * (0.4 * m_{WC}(N) + 0.6 * \sum_i *P_{cond,i} * m_i(N)) \tag{7.1}$$

In which:
IR(N) = Individual risk in neighbourhood N
f_e = Evacuation fraction (lower boundary of bandwidth)
P_f = Probability of flooding per year
$m_{WC}(N)$ = Median mortality in neighbourhood N for worst case scenario
$m_i(N)$ = Median mortality in neighbourhood N for scenario i
$P_{cond,i}$ = Conditional probability of scenario i

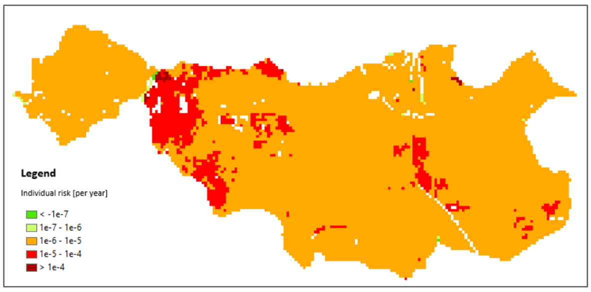
This formula is used to calculate the individual risk in order to compare the different model resolutions and mortality functions. The individual risk is thus found by multiplying the fraction of the people left behind with the probability of flooding and with the median mortality per neighbourhood since the weights were left out. The probability of flooding for dike trajectory 38-1 is calculated in the VNK2 project and equals 1/1.250 per year. The people left behind are estimated by 1 minus the evacuation fraction. Instead of using the average evacuation fraction, the guidelines state that the lower boundary of the bandwidth must be used corresponding to a poor-to-medium organized evacuation (Slootjes and Van der Most, 2016b). The lower value for dike ring 38-1 is 0.56 (Slootjes and Wagenaar, 2016).

7.2. Individual risk per model resolution

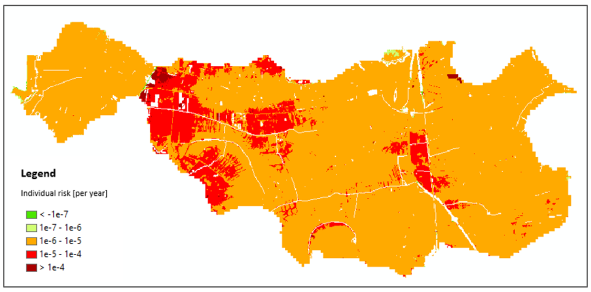
The individual risk is currently based on the 100m grid. This section looks into the impact on the individual risk when a model resolution of 25m or 5m is used compared to 100m.

Figure 7.2 gives the map when the mortality is multiplied with the fraction of the people left behind and the probability of flooding. The median mortality is not yet taken into account. This gives a first impression of the magnitudes.

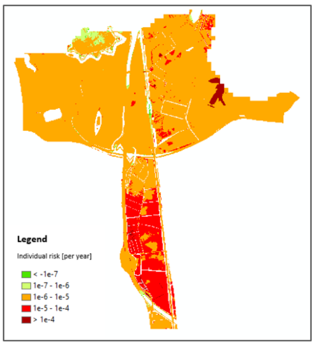
If the mortality exceeds approximately 3%, the individual risk criterion ($<10^{-5}$) is exceeded. The most dangerous category ($>10^{-4}$) corresponds to a mortality of around 30% or higher, which is the case at the breach zone and some locations upstream of the Meidijk. 100% mortality corresponds with an individual risk value of $3.52*10^{-4}$ per year, this is the maximum value.



(a) 100m resolution



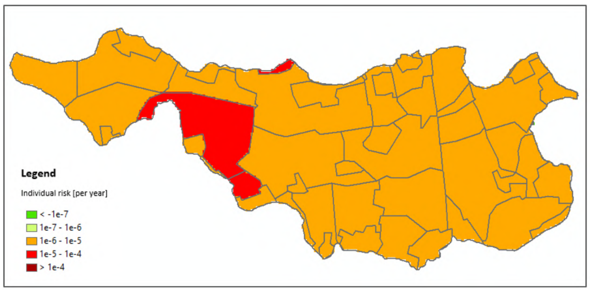
(b) 25m resolution



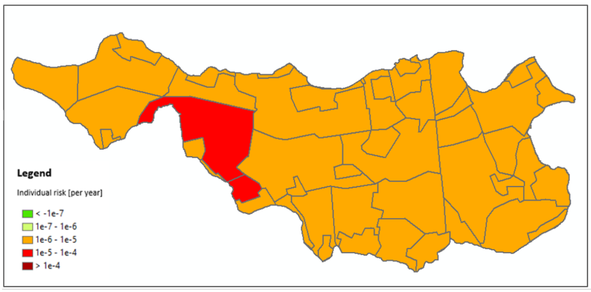
(c) 5m resolution

Figure 7.2: "Individual risk" maps when the median mortality is not yet applied per neighbourhood.

The median mortality per neighbourhood is calculated in order to calculate the individual risk per neighbourhood. It depends on the size and distribution of the neighbourhoods how the median mortality and hence individual risk turns out. Figure 7.3 shows the results for the 100m and 25m model.



(a) 100m resolution



(b) 25m resolution

Figure 7.3: Individual risk for both the 100m and 25m model. The grey lines represent the neighbourhoods.

The individual risk values for the 100m and 25m model fall almost everywhere in the same categories on the map, but the values differ. Overall, the individual risk values are approximately 6% higher for the 100m model than for the 25m model. This is consistent with the higher number of fatalities that is found for the 100m model than for the 25m or 5m model. Overall, the mortality rates for the coarser model are thus more conservative. In the 100m model, three neighbourhoods do not comply with the criterion ($<10^{-5}$), and two neighbourhoods in the 25m model. The neighbourhood that is non-complying (red) in the 100m model and complying (orange) in the 25m model is located at the upper edge of the dike ring. This area has a value of $9.9*10^{-6}$ per year in the 25m model and is thus close to the threshold of 10^{-5} per year.

However, the neighbourhood with the highest individual risk value (exceeding 10^{-5} per year) is most important. The neighbourhood with the maximum value has a higher value for the 25m model. The neighbourhood with the highest individual risk value has a value of $1.36*10^{-5}$ per year in the 100m model and of $2.49*10^{-5}$ per year in the 25m model. This maximum neighbourhood value is critical for the safety standard of the whole dike trajectory.

To analyze if the individual risk corresponds with the expectations, in Figure 7.4, the mortality map of the 100m model is shown one more time, including the neighbourhoods. It is observed that the area upstream of the Meidijk is split into two relatively large neighbourhoods. The upper part is orange and satisfies the individual risk criterion, but the lower part is red and does not meet the individual risk criterion. If the neighbourhood areas were smaller and more centered just upstream of the Meidijk, the values for the individual risk could have been significantly larger due to the high mortality rates in this area. Furthermore, the area between the obstacles came forward in the mortality map as a dangerous location, but is split into two relatively large neighbourhoods which results in a lower individual risk per neighbourhood. This shows the relative sensitivity of the individual risk for the distribution and size of the neighbourhoods. This needs further attention, see Section 7.4.

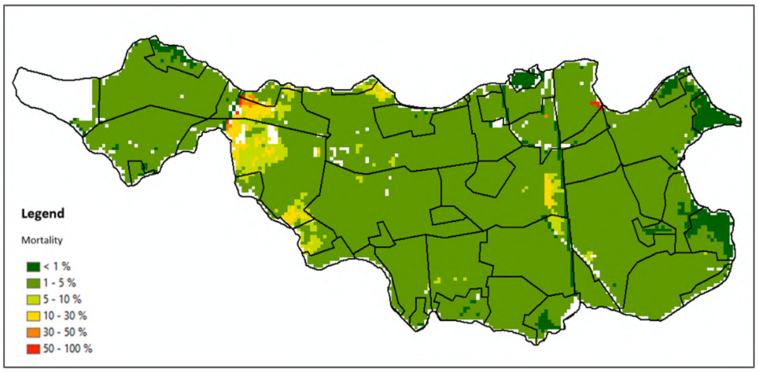


Figure 7.4: Mortality map of the 100m model with the neighbourhoods in grey.

Since the 5m resolution is only applied to the area close to the breach, a comparison is made with the neighbourhoods that fall into this zone. Some neighbourhoods have a larger extent than that fits within the refined area and are therefore cut-off. This affects the median mortality, so this is also done for the 100m and 25m model for comparison. This may vary from the map in Figure 7.3. Figure 7.5 shows the result.

The three models have the same map individual risk map. They all contain one red, non-complying, neighbourhood. This neighbourhood corresponds with the high mortality area due to the obstacles. The maximum values differ: the 100m model has a maximum value of $1.18*10^{-5}$, for the 25m model this is $2.29*10^{-5}$ and for the 5m model this is $2.73*10^{-5}$ per year. This shows that the individual risk value doubled for (a part of) this neighbourhood when using a finer model resolution. It was noticed that this only applies to this dangerous area with high rise rates, because the individual risk is approximately 8% higher in the 100m model for the other neighbourhoods. This is similar to the comparison between the 100m and 25m described above.

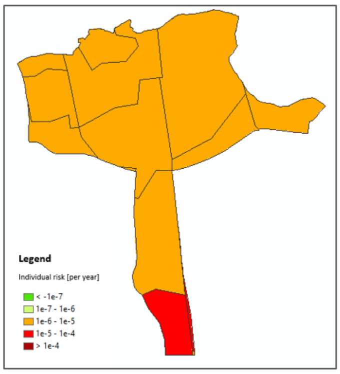


Figure 7.5: Individual risk maps for the refined area (for 100m, 25m, and 5m). The grey lines represent the neighbourhoods. Some neighbourhoods are cut-off to fit into the refined area.

In conclusion, the 100m model resolution causes higher individual risk values per neighbourhood, except for the most dangerous locations. The neighbourhood with the highest individual risk value has a higher value in the 25m and 5m models than in the 100m model. This shows that the finer model resolutions increase the maximum individual risk value and thus have a significant impact on the flood fatality risk in the Bommelerwaard, since the maximum value is critical for the safety standard of the whole dike trajectory. The higher value of the individual risk at the most dangerous locations can be lead back to the higher rise rates in the flood simulations which caused higher mortality rates.

7.3. Individual risk of alternative functions

Chapter 6 showed the sensitivity analysis of the mortality functions. The individual risk is calculated for the functions concerning water arrival time, building characteristics, and age. The results are shown in Table 7.1 and are explained below. The individual risks maps are shown in Appendix D.

Table 7.1: Individual risk for alternative mortality functions

	Maximum individual risk value [per year]	**Number of neighbourhoods exceeding 10^{-5} per year**
Base case (current mortality functions)	**$1.36*10^{-5}$**	**3**
Water arrival time: Flee fractions of De Bruijn and Slager (2014) (2b)	$6.30*10^{-6}$	0
Water arrival time: Flee fractions adapted for the Bommelerwaard (2c)	$5.40*10^{-6}$	0
Improved building characteristics (3a)	$1.12*10^{-5}$	1
Including age per neighbourhood (4c)	$1.37*10^{-5}$	3

It is observed that the water arrival time has a significant impact on the individual risk. In the base case, three neighbourhoods did not comply with the criterion of $<10^{-5}$ per year, but if the flee fractions are applied, all neighbourhoods satisfy the criterion. This shows once more the potential of including water arrival time in mortality estimations.

The improved building characteristics have also a significant influence on the individual risk. After implementation, two neighbourhoods went from non-compliance to compliance, and the neighbourhood that still does not meet the criterion, has a reduced maximum individual risk with almost 20%. In the previous chapter, the improved building characteristics did not have a large impact on the number of fatalities, but the large (positive) impact on the individual risk is not entirely unexpected. This is because the maximum individual risk is related to the high rise rates that cause the high mortality rates. The improved building characteristics result in lower mortality rates for the same high rise rates, hence making the most dangerous locations less dangerous. The median mortality is therefore lower with a lower maximum individual risk as a result.

