SMART COMBINATIONS: AN ALTERNATIVE TO DIKE REINFORCEMENTS?

APPLICABILITY TO REDUCE FLOOD RISK IN THE NETHERLANDS

MSc. Report Civil Engineering & Management
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Preface

Since my childhood I have been fascinated by water systems, it has been the red thread throughout my studies. Starting with projects at high school about the Room for the River project, it continued all the way to opt for the River and Coastal Engineering track of the master Civil Engineering and Management at the University of Twente. To complete this journey, it was only fair to do a thesis project that involves the Dutch flood safety system. With this research project, I have been able to understand the safety standards better, thereby obtaining insights into the strengths and flaws of the determination of the standards.

I would like to express my gratitude to all people that have helped me along the way. First, I would like to thank my colleagues at Royal HaskoningDHV, specifically my supervisors Ric Huting, Marcel van den Berg, and Sam Westerhof. The weekly meetings in which we discussed the progress, exchanged feedback, and planned ahead gave inspiration and motivation to reach the aim of the research. During the time at Royal HaskoningDHV I have also considered fellow intern Oscar Bakker as a colleague, I would like to thank him for the sparring sessions and the company during the travels from Enschede to Amersfoort and back.

Lastly, I would like to thank my UT supervisors Anouk Bomers and Jord Warmink. Their feedback to (draft) reports and questions proved valuable. Always raising new ideas and questions after they answered my questions kept me focussed on the topic and helping to define the scope made sure that the assignment was doable within the timeframe.

Niek Klein Wolterink, July 2022

Summary

The Dutch method to overcome flood risks is highly institutionalized, dikes are reinforced to reduce the flood risks hardly considering other options to prevent or mitigate floods. While other European member states have been able to implement more multi-layered flood safety – thereby improving their flood resilience – the Netherlands does not effectively use these other options. The other options considered in this research are smart combinations, which use a combination of measures from the different layers of the multi-layered flood safety approach, including the prevention of floods (layer 1), spatial planning (layer 2) and emergency response measures (layer 3).

The problem addressed in this research is that the Netherlands focusses mainly on flood prevention, thereby missing the other options such as smart combinations to improve flood resilience. The Netherlands continues to have a strong capacity to resist flooding, compared to absorbing, recovering, transforming, or adapting to flood risks. While previous studies have indicated smart combinations that could be introduced in the Netherlands, it is not yet known where they can be implemented and what the concept of smart combinations can contribute to reducing flood risk. To improve the use of a wider range of flood measures, it is critical to determine whether these smart combinations can be effective, where they can be effective, and how much they can contribute to reducing the risks.

To identify whether and where smart combinations can be effective, the characteristics of safety standard segments that allow for the implementation of smart combinations were found in literature. Segments where either the Vital Infrastructure (VI) is normative or where the Local Individual Risk (LIR) is normative, with a normative neighbourhood that has a significantly higher mortality than the other neighbourhoods (a LIR-hotspot). In total, there are 24 safety standard segments in the Netherlands that meet these criteria – 2 VI-normative segments and 22 LIR-normative segments.

To quantify the effects of the smart combinations of decompartmentalization and improved evacuation practices at a suitable safety standard segment, a conceptual model was set up. Using only a digital elevation model, dike material characteristics, and outer water levels the water depth and rise rate over a dike ring had to be determined. To set up the model, two assumptions were done: the flow velocities were assumed to be zero and each compartment fills up from the lowest points upwards, irrespective of the breach or overflow location.

The breach development over time was calculated with the Verheij-van der Knaap formula, after which inflow formulas were used to calculate the inflow volume into the first compartment. Once the water level in this first compartment exceeds the compartmentalizing dike, overflow to the next compartment is modelled. With the discretized water levels, and the time that it takes to move from one water level to the next, the rise rate could be determined. The results of the model include the maximum water depth maps and rise rate maps, which could be used to calculate the mortality, of which the median mortality per neighbourhood is used in the Local Individual Risk (LIR) calculation.

To calibrate and to validate the model, a case study area was chosen: safety standard segment 27-2 – Tholen en St. Philipsland 2. This segment in the province of Zeeland was chosen based on three quantitative parameters that considered the ratio between length of dike and the hinterland, and the number of casualties. The dike characteristics of the dike at dike ring 27 and the normative outer water levels of the Eastern Scheldt were used to calibrate the model to match safety standard segment 27-2.