The last applied function is the mortality function for age. Including a higher mortality for people aged over 65 had a large impact on the number of fatalities, but Table 7.1 shows that this is not the case for the individual risk. This is explainable, because the three most dangerous areas that exceed the criterion are neighbourhoods with fractions of people aged over 65 just above or below the 0.10. Some other neighbourhoods do have higher individual risks, but this did not result in exceedance of the criterion. If the (already) dangerous neighbourhoods had a high concentration of people aged over 65, the maximum individual risk could have been much higher.

7.4. Individual risk using other neighbourhoods

Section 7.2 shows that the size and distribution of the neighbourhoods have an influence on the individual risk. This section looks more into the neighbourhoods and their sensitivity. The 100m model is used again as base case to analyze the impact of using different neighbourhoods on the median mortality per neighbourhood and therewith the magnitude of the individual risk.

Firstly, the neighbourhoods of 2018 are applied instead of the neighbourhoods of 2008. Figure 7.6 shows that there are small differences between 2008 and 2018.

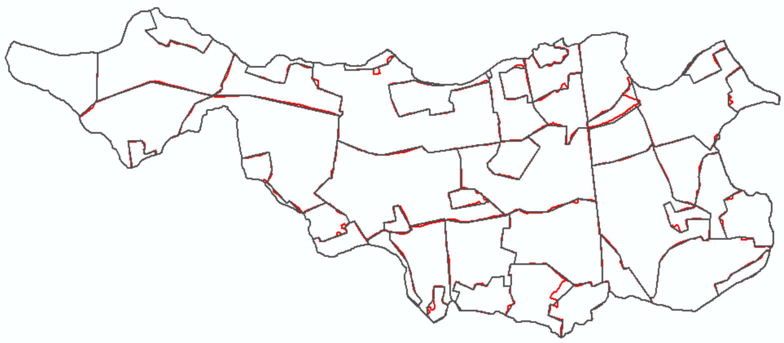


Figure 7.6: The distribution of neighbourhoods (data from CBS). The neighbourhoods in 2008 (used in VNK2 and in this study) are shown in black, the neighbourhoods in 2018 are shown in red.

Figure 7.7 shows the results when using the neighbourhoods of 2018. This resulted in two relevant differences. Firstly, the maximum individual risk has increased to $1.64{*}10^{-5}$ per year. Secondly, the small neighbourhood at the upper edge of the Bommelerwaard directly next to the Waal (neighbourhood 'Nieuwaal') went from noncompliance (red) to compliance (orange) of the individual risk criterion. Figure 7.8 zooms in on this neighbourhood. In 2018, the neighbourhood received a small extra area, and this reduced the median mortality from 2.97% to 2.65%. This made the difference for the individual risk criterion and highlights the sensitivity of the size of the neighbourhoods.

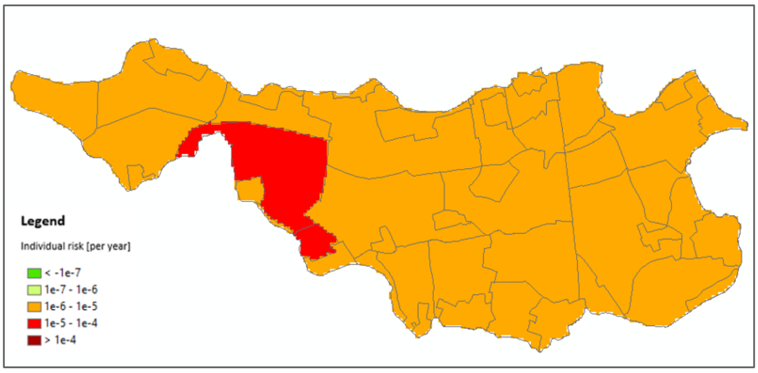


Figure 7.7: Individual risk for both the 100m model with neighbourhoods of 2018. The grey lines represent the neighbourhoods.

(a) Neighbourhood in 2008

(b) Neighbourhood in 2018

Figure 7.8: Individual risk zoomed-in on neighbourhood 'Nieuwaal' next to the Waal. The grey lines represent the neighbourhoods.

Secondly, the neighbourhoods of 2018 are used as a starting point and are then adapted based on land use. CBS divided the neighbourhoods based on the built-up area or socio-economic structure, but this can also be done based on land use as this is more in line with the approach of the flood simulations. An example of neighbourhoods based on land use is shown in Figure 7.9. The built-up areas form separate neighbourhoods, and the rural area is divided based on land use as much as possible, resulting in 34 neighbourhoods instead of 45.

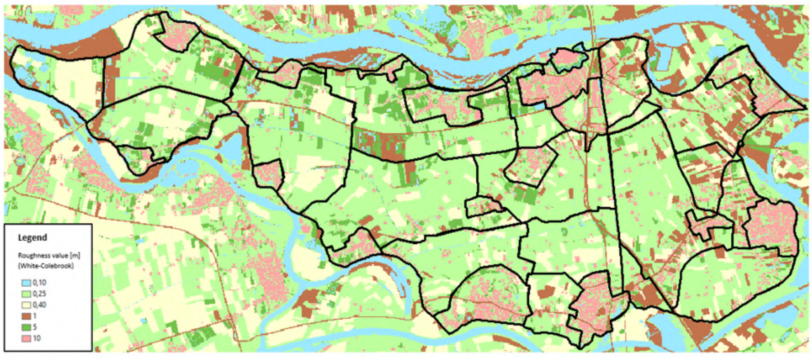


Figure 7.9: Possible division of neighbourhoods based on land use. The black lines represent the neighbourhoods.

Figure 7.10 shows the results for the individual risk. The proposed neighbourhoods result in values lower than 10^{-5} per year and meet the criterion of the individual risk. This illustrates that the neighbourhood configuration effects the outcomes and that it is possible that the outcomes result in all neighbourhoods complying the regulations by changing the configuration.

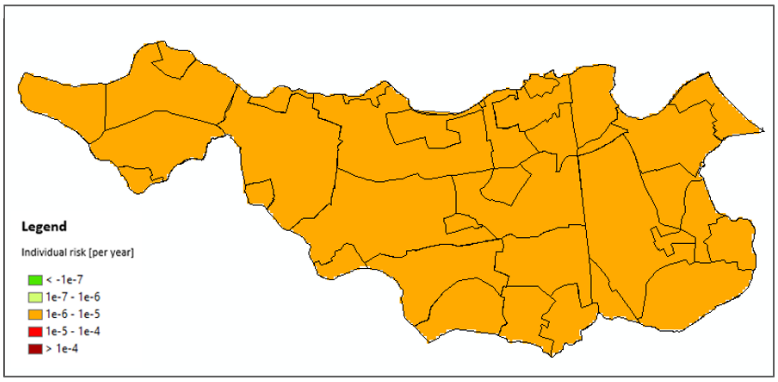


Figure 7.10: Individual risk for the neighbourhoods based on land use. The black lines represent the neighbourhoods.

Thirdly, a last more general check is done by using neighbourhoods with the same size. If a fair distribution of safety is pursued with no difference between locations where many people live (built-up areas) or only a few people live (rural areas), it may be of interest to use the same 'neighbourhood' sizes as median mortality is more likely to be lower in larger areas. The average area of the 45 neighbourhoods is 340 ha. Based on this average, neighbourhoods are made of 1800m x 1800m (324 ha). The overview of the neighbourhoods and the resulting individual risk map are shown in Figure 7.11. The outcomes seem reasonable, the red cells are recognized as the dangerous locations around the Meidijk. The outcomes can differ if the neighbourhoods are shifted or enlarged.

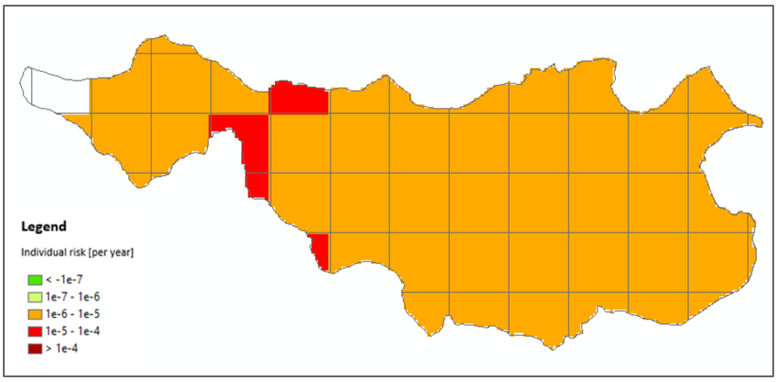


Figure 7.11: Individual risk for same sized neighbourhoods. The black lines represent the neighbourhoods.

In conclusion, the configuration of the neighbourhoods are important since small changes in the configuration effect the outcomes of the individual risk. Therefore, it is worth considering other more robust ways to estimate the individual risk. For example, 90% of the neighbourhood must satisfy the criteria.

7.5. Flood risk mitigation

Flood risk is determined by multiplying the probability of flooding with the consequences of the flood. Without intervention, the flood risk will increase in the coming years because both aspects are expected to increase (IPCC, 2012). The probability of flooding will increase due to climate change and land subsidence and the consequences will increase due to socio-economic developments. This section discusses what the possibilities for flood risk mitigation are.

Firstly, the probability of flooding can be decreased. For example, when proceeding with the current policy, traditional solutions are to strengthen or heighten the dikes. In the Bommelerwaard, this has to be done for the total dike trajectory, because it behaves as a bathtub and is filled up with water irrespective of the exact breach location in trajectory 38-1. An alternative is the reduction of the loads, for example by projects as 'Room for the River' where the river discharge is increased by widening of the river, lowering floodplains and creating bypasses. One must point out that the probability of flooding is dependent on the safety standards upstream. For example, differences exist between the standards in Germany and the Netherlands, and this means that some peak river discharges are not achieved in the Waal due to flooding upstream in Germany (Deltares, 2011).

Secondly, the consequences in case of flooding can be reduced by focusing on spatial planning and emergency management. First ideas can be to improve emergency response by including more shelters within the area such as high-rise buildings or elevated areas. It is also possible to raise the most vulnerable locations or adapt buildings to make them flood-proof. One step beyond, one can avoid the construction of new buildings and companies at vulnerable locations. It is also possible to introduce retention areas for temporary water storage during high water to avoid the formation of breaches. This way, flood events are more controllable.

Since the Bommelerwaard has very large water depths, some of these mentioned general strategies or measures will not be cost-effective for this area. Other mitigation strategies to reduce flood risk that are connected to the findings of this study:

- The Meidijk had a significant impact on the mortality rates. It caused high rise rates just upstream of the dike, and also large water depths in the east part of the Bommelerwaard. High mortality rates due to compartment dikes or obstacles can be reduced:
    1. It is recommended to explore the impact of making openings in compartment dikes. For example, create bike paths through the dike to allow water to flow through the obstacle in case of flooding to avoid the large rise rates and hence large mortality rates. When openings are made, the dike can still serve as escape route.
    2. It also recommended to investigate if the locations of the compartment dikes can be optimized to reduce the impact. Compartment dikes cause high rise rates and large water depths, but also provide more (flee) time for the inhabitants in the area behind. Optimization of the locations, and also considering to add or remove compartment dikes, can lead to lower flood risks.
- In this study, 3 of the 45 neighbourhoods do not meet the individual risk criterion. Therefore, it could be worthwhile to consider to apply the evacuation fraction per neighbourhood instead of the total dike ring. This can be achieved by adapting the evacuation strategy for the dangerous neighbourhoods to reach a higher evacuation fraction than 0.56. This way, the individual risk can be reduced significantly for very dangerous locations and therewith the overall safety standard.
- Raise public awareness about flood risk, especially in risky places, because this can improve human behaviour before and during flood events. Literature study had shown that in some flood events, fatalities were due to risk-taking behaviour.

7.6. Conclusions

The individual risk is the determining criterion for dike ring 38-1. Therefore, it is of importance to check the impact of potential changes of (more detailed) flood simulations and mortality functions on the individual risk and therewith the overall safety standard. This section presents the results and the potential generalization of the results to other river areas.

7.6.1. Conclusions

The conclusions about the impact on the individual risk are listed below:

- The maximum individual risk value of the neighbourhoods is significantly higher for the finer model resolutions compared to the 100m model. The most dangerous locations have higher median mortality values in the finer models, this is due to the higher water level rise rates. A higher maximum individual risk value has consequences for the overall safety standard of the dike ring since the probability of flooding has to be lowered to comply with the individual risk criterion, or the mortality for that neighbourhood has to be lowered. This indicates that the model resolution has a significant impact on the flood fatality risk.

- Overall, the 100m model has higher individual risk values per neighbourhood (approximately 6%). This is in line with the previous findings of a higher number of fatalities for the coarser model. Only the dangerous locations have lower individual risk values compared to the finer models (see point above).
- The inclusion of water arrival time in the mortality functions has great potential as the maximum individual risk is reduced with more than 50% for the applied flee fractions. As a result, all neighbourhoods comply with the individual risk criterion. Crisis management has an important role in the achievement of these flee fractions.
- Although the impact of the improved building characteristics was limited on the number of fatalities, it is large for the individual risk. The improved building characteristics cause lower mortality in the dangerous neighbourhoods, reducing the individual risk.
- The presence of vulnerable elderly did not result in a significant impact on the maximum individual risk in this study. It is recommended to check the number of fatalities and cost-benefit analysis, as it might influence these aspects.
- It is common practice to use the neighbourhoods of CBS from 2008. However, this study showed that even small changes in neighbourhood can change the individual risk locally. The application of the neighbourhoods of 2018 instead of 2008 resulted in different outcomes and it was also shown possible for a configuration of neighbourhoods that all neighbourhoods comply the individual risk criterion. This demonstrated that the maximum individual risk is sensitive to the distribution and size of the neighbourhoods.

7.6.2. Generalization of results to other river areas

Sections 5.5.5 and 6.3.3 discussed to what degree the conclusions are transferable to other river areas concerning the flood characteristics and the alternative mortality functions. This section discusses briefly the generalization of the additional findings of this chapter about the individual risk.

The impact of the flee fractions on the individual risk is large in the Bommelerwaard and is also considered large for other dike ring areas with large water arrival times. Since most river areas have larger arrival times than the Bommelerwaard, this is thus expected to be of importance in the other dike ring areas as well.

The change of the distribution parameters of the mortality function for the rapidly rising water zone, is expected to be large in deep areas (>2.1m) with high rise rates (>0.5 m/h). Since these flood characteristics also occur in other river areas, the building characteristics are also expected to be relevant in those case studies.

Lastly, the impact of age is very case specific. If many elderly are living in dangerous zones in other dike rings, the impact can be large. However, this was not the case in the Bommelerwaard and this could be the same in the other areas. The impact on the estimated number of fatalities can be of relevance similar to this case study.

Part III: Closure

8

Discussion

This study focused on two parts: (1) possible improvements of the mortality functions for river flooding in the Netherlands; and (2) the level of detail of the hydrodynamic models, including the applicability of the mortality functions. The Bommelerwaard was chosen as the case study area, because the safety standard for this dike ring is based on the individual risk (LIR) and it is located between three rivers. This chapter discusses the methodology, the limitations, and the results of this study compared to other studies.

8.1. Methodology

In this study, a case study was performed for a river area in the Netherlands. One breach scenario was considered, this was the worst case scenario with the largest contribution to the individual risk of the total dike ring. This was the best scenario to choose since the focus is on fatality assessment. However, if other scenarios were included as well (other locations, breach discharge, breach width, etc.), this could show additional insights into dangerous locations.

The flood simulations were carried out with the new software program D-Flow Flexible Mesh (D-Flow FM) from Deltares. This hydrodynamic software program is the intended follow-up software for the current SOBEK software (HydroLogic, 2019). The main advantage of this new innovative software is the possibility to refine areas of interest. This thesis describes one of the first studies carried out with D-Flow FM, especially regarding fatality assessment, and therefore the set-up of the case study is comprehensively described in Chapter 4. This case study can be of great importance for further development of the software program, might be an inspiration for new modelling guidelines, and could also be useful for water boards and crisis management organizations for more experience with the system behaviour in the Bommelerwaard.

The general guidelines for flood simulations as described by De Bruijn and Slager (2018) were followed as much as possible for consistency with other (modelling) studies and for potential reproductions of this case study. As modelling is an iterative process, some model assumptions or settings had to be reconsidered and adjusted during the process. For example, the fixed weirs were added at the outflow boundaries and the time settings were updated to avoid unstable behaviour.

The most relevant model assumptions are discussed here:

- Inclusion of the breach
  The breach was included as a horizontal boundary condition with a Q-t relation. The reliability of the flood simulation will increase if the river model is connected to the flood model, because it takes into account breach growth and also the interplay between the flooded area and the water level of the river. Inclusion of the river model could influence

the inundation pattern and more specifically, the size of the breach zone. However, one has to keep in mind that there is still much uncertainty about the modelling of the breach growth.

- Outflow boundaries
  The outflow boundaries at the southern edge of the Bommelerwaard were added in a later stage by imposing fixed weirs with the elevation of the dike. The elevation of the dikes was rounded to half meters. More precise inclusion from all boundaries and inclusion of the adjacent dike ring will give more accurate results.
- Obstacles
  The obstacles were assumed to be able to retain water until its maximum elevation ('standzeker' in Dutch). This assumption was of major importance in the mortality assessment, because the Meidijk retains the water and causes large upstream water depths and high rise rates just upstream of the dike. Hence, this was a conservative assumption. Local failure of an obstacle is expected to lower the overall mortality in the Bommelerwaard, but could increase local mortality downstream of the failure location as well as a flow pattern resembling a second breach zone will develop.
- Roughness grid
  The land use in the area of the Bommelerwaard is spatially varying, and therefore a roughness grid is applied instead of a uniform roughness value. This is expected to give more accurate results, especially in areas where the elevation does not vary much. The guidelines of De Bruijn and Slager (2018) were used to translate land use classes into White-Colebrook roughness values (see Appendix B). In this study, no sensitivity analyses have been conducted regarding the hydraulic roughness. The impact of the roughness grid and its limitations on the outcomes could be further assessed.
- Simplification input
  Many more aspects should be included when making flood simulations for flood risk management purposes, e.g. drainage canals, rainfall, pumps, noise barriers, etc. The model input was simplified because it is not necessary to include all these aspects to answer the research questions of this study.

8.2. Limitations

Fortunately, no recent floods have occurred in the Netherlands with fatalities as a result. The last event was in 1953 and formed the basis of the mortality functions. No data is available to validate the models and mortality functions for the case study of the Bommelerwaard because no recent flooding occurred. It is not possible to prove if and which alternative mortality functions give more accurate results. Even though no local recent data can be used to evaluate alternative mortality functions, (published) expert opinion and reasoning in addition to literature studies on other past flood events abroad were the base of the model assumptions in this thesis.

The aim of the case study about the level of detail of the hydrodynamic model was to compare the flood characteristics and mortality outcomes for different model resolutions. The 'real' values of the flood characteristics were not pursued, but it had the intention to model a realistic flood pattern. The magnitude of the deviation of the computed characteristics from the 'real' characteristics is not known since this flood scenario has not taken place, but the next section shows that the outcomes correspond very well to findings of other (hydrodynamic modelling) studies. This is described in the next section.

8.3. Comparison of results to other studies

This is one of the first studies that used D-Flow FM to compare mortality outcomes for different model resolutions. However, some aspects of this study can be compared to other conducted studies.

The outcomes can be compared to the expected results as described in Section 4.3. The flood maps of this study are similar to the outcomes of the study of VNK2 on which most assumptions were based, but VNK2 used the software program FLS to create the flood maps. Both studies result in large water depths and present the same dangerous locations. The flood maps created by D-Flow FM seem very reasonable compared to VNK2. The study of VNK2 estimated 504 fatalities in case of no evacuation, and this study estimated 598. This difference can be explained by the observation that the Meidijk overflows faster in the VNK2 study, resulting in slightly lower water depths upstream with lower mortality as a result. Another difference that is observed is that the floodwater propagates faster in their model. This can be caused by multiple aspects, such as the inflowing breach discharge, the hydraulic roughness, or the inclusion of waterways. Overall, both models represent similar information and the results of this study utilizing D-Flow FM can therefore be trusted to be reasonable and realistic compared to benchmark software.

The impact of the roughness approach has also been assessed in other studies. For example, Asselman (2009) used the software program SOBEK. She analyzed three case study areas and also found similar maximum water depths and arrival times for both roughness approaches, and higher velocities when buildings are schematized as solid objects instead of a higher hydraulic roughness at these locations. This is in line with the findings of this study.

The pilot study of HydroLogic (2019) simulated a breach in dike trajectory 38-2 (next to the Meuse) and also looked into the impact of some model resolutions on the flood characteristics. They found small differences in water arrival time around obstacles and underpasses for different model resolutions, and this is consistent with this study. The pilot study also found large computation times for 5m model resolutions using software program D-Flow FM. They recommended to schematize obstacles as fixed weirs and underpasses as 1D elements. Since this recommendation about fixed weirs is not acknowledged yet in the current guidelines, it was not yet implemented for the obstacles in this case study. However, the use of fixed weirs was explored by applying it to the outflow boundaries.

9
Conclusions and recommendations

In Chapter 1, the objective of this study was stated by formulating the main research question:

> *What are the possibilities for potential alternative mortality functions for river flooding in the Netherlands and what is the impact of the level of detail of hydrodynamic models on the estimated mortality?*

This main research question is answered in Section 9.1 by providing a set of conclusions and by answering the formulated five (sub) research questions. Section 9.2 follows with a set of recommendations for future studies.

By answering the main research question, this study contributes to a better understanding of the connection between flood simulations and flood fatality assessment and to possible directions to improve flood fatality risk. This study provides insight and gives conclusions and recommendations that may lead to a (model-supported) discussion among experts on the use of the mortality functions and the individual risk criterion.

9.1. Conclusions

9.1.1. General conclusions

This paragraph will first give conclusions related to the level of detail of the hydrodynamic models and then provide conclusions related to the possibilities for improved flood fatality risk analysis.

Level of detail of hydrodynamic models

Hydrodynamic models are key in flood risk management. The flood simulations provide insight into the inundation pattern and characteristics and form the basis for mortality calculations. The created flood maps enable comparison of different scenarios and areas, and also strategies and measures. In this study, the impact of the level of detail of the flood simulations (100m, 25m, and partly 5m resolution) on mortality and fatality assessment was analyzed. The model resolution (grid cell size), and also the schematization of buildings were thoroughly analyzed.

Conclusions:

- All three models resulted in similar inundation patterns and large water depths in the Bommelerwaard. The model resolution influenced the discharge through the underpasses and resulted in slightly different arrival times. Overall, the models represented the same information for this flood scenario.
- The breach zone is assumed in current models to have the highest mortality (100%).

Finer model resolutions resulted in a larger sized area where flow velocities are higher than 2 m/s, and with the combination of large water depths, it was observed that the size of the breach zone is larger for finer model resolutions. This indicates that model resolutions impact the outcomes, and should thus always be reported when simulating new scenarios.

- The size of the breach zone increased significantly in the 5m resolution model when the buildings are included as solid objects instead of higher hydraulic roughness. This is also ascribed to larger velocities to a larger extent when buildings are located before the breach location, indicating that the assumptions on inclusion of objects are relevant when estimating the size of breach zone. This is particularly relevant for floods with high flow velocities or areas with many obstacles.
- When buildings are schematized as solid objects, no water stands in or flows through the buildings and hence no mortality is assigned to these locations. Mortality can be estimated by interpolation of the flood characteristics followed by the application of the mortality functions or by direct interpolation of the mortality. Both interpolations gave the same outcomes and seem suitable to correct the values at the building locations.
- The roughness approach of buildings as solid objects had limited influence on the mortality outcomes in the city of Zaltbommel as velocities did not exceed 2 m/s.
- The model resolution can have a significant impact on the water level rise rate, depending on the area. In the 100m model, the peak values are averaged over a larger cell and have less effect than the finer model resolutions. The differences were the largest between the obstacles and in waterways. These areas thus need extra attention when choosing a model resolution.
- Waterways came forward with higher mortality rates but should be left out of consideration since people are never located in waterways. For the 5m model, also ditches needed to be removed to determine the individual risk. This is important, because it can increase the median mortality and subsequently the individual risk unjustifiably.
- The benefits of estimating the number of fatalities with finer model resolutions are limited for the Bommelerwaard and the area of Zaltbommel since the outcomes were close to each other. However, the impact on the maximum individual risk was significant. Since the individual risk is determinative for the safety standard in the Bommelerwaard, this is an important finding.
- During the analysis of the impact of the model resolution on the individual risk, it was noticed that the individual risk is sensitive to the configuration of the neighbourhoods. It was observed that small differences in the size of neighbourhoods resulted in different outcomes. This shows that the neighbourhoods have to be applied with care.