The water depths, rise rates and mortality maps that were obtained from the model were comparable to the data found in the database which contains all flood scenarios that were used to determine the norms in the Netherlands – the LIWO. Using the median mortality per neighbourhood, the Local

Individual Risk differed less than 1% from the LIR values used in the norm derivations (16,742 years compared to 16,600 years for the alert value and 8,371 years compared to 8,300 years for the lower limit value). It was concluded that the model could be used to determine the effects of the two smart combinations on the mortality and the Local Individual Risk.

The process of determining the water depths and rise rates with the model and using these results to calculate the (median) mortality and flood risk was repeated for three scenarios – the lowering of the compartmentalizing dike of 1 meter, the lowering of 2 meters and a complete removal of the dike – to determine the effects of various decompartmentalization strategies on mortality and the LIR. Parallel to that, a sensitivity analysis of a variation of evacuation percentages is done, to determine the effects of improved evacuation procedures.

The Local Individual Risk for the different scenarios could be reduced by 5% (compartmentalizing dike one meter lower), 16% (compartmentalizing dike two meters lower) and 26% (removal of compartmentalizing dike) respectively. Combining the decompartmentalization with the improvement of evacuation procedures, the flood risks in the area could be decreased more. The evacuation percentage used in the norm derivation of safety standard segment 27-2 is conservative, estimated to be only 6%. Using the average evacuation percentage for Zeeland – 26% - the lower limit LIR for 27-2 can be reduced by one safety standard class if the measure is combined with decompartmentalizing the dike ring. Each improvement of 10% evacuation percentage results in roughly 10% flood risk reduction. Implementing the second- and third layer measures in other areas will require calculating the effects specific for that area, which can lead to other optimal smart combinations for the specific characteristics of the other areas.

From the analysis, it could be concluded that there are 24 safety standard segments in the Netherlands where the smart combinations can be effective. Decompartmentalization of a part of dike ring 27 resulted in a decrease of flood risks with 26%, which could be improved by addressing the low evacuation percentage as well. The research has shown that – while the optimal implementation will differ for each segment – smart combinations such as decompartmentalization and improving evacuation procedures can effectively be used to reduce flood risk at 24 safety standard segments, as an alternative or addition to the standard procedure of reinforcing dikes.

Glossary

Term	Dutch translation	Definition
Multi-layered flood safety	Meerlaagsveil-igheid	Method to reduce flood risks by using 3 layers of flood prevention and mitigation; layer 1 is the prevention of floods using flood defences, layer 2 uses spatial planning to reduce the impacts of floods, and layer 3 uses emergency responses to reduce the impacts of floods.
Smart combination	Slimme combinatie	A smart combination is a form of multi-layered safety, where spatial planning (layer 2) and/or emergency response (layer 3) completely or partly replace dike reinforcements.
Dike ring	Dijkring	A series of flood defence structures and high grounds that form a ring to protect the enclosed area against floods from the sea, the IJssel Lake, the Marker Lake, or the big rivers.
Safety standard segment	Dijktraject	Part of a dike ring for which separate flood safety standards are defined.
Dike section	Dijkvak	Part of a flood defence structure for which the strengths and loads are considered homogeneous. The exact location of a breach does not affect the flood patterns or the damages that occur.
Hinterland	Dijkringgebied	The area protected by a series of flood defence structures and high grounds against floods from the sea, the IJssel Lake, Marker Lake, or the big rivers.
Compartment	Compartiment	Area in the hinterland that is enclosed by raised line features such as dikes.
Compartmentalizing dike/regional barrier	Compartimen-teringsdijk/re-gionale kering	The raised line features that surround a compartment.
Decompartmentalization	Decompartim-enteren	The removal of a compartmentalizing dike to connect two compartments.
Flood casualties	Doden	People that die of a flood.
Flood victims	Getroffenen	People that are affected by a flood.
Local Individual Risk (LIR)	Lokaal Individueel Risico (LIR)	Flood risk criterion that expresses the yearly probability of a person to die at a specific location due to a flood.
LIR hotspot	LIR hotspot	A safety standard segment where the Local Individual Risk is much higher in the normative neighbourhood than in the other neighbourhoods of the hinterland, thereby increasing the LIR massively at one specific location.
Societal Cost-Benefit Analysis (SCBA)	Maatschappel-ijke Kosten-Baten Analyse (MKBA)	Flood risk criterion that expresses a monetary balance between the economic damages due to a flood and the costs corresponding to reducing the flood risk.