Possibilities for improved flood fatality risk

The mortality functions are based on three flood characteristics: water depth, flow velocity, and the water level rise rate. The functions are based on data of 1953 and hence implicitly include the circumstances of Zeeland in 1953. This study looked into the possibilities to change the current relations and to include also additional aspects explicitly.

The possibilities for alternative functions are based on the literature study, on knowledge of past events and international loss of life approaches. The contributing factors were categorized into flood hazard, flood exposure, social vulnerability, and other characteristics and further analyzed based on their relevance and change over time since 1953.

In this study, the focus was on the water arrival time, building characteristics, and age within the mortality functions. The literature study has shown that water arrival time is a commonly accepted parameter in loss of life approaches (e.g. ‘Risk to People’, LifeSim, and LSM). Also many Dutch research papers highlight this parameter and recommend to implement it. Water arrival time is often defined within the parameter warning time. However, for the sake of clarity and the avoidance of double-counting, this study defines warning time as the time available before the occurrence of the breach, while the water arrival time is defined as the time available after the occurrence of the breach.

The effect of improved building quality on mortality is acknowledged in literature, but the precise quantification is still being analyzed. A first approximation for mortality with improved building characteristics has been done in the literature and was tested in this case study. Moreover, age came forward in many past flood events and in international loss of life approaches (e.g. 'Risk to People', IPET) and is widely accepted to be an important aspect in people vulnerability.

Conclusions:

- Some locations are very dangerous but did not result in fatalities because currently no people are living there. This could change in the future and should be kept in mind.
- Including water arrival time by flee fractions has a significant impact on the number of fatalities and mortality. In the case study for the Bommelerwaard, the number of fatalities was more than halved for the proposed flee fractions. The median mortality per neighbourhood was also sensitive to these changes, and the maximum individual risk reduced significantly. When comparing the current mortality map and the map including water arrival time, it shows the locations where many lives can be saved. After implementation of the flee fractions, all neighbourhoods fulfilled the individual risk requirement. This shows the potential of focusing on water arrival time.
- The improved building characteristics can be implemented for the rapidly rising water zone and indirect also for the transition zone. This had a limited impact on the number of estimated fatalities due to the limited fatalities in these zones in the base case. The influence on the individual risk was significant, because the improved building characteristics reduced the mortality rates and resulted in lower median mortality per neighbourhood. This indicates that the inclusion of improved building characteristics is also worthwhile.
- The introduced correction factor for people aged over 65 years had a significant impact on the number of estimated fatalities. The inclusion of age had no significant impact on the maximum individual risk outcomes. This is due to the spatial distribution of the elderly, but should be further analyzed.

Generalization of the results to other river areas

The breach zone is assumed to be the most dangerous location, this is unrelated to the Bommelerwaard. The impact of the roughness approach and model resolution on the size of the breach zone is therefore also expected to be of relevance in other river areas. River flooding in the Bommelerwaard is especially dangerous because this dike ring behaves as a bathtub with large water depths as a consequence. These large water depths can also occur in the deeper parts of other river areas, causing high mortality. Also, obstacles can cause high mortality due to high rise rates. The findings of the modelling approach and the impact of the model resolution on the flood characteristics around obstacles and underpasses are expected to be of relevance in other case studies as well.

Concerning the alternative mortality functions, most results also apply to other river areas. The inclusion of flee fractions connected to the water arrival times had a significant impact on the number of estimated fatalities, mortality, and individual risk. This impact also applies to other river areas with large arrival times. Since most river areas have longer arrival times than the Bommelerwaard, this impact is even expected to be larger. The improved building characteristics have especially impact in areas with large rise rates (>0.5 m/h) and sufficiently large water depths (>2.1m). Since these flood characteristics occur in dangerous locations, inclusion of the improved building characteristics can also lower the local individual risk values in other river areas. Finally, age is also considered of relevance in other dike rings (not only in river areas), but this study shows that it depends on the spatial distribution what the impact is on the number of estimated fatalities and if there is an impact on the individual risk.

9.1.2. Answers to research questions

The five (sub) research questions are briefly answered below:

1. How is mortality included in the determination of flood risk in the Netherlands and what are the most important factors in the Netherlands and elsewhere?

Flood risk in the Netherlands is quantified in three ways: the individual, societal, and economic risk. Mortality is included in all these three risks; median mortality per neighbourhood is included in the individual risk, the number of fatalities is estimated based on mortality maps of the flood scenarios for the societal risk, and human life is quantified as 6.7 million euros in the cost-benefit analysis.
Mortality is based on the flood characteristics water depth, flow velocity, and water level rise rate, but many more are implicitly included as the functions are based on the flood event of 1953. These can be summarised into flood hazard, flood exposure, social vulnerability, and other characteristics, see Figure 9.1. The most important factors (other than mentioned above) in international loss of life approaches are water arrival time, people vulnerability, building collapse, and for agent-based models also human behaviour.

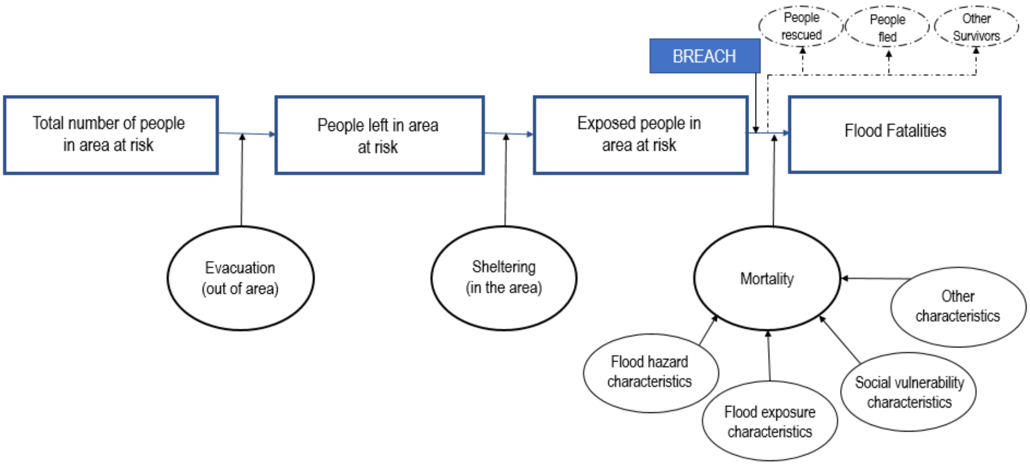


Figure 9.1: Overview of loss of life, based on Jonkman (2007) and De Bruijn and Van Kester (2015). This figure is also shown in Chapter 3.

2. Which factors changed since the flood event of 1953 and what are the discussion points in the current functions?

The main discussion point is related to the fact that the mortality functions are based on the conditions in Zeeland in 1953 and therefore, the implicit factors are assumed representative also for other potential events and locations in the present time. The factors building characteristics, infrastructure and transport, shelter possibilities, and warning time have changed since 1953. Moreover, the factors water arrival time, age, and human behaviour are assumed relevant. Since some factors are not included in the mortality functions, but in the evacuation fraction, the preliminary mortality functions were focused on building characteristics, water arrival time, and age.

3. What is the effect of using new knowledge or adapted functions in the case study of a potential river flood in the Netherlands?

Several sensitivity analyses were performed to test the effect of new knowledge or alternative functions on the number of estimated fatalities in the case study, the overview of the results is given in Table 6.6. Inclusion of the water arrival time by flee fractions has great potential as it reduces the number of fatalities significantly (~60%). The comparison of the current mortality map with the mortality map including water arrival time, shows that many lives can be saved at dangerous locations with relatively large time before the arrival of the floodwater. The number of estimated fatalities is also sensitive to correction factors for the elderly (~20%) and to a smaller extent to the improvement of building characteristics (~5%).

4. What is the sensitivity of the level of detail of the model on the estimated mortality in this case study?

The flood simulations were carried out with a model resolution of 100, 25, and partly 5m. The estimated mortality for the three models were very close to each other and the differences between the number of estimated fatalities were thus limited. The dangerous locations were similar, but the precise values differed. However, the model resolution had on some locations a significant impact on the water level rise rate, and since the water depths are large, also on the mortality. Moreover, the size of the breach zone increased for finer model resolutions. The modelling approach of the roughness had also influence on the size of this zone.

5. What is the impact of the potential alternative mortality functions on the flood fatality risk in the Netherlands?

The alternative mortality functions were tested on their impact on the individual risk, the results are shown in Figure 7.1. The sensitivity analysis of the water arrival time showed that the maximum individual risk value was decreased (~60%) and that all neighbourhoods met the individual risk criterion of the Water Act. The flee fractions are potentially very useful and insightful for preparing strategies and emergency response. The improved building characteristics also lower the maximum individual risk value (~20%), while the introduction of an age correction factor had limited impact (~1%). Finally, this analysis has drawn attention to the used distribution of the neighbourhoods. Small changes in size can result in a different median mortality and hence in a different individual risk value.

9.2. Recommendations

Based on the discussion and conclusions, recommendations are made, either general or specific for the modelling approach. These recommendations do not only apply to the Bommelerwaard, but to other river areas in the Netherlands as well.

9.2.1. General recommendations

Collection of data in future flood events

Since the validation of possible alternative functions is not possible due to the lack of data, it is strongly recommended to collect data in future flood events if the circumstances are similar to the Dutch circumstances. It is especially important to collect the locations of the fatalities as precisely as possible so that they can be connected to the flood characteristics. Data on mortality for high water level rise rates (>≈ 0.5 m/h) and large water depths (>≈ 3.5 m) are scarce, hence such data in future flood events can improve the mortality functions.

In addition, it is recommended to pay extra attention to the relation between mortality and building collapse, and between mortality and water arrival times, since these are assumed to be very relevant. Moreover, general information about age, gender, health, and the activity of fatalities improves the understanding of causes of death.

For example, the Delft University of Technology has launched an open access flood database *(`http://floodfatalities.tudelft.nl/floodfatality/`)* in order to store data of flood events in a standardized matter, including the hazard, impact and response.

Flood event management

It is recommended to develop a mortality map that takes into account the water arrival time by flee fractions. In the case of large water arrival times, it is possible for people to flee to safe areas and this reduces the number of fatalities significantly. This way, the dangerous locations due to severe flood conditions are still visible in the current mortality map, and the comparison of this map with the mortality map including water arrival times shows where many lives can be saved.

It is understandable that the flee fraction cannot be suddenly implemented into flood risk assessment, as it is sensitive to underlying aspects as communication and human behaviour. Moreover, people give rather conservative advice as we are dealing with human lives and to avoid having lower investments in the prevention of floods. However, the impact of water arrival time on the outcomes is profound and many lives can be saved if this is included in emergency response policy. Therefore, it is strongly recommended to start further research on the precise form of the flee fractions and to start a discussion among experts.

To include the flee fractions, an advanced warning system must be developed as well to provide information and clear advice to the people exposed about the actions they should undertake. These communication plans need to be anticipated based on information about the flood scenarios (flood pattern, characteristics, arrival times), available road network, people in the area, and time required for fleeing.

As it was observed in past flood events that the elderly are more vulnerable, it is recommended to include vulnerable people and locations in the emergency plans, such as hospitals, nursing homes, and schools. Furthermore, it is also recommended to communicate these plans with the exposed people to create flood risk awareness as this could improve human behaviour before and during flood events.

Spatial planning

The Meidijk had a significant impact on the flood pattern and flood characteristics, and hence on the mortality outcomes.

Firstly, it is strongly recommended to investigate if mortality can be minimized by optimizing the location (and number) of compartment dikes. In addition, if the recommendation of the inclusion of flee fraction is adopted to reduce the loss of life in the future, the water arrival times can be taken into account in the optimization, since water arrival times downstream of the compartment dikes increase.

Secondly, it is recommended to look into local solutions for risky places, such as openings in obstacles or local elevation of the area. It may be more beneficial to avoid a higher individual risk outcome and the corresponding higher protection standard for the whole Waal embankment. The recommendation is to also explore the options of local evacuation fractions.

Model resolution

The conclusions show that the coarse hydrodynamic model with 100m resolution performed well when compared on flood characteristics to finer model resolutions (25m, 5m). This means that the 100m model can be used for the indication of dangerous locations and the order of magnitude of the flood characteristics. The 100m model gives a conservative result for fatality assessment since this model resulted in a slightly larger number of fatalities than the finer resolutions. This study found that the model resolution influences the flood characteristics around obstacles and underpasses. These locations are therefore, recommended to be modelled with finer resolutions, with 1D objects or with fixed weirs.

In addition, the breach zone is recommended to be modelled with finer resolutions. Finer model resolutions provide higher local velocities which are relevant for building collapse.

It depends on the characteristics of the city if finer resolutions are also needed for urban areas. The flow velocities are higher for finer model resolutions, but in this study, it did not reach the critical value of 2 m/s and thus did not influence the mortality outcomes. For other research purposes, it could be of relevance and therefore, it must be kept in mind that coarser resolutions average these velocities out to lower values.

Finally, the model resolution had an impact on the magnitude of the mortality at risky places. Further research is recommended on this topic because it has an impact on the maximum individual risk values. It is recommended for spatial planners and crisis managers to get familiar with these local values as these are very hazardous.

Mortality functions

The possibilities for alternative functions are already covered in the previous sections. In short, it is recommended to look further into and start a discussion about the factors: improved building characteristics, age, and water arrival time. The building characteristics are significantly improved since 1953 and this study showed that the maximum individual risk is sensitive to this. In addition, this study emphasized that the elderly are more vulnerable and that the age distribution shifted since 1953. Especially for places with a high concentration of elderly, this is relevant. Lastly, the water arrival time is assumed very relevant and is recommended to take into account. This is further explained under 'Flood event management'.

9.2.2. Recommendations for or adjustments to modelling approach

It is recommended to undertake more case studies. Not only for further experience with the new software program D-Flow FM, but also because more studies contribute to a better understanding of flood patterns per area, especially with different resolutions.

For a fair comparison between different models, scenarios, or measures, it is important to have clear and up-to-date guidelines on the modelling approach. For example, obstacles can be included using the maximum elevation (as in this study), but obstacles can also be included by fixed weirs in the new software.

Other recommendations:

- Improved schematizing of breach zone
  It is recommended to include the breach growth and interaction with the river. Since the size of the breach zone depends on the local area, more case studies with different model resolutions and roughness approaches contribute to a better understanding of the size of the breach zone.
- Improved modelling of outflow boundaries
  The recommendation is to include all boundaries with accurate elevations and the adjacent dike ring area if overflow is expected.
- Sensitivity analysis about failure obstacles
  It is uncertain if obstacles are able to retain the water till its maximum elevation or that it fails in an earlier stage. The impact of the Meidijk was considered large, but other obstacles, such as highways and railways, can also have an influence. This should be further analyzed in case studies.
- Improved computation efficiency
  The computation times of the fine model resolutions in D-Flow FM are very large. If many scenarios or measures are tested with fine resolutions, it is not workable with the current settings. It is recommended to model only areas of interest with fine resolutions to limit the computation times. Always consider the characteristics of the area to be modelled when this choice is made (e.g. small streets, presence of obstacles, steep slopes, varying elevations or land use, etc.).

Finally, this is an independent study for research purposes. If the aim is to use it for actual flood risk and emergency response, it is recommended to involve or work together with the waterboard and crisis management organizations and other important stakeholders from an early stage.

References

Aboelata, M. and D. S. Bowles (2005). “LIFESim: A Model for Estimating Dam Failure Life Loss”. In: *ISSH - Stochastic Hydraulics 2005*.

Aboelata, M. and D. S. Bowles (2008). “LIFESim: A tool for estimating and reducing life-loss resulting from dam and levee failures”. In: *Association of Dam Safety Officials - Dam Safety 2008*.

Arcement, G. J. and V. R. Schneider (1989). “Guide for Selecting Manning’s Rougness Coefficients for Natural Channels and Flood Plains”. In: *U.S. Geological Survey Water-Supply*.

Ashley, S. T. and W. S. Ashley (2008). “Flood Fatalities in the United States”. In: *Journal of Applied Meteorology and Climatology* 47, pp. 805–818.

Assaf, H. and D. N. D. Hartford (2002). “A Virtual Reality Approach to Public Protection and Emergency Preparedness Planning in Dam Safety Analysis”. In: *Canadian Dam Association, Annual Conference 2002*.

Asselman, N. (2005). *Consequences of floods: Damage to buildings and casualties*. Tech. rep. WL | Delft Hydraulics.

Asselman, N. (2009). *Flood inundation modelling*. Tech. rep. FLOODsite.

Asselman, N. and S. N. Jonkman (2003). *Consequences of floods: the development of a method to estimate the loss of life*. Tech. rep.

Boudou, M., M. Lang, F. Vinet, and D. Coeur (Oct. 2016). “Lessons from analysing mortality from six major flood events in France (1930-2010)”. In: *E3S Web of Conferences*. Vol. 7. EDP Sciences.

Bouwer, L. M. and S. N. Jonkman (2018). “Global mortality from storm surges is decreasing”. In: *Environ. Res. Lett.* 13(014008).

Boyd, E., M. Levitan, and I. van Heerden (2005). “Further Specification of the Dose-Response Relationship for Flood Fatality Estimation”. In: *Conference: US-Bangladesh workshop on innovation in windstorm/ storm surge mitigation construction*.

Bricker, J. D., S. Gibson, H. Takagi, and F. Imamura (2015). “On the need for larger Manning’s roughness coefficients in depth-integrated tsunami inundation models”. In: *Coastal Engineering Journal* 57(2).

Brown, C. A. and W. J. Graham (1988). “Assessing the Threat To Life From Dam Failure”. In: *JAWRA Journal of the American Water Resources Association* 24(6), pp. 1303–1309.

De Bruijn, K. M., P. Cappendijk, J. Beckers, R. Van Buren, and A. Hendriks (2011). *Analyse van slachtofferrisico’s Waterveiligheid 21e eeuw*. Tech. rep. Deltares.

De Bruijn, K. M. and K. Slager (2014). *Mortality functions in the flood impact module*. Tech. rep. Deltares.

De Bruijn, K. M. and K. Slager (2018). *Leidraad voor het maken van overstromingssimulaties*. Tech. rep. Deltares.

De Bruijn, K. M., R. Van Buren, and K. Roscoe (2008). *Mapping casualty risks in the Netherlands; locational and group risk*. Tech. rep. Deltares.

De Bruijn, K. M. and B. Van Kester (2015). *Possibilities to improve flood fatality functions for the Netherlands: Research on international models and events*. Tech. rep. Deltares.

DeKay, M. L. and D. M. McClelland (Apr. 1993). “Predicting Loss of Life in Cases of Dam Failure and Flash Flood”. In: *Risk Analysis* 13(2), pp. 193–205.

Deltares (2011). *Maatschappelijke kosten-batenanalyse Waterveiligheid 21e eeuw*. Tech. rep.

Deltares (2019). *D-Flow Flexible Mesh User Manual*. Tech. rep.

Deltares (2020). *D-Flow Flexible Mesh - Technical Reference Manual*. Tech. rep.

Deltawerken Online (2004). URL: www.deltawerken.com (visited on 11/08/2019).

Di Mauro, M. and K. M. De Bruijn (2012). “Application and validation of mortality functions to assess the consequences of flooding to people”. In: *Journal of Flood Risk Management* 5(2), pp. 92–110.

Di Mauro, M., K. M. De Bruijn, and M. Meloni (2012). “Quantitative methods for estimating flood fatalities: Towards the introduction of loss-of-life estimation in the assessment of flood risk”. In: *Natural Hazards* 63(2), pp. 1083–1113.

Di Mauro, M. and D. Lumbroso (2008). “Hydrodynamic and loss of life modelling for the 1953 Canvey Island flood”. In: *Flood Risk Management: Research and Practice*, pp. 1117–1126.

Diakakis, M. and G. Deligiannakis (2017). “Flood fatalities in Greece: 1970–2010”. In: *Journal of Flood Risk Management* 10(1), pp. 115–123.

EM-DAT: The Emergency Events Database - Université catholique de Louvain (UCL) - CRED (2019). URL: www.emdat.be (visited on 10/24/2019).

Feinberg, B., W. Engemoen, W. Fiedler, and D. Osmun (2016). “Reclamation’s Empirical Method for Estimating Life Loss Due to Dam Failure”. In: *E3S Web of Conferences* 7(06002).

FitzGerald, G., W. Du, A. Jamal, M. Clark, and X. Hou (Apr. 2010). “Flood fatalities in contemporary Australia (1997-2008)”. In: *Emergency Medicine Australasia* 22(2), pp. 180–186.

Graham, W. J. (1999). *A Procedure for Estimating Loss of Life Caused by Dam Failure*. Tech. rep. Denver, Colorado: U.S. Department of Iinterior, Bureau of Reclamation.

Henckens, G. and W. Engel (2017). *Benchmark inundatiemodellen: modelfunctionaliteiten en testbank berekeningen*. Tech. rep. STOWA.

HydroLogic (2019). *TKI D-Hydro voor Waterschap Rivierenland: Pilot overstromingsmodel Bommelerwaard*. Tech. rep.

IPCC (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Tech. rep. Cambridge University Press, Cambridge, UK, and New York, NY, USA.

Jansen, L. (2019). “Structural damage to Dutch terraced houses due to flood actions”. MSc thesis. Delft University of Technology.

Johnstone, W. M., D. Sakamoto, H. Assaf, and S. Bourban (2005). “Architecture, Modelling Framework and Validation of BC Hydro’s Virtual Reality Life Safety Model”. In: *ISSH - Stochastic Hydraulics 2005*.

Jongman, B., H. C. Winsemius, J. C. J. H. Aerts, E. Coughlan De Perez, M. K. Van Aalst, W. Kron, and P. J. Ward (2015). “Declining vulnerability to river floods and the global benefits of adaptation”. In: *Proceedings of the National Academy of Sciences* 112(18), E2271–E2280.

Jonkman, S. N. (2004). *Methode voor de bepaling van het aantal slachtoffers ten gevolge van een grootschalige overstroming*. Tech. rep.

Jonkman, S. N. (2007). “Loss of life estimation in flood risk assessment: theory and applications”. Doctoral thesis. Delft University of Technology.

Jonkman, S. N., M. Godfroy, A. Sebastian, and B. Kolen (2018a). “Brief communication: Post-event analysis of loss of life due to hurricane Harvey”. In: *Natural Hazards and Earth System Sciences Discussions*, pp. 1–8.

Jonkman, S. N., R. E. Jorissen, T. Schweckendiek, and J.P. van den Bos (2018b). *Lecture notes CIE5314 3rd edition 2018: Flood Defences*.

Jonkman, S. N. and I. Kelman (2005). "An analysis of the causes and circumstances of flood disaster deaths". In: *Disasters* 29(1), pp. 75–97.

Jonkman, S. N., B. Maaskant, E. Boyd, and M. L. Levitan (2009). "Loss of life caused by the flooding of New Orleans after hurricane Katrina: Analysis of the relationship between flood characteristics and mortality". In: *Risk Analysis* 29(5), pp. 676–698.

Jonkman, S. N., B. Maaskant, B. Kolen, and J. T. Needham (2016). "Loss of life estimation - Review, developments and challenges". In: *E3S Web of Conferences*. Vol. 7. EDP Sciences.

Jonkman, S. N., B. Maaskant, B. Kolen, M. Zethof, W. P. Lehman, and J. T. Needham (2014). "A Comparative Study on Methods for Loss of Life Estimation - Applications to Case Studies in the United States". In: *6th International Conference on Flood Management - Sept. 2014 - Brazil*.

Jonkman, S. N., J. K. Vrijling, and A. C.W.M. Vrouwenvelder (2008). *Methods for the estimation of loss of life due to floods: a literature review and a proposal for a new method*.

Kolen, B., B. Maaskant, and T. Terpstra (2013). *Evacuatieschattingen Nederland Addendum*. Tech. rep. december. HKV Lijn in Water.

Kolen, B., R. Slomp, W. van Balen, T. Terpstra, M. Bottema, and S. Nieuwenhuis (2010). *Learning from French experiences with storm Xynthia: Damages after a flood*. Tech. rep. HKV Lijn in Water and Rijkswaterstaat.

Kolen, B. and J. Van Alphen (2017). *The contribution of disaster management to integrated flood risk management strategies: lessons learned from the Netherlands*.

Link, L.E., J.L. Foster, R.C. Patev, H.W. Jones, G.B. Baecher, M.W. McCann, and T. McAllister (2009). *A General Description of Vulnerability to Flooding and Risk for New Orleans and Vicinity: Past, Present, and Future - Supplemental Report of the Interagency Performance Evaluation Task Force*. Tech. rep.

Maaskant, B. (2007). "Research on the relationships between flood characteristics and fatalities". MSc thesis. Delft University of Technology.

Maaskant, B., S. N. Jonkman, and M. Kok (2009). *Analyse slachtofferaantallen VNK-2 en voorstellen voor aanpassingen slachtofferfuncties*. Tech. rep.

Maaskant, B., B. Kolen, R. Jongejan, S. N. Jonkman, and M. Kok (2009). *Evacuatieschattingen Nederland*. Tech. rep. HKV Lijn in Water.

Marriott, M.J. and R. Jayaratne (2010). "Hydraulic roughness – links between Manning's coefficient, Nikuradse's equivalent sand roughness and bed grain size". In: *Proceedings of Advances in Computing and Technology, The School of Computing and Technology 5th Annual Conference, University of East London*, pp. 27–32.

McClelland, D. M. and D. S. Bowles (2002). *Estimating life loss for dam safety risk assessment–a review and new approach*. Tech. rep.

Miller, A., S. N. Jonkman, and M. Van Ledden (Jan. 2015). "Risk to life due to flooding in post-Katrina New Orleans". In: *Natural Hazards and Earth System Sciences* 15(1), pp. 59–73.

Morelissen, R. and B. van Vossen (2009). *Modelleerstrategieën*. Tech. rep. Deltares.

Needham, J. T. (2010). "Estimating Loss of Life from Dam Failure with HEC-FIA". In: *2nd Joint Federal Interagency Conference, Las Vegas, NV, June 27 - July 1, 2010*.

Needham, J. T., W. Fields, and W. Lehman (Oct. 2016). "The US Army Corps of Engineers Scalable Approach to Estimating Loss of Life from Flooding". In: *E3S Web of Conferences*. Vol. 7. EDP Sciences.

Ozdemir, H., C. C. Sampson, G. A.M. De Almeida, and P. D. Bates (2013). “Evaluating scale and roughness effects in urban flood modelling using terrestrial LIDAR data”. In: *Hydrology and Earth System Sciences* 17(10), pp. 4015–4030.

Paprotny, D., A. Sebastian, O. Morales-Nápoles, and S. N. Jonkman (Dec. 2018). “Trends in flood losses in Europe over the past 150 years”. In: *Nature Communications* 9(1).

Peng, M. and L. Zhang (2012). “Analysis of human risks due to dam-break floods-part 1: A new model based on Bayesian networks”. In: *Natural Hazards* 64(1), pp. 903–933.

Pereira, S., J. L. Zêzere, I. Quaresma, P. P. Santos, and M. Santos (2016). “Mortality Patterns of Hydro-Geomorphologic Disasters”. In: *Risk Analysis* 36(6), pp. 1188–1210.

Petrucci, O. et al. (2019). “MEFF: The database of MEditerranean Flood Fatalities (1980 to 2015)”. In: *Journal of Flood Risk Management* 12(2), pp. 1–17.

Pleijter, G. and B. Kolen (2016). *Effecten van evacueren in SSM2015*. Tech. rep. HKV Lijn in Water.

Priest, Sally (2007). *Building a model to estimate Risk to Life for European flood events - Final Report*. Tech. rep. FLOODsite, Integrated Flood Risk Analysis and Management Methodologies.

Ramsbottom, D., P. Floyd, and E. Penning-Rowsell (2003). *Flood Risks to People - Phase 1*. Tech. rep. Defra, Environment Agency.

Salvati, P., O. Petrucci, M. Rossi, C. Bianchi, A. A. Pasqua, and F. Guzzetti (2017). “Gender, age and circumstances analysis of flood and landslide fatalities in Italy”. In: *Science of the Total Environment* 610, pp. 867–879.

Slager, K. and D. Wagenaar (2017). *Standaardmethode 2017: Schade en slachtoffers als gevolg van overstromingen*. Tech. rep. Deltares.

Slootjes, N. and H. Van der Most (2016a). *Achtergronden bij de normering van de primaire waterkeringen in Nederland*. Tech. rep. Ministerie van Infrastructuur en Milieu.

Slootjes, N. and H. Van der Most (2016b). *Technisch-inhoudelijke uitwerking van eisen aan primaire keringen: Bijlagen*. Tech. rep. Ministerie van Infrastructuur en Milieu.

Slootjes, N. and D. Wagenaar (2016). *Factsheets normering primaire waterkeringen*. Tech. rep. Deltares.

Smith, G .P. and P. F. Rahman (2016). *Approaches for Estimating Flood Fatalities Relevant to Floodplain Management*. Tech. rep. Water Research Laboratory - University of New South Wales.

TAW (1994). *Water tegen de dijk 1993 - De toestand van de rivierdijken tijdens het hoogwater van december 1993*. Tech. rep.

UNICEF (2014). *Floods in South East Europe. Humanitarian Situation Report 21 May 2014*. Tech. rep.

USACE (2006). *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System - Draft Final Report of the Interagency Performance Evaluation Task Force*. Tech. rep.

Van den Hengel, D. (2006). “Slachtoffers bij overstromingen”. MSc thesis. Delft University of Technology.

Vergrouwe, R. and J.C. Bossenbroek (2010). *Veiligheid Nederland in kaart (VNK2): Overstromingsrisico Dijkring 38 Bommelerwaard*. Tech. rep.

Waarts, P. H. (1992). *Methoden voor de bepaling van het aantal doden als gevolg van inundatie (TNO-rapport)*. Tech. rep. TNO.

Wade, S et al. (2005). “Risks to people: developing new approaches for flood hazard and vulnerability mapping”. In: *Proceedings of the 40th Defra Flood and Coastal Management Conference (2005)*.

Woodhead, S. (2007). *Evaluation of Inundation Models: Limits and Capabilities of Models.* Tech. rep. FLOODsite.

Zhai, G., T. Fukuzono, and S. Ikeda (Aug. 2006). “An Empirical Model of Fatalities and Injuries due to Floods in Japan”. In: *Journal of the American Water Resources Association* 42(4), pp. 863–875.

List of Figures

List of Tables

List of Terms

Breach zone	The most severe mortality zone in the Dutch approach directly next to the dike breach, with a size of around several hundred meters. The mortality is assumed to be 100% in this zone.
Breach	An opening in the dike due to (local) failure allowing the water to flow into the area causing flooding
Dv-product	The factor water depth multiplied with the factor flow velocity
Economic risk	Concerns cost-benefit analyses for cost-efficiency. Expressed in the expected economic damage in euros per year.
Escape	In this study defined as people trying to move to safe areas outside the endangered area
Evacuation fraction	The part of the inhabitants that can be evacuated before the occurrence of the breach
Evacuation	People moving out of the endangered area to safe areas
Fatalities	The number of persons getting killed as a direct consequence of a flood event
Fleeing	In this study defined as people moving successfully to safe areas outside the endangered area after the occurrence of the breach. This study utilizes flee fractions for this.
Flood exposure characteristics	In this study, the category that describes the situation of the people, the built environment, infrastructure, and other assets, values, or factors related to the endangered area, for example, infrastructure and shelter possibilities
Flood hazard characteristics	In this study, the category that describes the severity of the flood, for example, water depth and flow velocity
Flood risk	The combination of the probability of flooding and the consequences. In the Netherlands, risk is quantified in three risks, namely individual risk, group risk, and economic risk.
Hydrodynamic model	Model to simulate hydrodynamic processes making use of fundamental fluid equations. Utilizing this model, it is possible to simulate a flood scenario including information about the flood characteristics.
Individual risk	Describes the probability of death per year of a person at a location due to flooding. Evacuation is included, but the spatial distribution of the inhabitants is not taken into account.
Inhabitants	The people living in the area. This number is used as the number of people at risk. This means that there is not corrected for evacuation, fleeing, shelter, etc.
Interacter	The core of the software program D-Flow Flexible Mesh is called the 'interacter'. The interacter is used to perform the flood simulations.

Loss of Life	The number of fatalities as the direct consequence of a flood event. Loss of life is calculated by multiplying the mortality with the people left behind.
Model resolution	The size of the grid cells in the model. The smaller the value of the model resolution, the higher the level of detail of the model.
Mortality functions	These functions describe the relationship between flood characteristics and mortality
Mortality rate	The rate of number of deaths and number of affected people
Obstacles	In this study, landscape objects with higher elevations than their surroundings, such as regional dikes, are called obstacles. These obstacles are able to retain water and play therefore an important role in the hydrodynamic model.
People at risk	Number of people present in the endangered area. There is not corrected yet for evacuation, fleeing, shelter, etc.
People exposed	People present in the area at the actual occurrence of the flood event. This means that there is corrected for the people who are evacuated or present in public shelters.
Preventive evacuation	Evacuation to safe areas before the occurrence of the breach
Rapidly rising water zone	The second most severe mortality zone in the Dutch approach characterized by high water level rise rates
Rescue	Persons rescued out of the endangered area during the flood event by professionals or others
Safety standards	Minimum safety level, expressed in the probability of flooding per year, required for the primary flood defences in the Netherlands. These are laid down in the Dutch Water Act.
Shelter	A safe place during the flood event, e.g. high-rise buildings. Persons in public shelters are not taken into account in the number of people exposed.
Social vulnerability characteristics	In this study, the category that describes factors that influence the susceptibility of an individual person (e.g. health condition) or the population as a whole (e.g. timing of the flood)
Societal risk	Relates the probability of exceedance in a year to the number of fatalities with FN-curves
Transition zone	Mortality zone in the Dutch approach that is based on the interpolation of the rapidly rising water zone and the remaining zone
Vertical evacuation	Evacuation to higher areas within the endangered area before or during the flood event
Warning time	In this study defined as the time between the warning and occurrence of the breach. This means that the floodwater is not yet present in the endangered area.
Water arrival time	In this study defined as the time between the occurrence of the breach and the arrival of the floodwater at a location (measured at a water depth of 0.02m)
Water depth	Water level minus the bed level
Water level rise rate	The average time of rising of the flood water between 0.02 and 1.5 meters

Abbreviations

AHN	Actueel Hoogtebestand Nederland (Database for elevations in the Netherlands)
BC Hydro	British Columbia Hydro
CBS	Centraal Bureau voor de Statistiek (Statistics Netherlands)
CRED	Centre for Research on the Epidemiology of Disasters
D-Flow FM	D-Flow Flexible Mesh
DEFRA	Department of Environment, Food, and Rural Affairs
DEM	Digital Elevation Model
EM-DAT	Emergency Events Database
GIS	Geographic Information System
HEC-FIA	Hydrologic Engineering Center - Flood Impact Analysis
HURAM	Human Risk Analysis Model
IPET	Interagency Performance Evaluation Task
LGN	Landelijk Grondgebruik Nederland (Land use in the Netherlands)
LIR	Lokaal Individueel Risico (Individual Risk)
LIWO	Landelijk Informatiesysteem Water en Overstromingen (Information system for water and flooding in the Netherlands)
LSM	Life Safety Model
NAP	Normaal Amsterdams Peil (Amsterdam Ordnance Datum)
PBL	Planbureau van de Leefomgeving (Netherlands Environmental Assessment Agency)
SSM	Schade en Slachtoffer Module (Standard damage and fatality assessment model)
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
VNK	Veiligheid Nederland in Kaart (Project about flood risk in the Netherlands)

Appendices

A

Classification flood fatalities

Jonkman and Kelman (2005) made a division in medical cause, activity, timing, gender, age and lack of judgement. The distribution of the causes of death for the 13 flood events are shown in Figure A.1.

Cause of death and the surrounding circumstances		Total deaths	Total deaths (%)	Aggregates
Drowning	As a pedestrian	62	25.1	All drownings 167 (67.6%)
	In a vehicle	81	32.8	
	From a boat	7	2.8	
	During a rescue attempt	2	0.8	
	In a building	15	6.1	
Physical trauma	In water	0	0	All physical trauma 29 (11.7%)
	As a pedestrian	4	1.6	
	In a vehicle	14	5.7	
	On a boat	2	0.8	
	During a rescue attempt	1	0.4	
	In a building	8	3.2	
Heart attack		14	5.7	
Electrocution		7	2.8	
Carbon monoxide poisoning		2	0.8	
Fire		9	3.6	
Other		3	1.2	
Unknown or not reported		16	6.5	
Total		**247**	**100**	

Figure A.1: Distribution of the causes of death for 13 flood events (Jonkman and Kelman, 2005)

B

Hydraulic roughness

The roughness affects the inundation pattern and the corresponding flood characteristics, such as reducing the flow velocity and increasing the water depth. The hydraulic roughness coefficient represents the resistance that the flood flow experiences across the surface. This appendix presents a brief literature review on roughness.

B.1. Literature on roughness

Many experiments have been done to derive empirical formulae for the roughness coefficients. These formulae are used in many different contexts. Open channel flow often concerns a main (deep) channel with one or two (shallow) floodplains. The roughness coefficient must be determined separately for the main channel and floodplain since the shape, composition and vegetation differ from each other (Arcement and Schneider, 1989). The roughness coefficient in the main channel is mainly determined by the characteristics of the bed (e.g. grain size, bed form). The floodplain is a flat area directly next to the river with the purpose to store water temporarily during (possible) flood events or for conveyance purposes, and additionally to enhance nature. The floodplains are shallow and are generally covered with vegetation, and therefore, are mainly determined by the combination of vegetation and bed forms (Deltares, 2019). For open channel flow, Manning's equation is often applied, derived at normal depth for fully turbulent, steady, uniform flow; the n values of Manning are based on large-scale laboratory experiments and field measurements (Bricker et al., 2015).

Semi-empirical equations, such as Manning, are also applied in hydrodynamic models for flood simulations. The roughness coefficient is often linked to land use classes. For example, urban area with many buildings have a higher roughness coefficient than rural area. Spatially distributed roughness parameters lead to a more accurate stream flow than a uniform value (Ozdemir et al., 2013). This approach is also used in the hydrodynamic model in this study.

The bed shear stress is estimated by a quadratic friction law (Deltares, 2019):

$$\tau_b = \frac{\rho_0 * g * U * |U|}{C^2} \tag{B.1}$$

In which:
τ_b = Bed shear stress [Pa]
ρ_0 = Density [kg/m^3]
g = Gravity [m/s^2]
U = Depth-averaged horizontal velocity [m/s]
C = Roughness coefficient

D-Flow FM supports four roughness coefficients: the White-Colebrook or Nikuradse coefficient [m], the Chézy coefficient [$m^{1/2}/s$], the Manning coefficient [$s/m^{1/3}$], or the z_0 coefficient [m].

The Chézy coefficient is calculated by using the relation v = C*$\sqrt{R*i}$, with C the Chezy coefficient, R the hydraulic radius, and i the bed slope. The roughness coefficent can also be calculated using other formulations, such as Manning and White-Colebrook.

Manning is applied in many river engineering projects since it is suitable for rough turbulent regions (Marriott and Jayaratne, 2010). Manning's formulation, sometimes referred to as Gauckler-Manning-Strickler, is calculated with:

$$C = \frac{\sqrt[6]{R}}{n} \tag{B.2}$$

In which:
C = Roughness coefficient
R = Hydraulic radius (Cross-sectional area divided by the wetted perimeter) [m]
n = Manning coefficient [$s/m^{1/3}$]

The White-Colebrook formula calculates the Chezy coefficient using the equivalent roughness based on Nikuradse:

$$C = 18 * \log(\frac{12 * R}{k_n}) \tag{B.3}$$

In which:
C = Roughness coefficient
R = Hydraulic radius (Cross-sectional area divided by the wetted perimeter) [m]
k_n = Nikuradse roughness length [m]

The White-Colebrook roughness is used following the guidelines for flood simulations of De Bruijn and Slager (2018). Seasonal variability exists as in the summer the land use is different than in the winter (less vegetation). This study uses the winter season because river flooding in the Netherlands is more likely to occur in winter.

B.2. Land use classes and roughness values

The land use classes of LGN6 are shown in Figure B.1. The land use classes are translated into (winter) roughness values. The used conversion table is shown in Table B.1. The table is based on the conversion table of De Bruijn and Slager (2018).

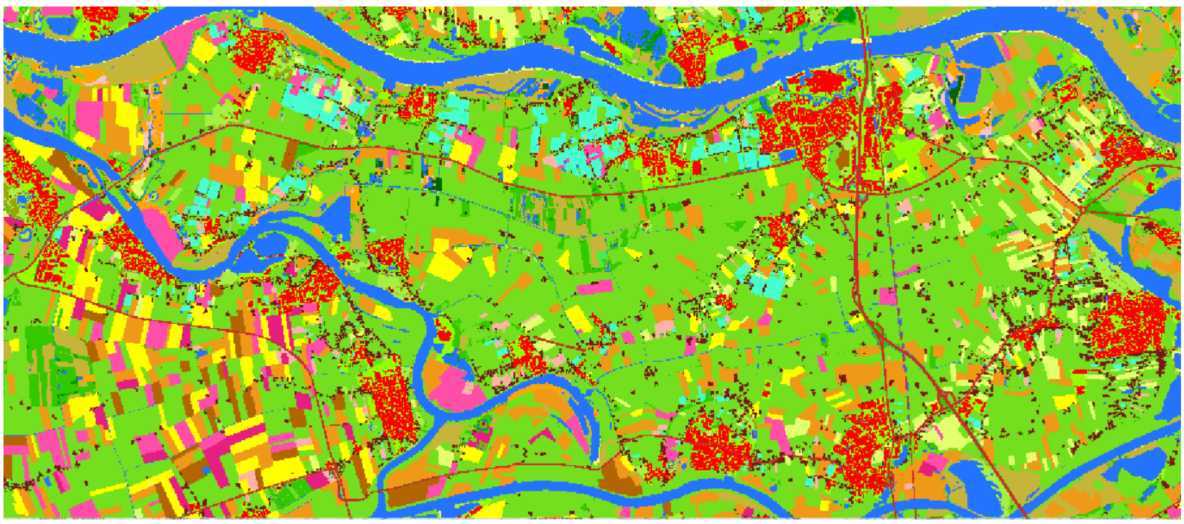


Figure B.1: Land use in the Bommelerwaard, LGN6

Table B.1: Overview of land use classes and corresponding roughness values

LGN6 code	LGN6 description	Roughness value [m] (White-Colebrook)
1	Agricultural grass	0.25
2	Mais	0.40
3	Potatoes	0.40
4	Beet	0.40
5	Grain	0.40
6	Other agricultural crops	0.40
8	Greenhouse horticulture	5.00
9	Groves	5.00
10	Flower bulbs	0.40
11	Deciduous forest	5.00
12	Coniferous forest	5.00
16	Fresh water	0.10
17	Salt water	0.10
18	Buildings in primary built-up area	10.00
19	Buildings in secondary built-up area	10.00
20	Forest in primary built-up area	5.00
22	Forest in secondary built-up area	5.00
23	Grass in primary built-up area	0.25
24	Bare ground in primary built-up area	0.25
25	Main roads and railways	1.00
26	Buildings in outskirts	10.00
28	Grass in secondary built-up area	0.25
39	Raised bog	1.00
40	Forest in raised bog area	5.00
41	Other bog vegetation	1.00
42	Reed vegetation	1.00
43	Forest in marshland	5.00
45	Natural grasslands	1.00
61	Tree nursery	5.00
62	Orchard	1.00

C
Mortality maps from sensitivity analysis

The mortality maps of the sensitivity analysis in Chapter 6 are given in this appendix. Firstly, the sensitivity outcomes of the water level rise rate and water arrival time are shown in Figures C.1, C.2, and C.3.

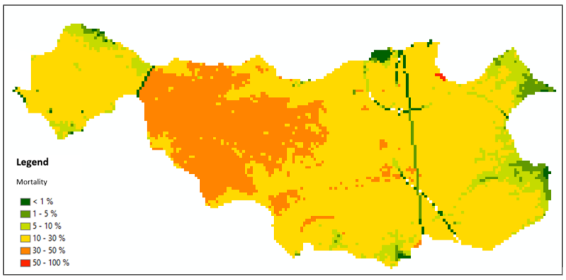
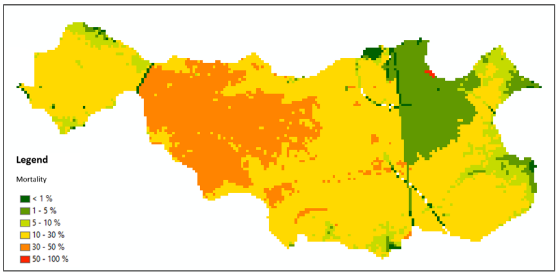
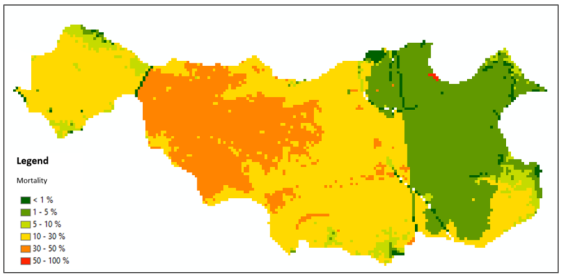


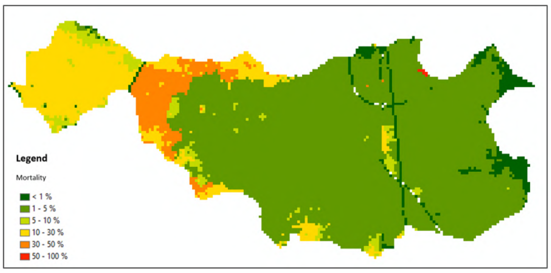
Figure C.1: Water level rise rate left out (sensitivity analysis 1a)



(a) After 6 hours

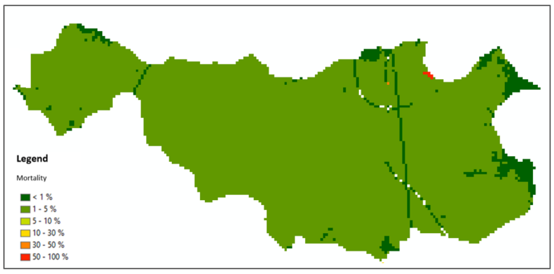


(b) After 12 hours

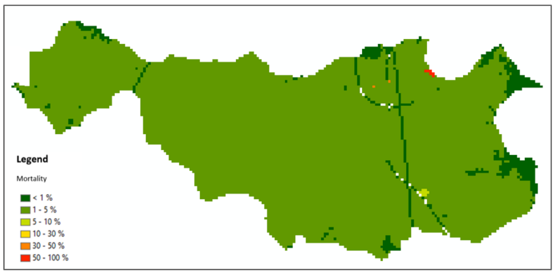


(c) After 24 hours

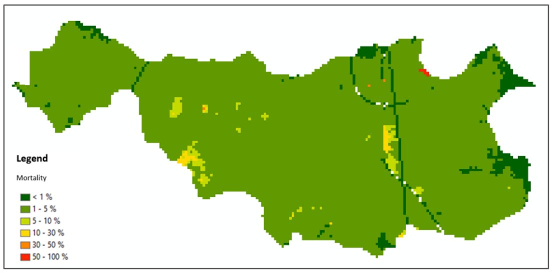
Figure C.2: Water level rise rate left out after a specified water arrival time (sensitivity analysis 1b)



(a) After 6 hours



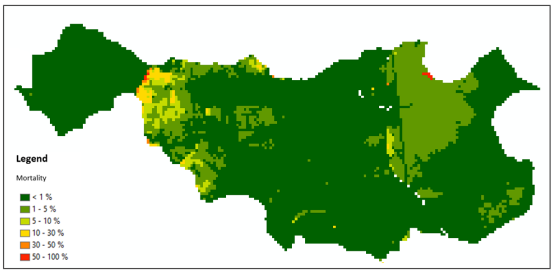
(b) After 12 hours



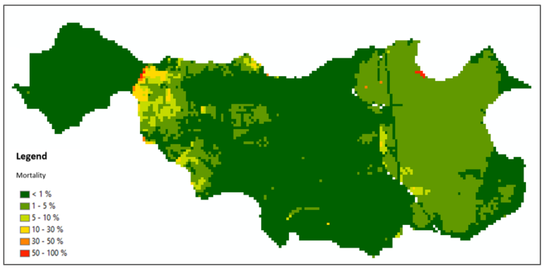
(c) After 24 hours

Figure C.3: Remaining zone applied after a specified water arrival time (sensitivity analysis 1c)

The second sensitivity check concerns the water arrival time. The mortality maps are shown in Figures C.4, C.5, and C.6.



(a) After 6 hours



(b) After 12 hours

Figure C.4: Water arrival time included by preparedness (sensitivity analysis 2a)

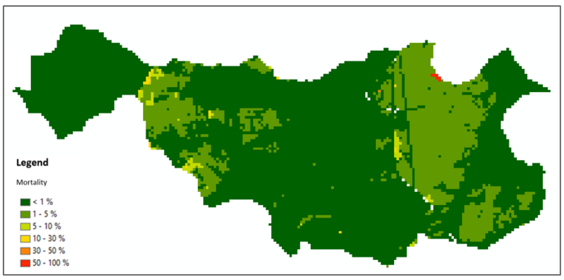


Figure C.5: Water arrival time included by flee fraction based on De Bruijn and Slager (2014), (sensitivity analysis 2b)

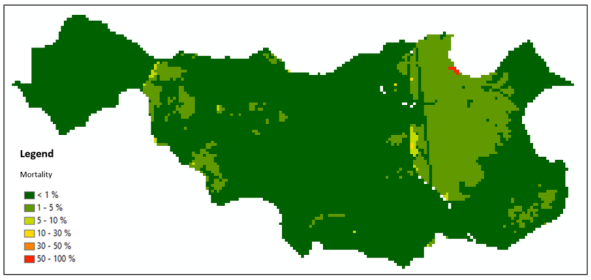


Figure C.6: Water arrival time included by flee fraction, adapted from De Bruijn and Slager (2014) for the Bommelerwaard (sensitivity analysis 2c)

The sensitivity analyses concerning building characteristics are given in Figures C.7 and C.8, followed by the age corrections in Figures C.9, C.10 and C.11.

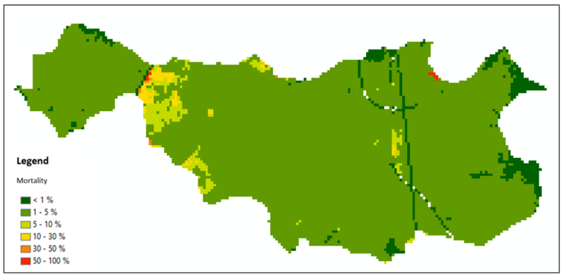


Figure C.7: Improved building characteristics in rapidly rising water zone assuming 50-50 distribution between brick cavity walls and concrete as building materials (sensitivity analysis 3a)

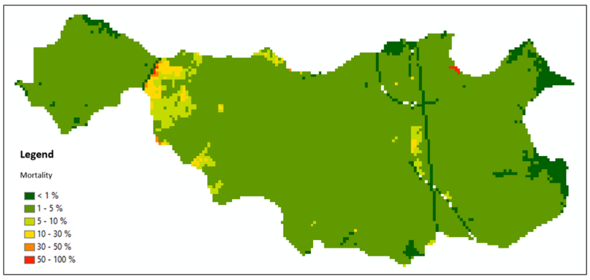


Figure C.8: Improved building characteristics in rapidly rising water zone based on construction year (sensitivity analysis 3b)

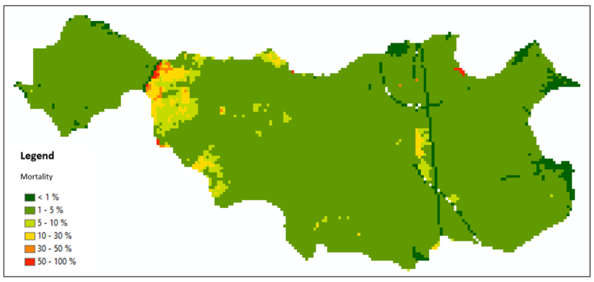


Figure C.9: Increased mortality per neighbourhood due to more people aged over 65 in society since 1953 (sensitivity analysis 4b)

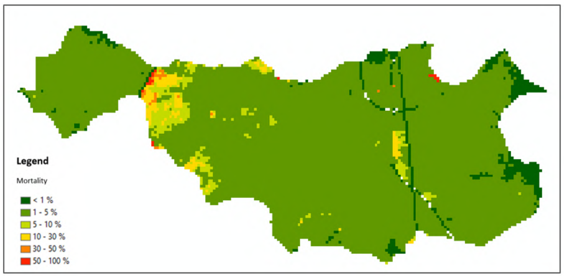


Figure C.10: Increased mortality per neighbourhood per fraction of people aged over 65 (sensitivity analysis 4c)

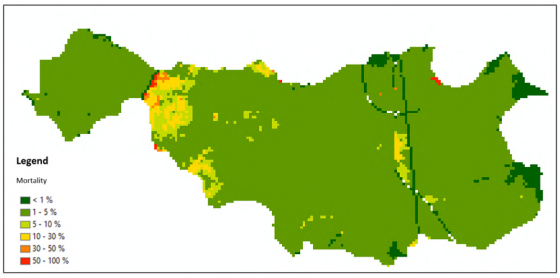


Figure C.11: Increased mortality for people aged over 65 per neighbourhood when no dry floors are available (sensitivity analysis 4d)

D

Individual risk

D.1. Neighbourhoods

Table D.1: Neighbourhoods in 2008 from data of CBS

Municipality	Neighbourhood (code)	Neighbourhood (name)	Inhabitants	Population density [inhabitants/km^2]	Area [ha]
Maasdriel	BU02630000	Kerkdriel	6500	3048	215
Maasdriel	BU02630001	Velddriel	860	1620	53
Maasdriel	BU02630002	Hoenzadriel	160	271	60
Maasdriel	BU02630006	Verspreide huizen Noord Beemden	190	98	198
Maasdriel	BU02630007	Verspreide huizen Kerkdriel, Berm en Hoorzik	500	255	206
Maasdriel	BU02630008	Verspreide huizen Velddriel, Vlierd en Beemden	440	61	723
Maasdriel	BU02630009	Verspreide huizen Maasdijk en Uiterwaarden	260	39	886
Maasdriel	BU02630010	Verspreide huizen Alem	90	19	572
Maasdriel	BU02630100	Ammerzoden	3140	2387	131
Maasdriel	BU02630101	Well	470	1297	36
Maasdriel	BU02630102	Wellseind-Slijkwell	320	426	76
Maasdriel	BU02630108	Verspreide huizen Het Heust	180	47	426
Maasdriel	BU02630109	Verspreide huizen Uilecoten	450	124	376
Maasdriel	BU02630200	Hedel	3230	2180	153
Maasdriel	BU02630208	Verspreide huizen in het bouwgebied	1270	215	656
Maasdriel	BU02630209	Verspreide huizen in de polder Hedel	180	35	506
Maasdriel	BU02630400	Rossum	2110	1866	140
Maasdriel	BU02630401	Hurwenen	640	901	77
Maasdriel	BU02630408	Verspreide huizen Hurwenen en Rossum	550	63	1070
Maasdriel	BU02630409	Overige verspreide huizen	80	38	204
Zaltbommel	BU02970000	Zaltbommel Binnenstad	1800	3974	56
Zaltbommel	BU02970001	Zaltbommel Vergt en omgeving	4480	2731	169
Zaltbommel	BU02970002	Zaltbommel Spellewaard	3800	5750	67
Zaltbommel	BU02970007	Verspreide huizen Hoeven	1460	903	163
Zaltbommel	BU02970008	Verspreide huizen Oostzijde	190	65	348
Zaltbommel	BU02970009	Verspreide huizen Westzijde	120	60	229
Zaltbommel	BU02970100	Brakel	2490	1798	141
Zaltbommel	BU02970101	Poederoijen	630	1725	36
Zaltbommel	BU02970102	Aalst	1610	1671	106
Zaltbommel	BU02970103	Zuilichem	1280	1474	90
Zaltbommel	BU02970104	De Rietschoof	130	599	23
Zaltbommel	BU02970105	Verspreide huizen in de polder Aalst	400	44	998
Zaltbommel	BU02970106	Verspreide huizen in de polder Poederoijen	290	54	589
Zaltbommel	BU02970107	Verspreide huizen in de polder Brakel	340	45	893
Zaltbommel	BU02970108	Verspreide huizen in het Munnikenland	10	2	561
Zaltbommel	BU02970109	Verspreide huizen in de polder Zuilichem en omgeving	230	78	360
Zaltbommel	BU02970200	Kerkwijk	340	795	43
Zaltbommel	BU02970201	Bruchem	1370	1218	112
Zaltbommel	BU02970202	Beneden-Delwijnen	260	736	35
Zaltbommel	BU02970203	Gameren	1900	1119	173
Zaltbommel	BU02970204	Nieuwaal	550	1179	49
Zaltbommel	BU02970207	Verspreide huizen polders Delwijnen en Bruchem	240	29	829
Zaltbommel	BU02970208	Verspreide huizen Kerkwijk en Bruchem	370	54	685
Zaltbommel	BU02970209	Verspreide huizen polders Gameren en Nieuwaal	410	42	1148
Zaltbommel	BU02970300	Nederhemert-Noordzijde	1320	1567	92
Zaltbommel	BU02970309	Verspreide huizen Nederhemert	120	16	889

D.2. Individual risk maps of alternative functions

The individual risk maps of the alternative mortality functions are shown in Figures D.1, D.2, and D.3 respectively.

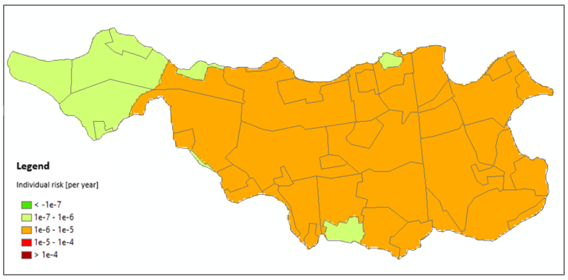


Figure D.1: Individual risk for inclusion of water arrival time using flee fractions. The grey lines represent the neighbourhoods (sensitivity analysis 2b and 2c)

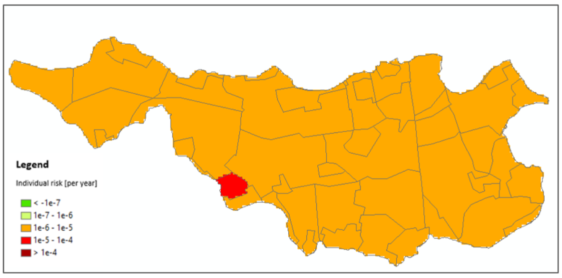


Figure D.2: Individual risk for improved building characteristics. The grey lines represent the neighbourhoods (sensitivity analysis 3a)

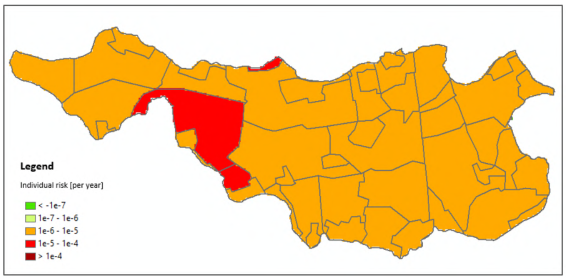


Figure D.3: Individual risk for inclusion of age per neighbourhood. The grey lines represent the neighbourhoods (sensitivity analysis 4c)