Group Risk (GR)	Groepsrisico	Flood risk criterion that aims to limit the total amount of casualties that can occur due to one flood.
Vital Infrastructure (VI)	Vitale infrastructuur	Flood risk criterion that aims to protect essential infrastructure to Dutch society: electricity, communication, transport (harbours and (rail)roads), gas, drinking water and vulnerable objects.
LIWO	LIWO	The LIWO (Landelijk Informatiesysteem Water en Overstromingen, or National Information system Water and Flooding) is a database that contains all flood scenarios used for the derivation of the Dutch flood safety standards.
Lower limit standard	Ondergrensw-aarde	Annual probability of a safety standard segment for which it marginally meets the dominant flood risk criterion.
Alert standard	Signaalwaarde	The moment in time when flood defence managers should start planning interventions to prevent that the lower limit standard will be exceeded later.
Safety standard class	Normklasse	The lower limit standard and alert standard values are classified in 6 classes.
Test level hydraulic conditions (TL)	Toetspeil	Hydraulic conditions that the primary flood defence system should be able to withstand without breaching according to the old safety standards. For the safety standard segment 27-2 considered in this research: 1/4,000 years.
Test level + 1 decimal height hydraulic conditions (TL + 1D)	Toetspeil + 1 decimeringshoogte	Hydraulic conditions with a 10 times lower probability of occurring compared to the test level hydraulic conditions. For the safety standard segment 27-2 considered in this research: 1:40,000 years.
Maximum scenario	Maximaal scenario	Scenario in which all breach locations breach at the same time, for the test level + 1 decimal height hydraulic conditions (TL + 1D).
Preventive evacuation	Preventieve evacuatie	The relocation of people to shelters or other safe locations before a flood arrives.
Vertical evacuation	Verticale evacuatie	The relocation of people to shelters or other safe locations after a flood has happened and people are stuck at rooftops or other elevated locations.

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1. Introduction

The Dutch flood safety systems are monitored and reinforced to ensure the safety of the hinterland. When it is determined that a safety standard segment does not comply to the norms required by the Dutch Water Act ("Waterwet"), it gets reinforced. Using a combination of models (GIS analyses, statistical analyses) the most suitable dike design is calculated and subsequently constructed. This standard procedure of ensuring the safety of the hinterland only considers the dimensions and materials of the primary flood defence and the river itself. This policy of focussing on flood prevention to reduce flood risk is narrow-minded, including other options to reduce flood risk in the Netherlands can improve the Dutch flood resilience. Therefore, it would be interesting to consider other types of flood-measures in the Dutch flood safety approach.

Instead of dike reinforcements or measures in the river, also measures can be taken in the hinterland. These other options to meet the flood safety standards – called "smart combinations" – were introduced in the Dutch Water Act but are often left unconsidered, while it is possible that these measures such as secondary dikes and improved evacuation procedures are also effective at reducing flood risk, next to or parallel to the reinforcement of dikes.

1.1. Smart combinations

The Deltabeslissing Waterveiligheid allows for smart combinations of measures to be developed for specific areas to meet the required safety standards. A smart combination is a form of multi-layered safety, where spatial planning (layer 2) and/or emergency response (layer 3) completely or partly replace dike reinforcements (layer 1) (Kaufmann, Mees, Liefferink, & Crabbé, 2016), see Figure 1. Van der Most et al. (2017) further defines the 3 layers as:

- Layer 1: measures to prevent floods such as dikes and river widening.
- Layer 2: reducing the impacts of floods using spatial planning.
- Layer 3: reducing the impacts of floods using emergency responses.

It is theorized that by introducing a smart combination in certain areas the flood damage, mortality, and associated flood risk can be decreased. For example, Nannenberg (2020) has shown that two neighbourhoods in Tiel and Rijswijk are both normative for safety standard segments of 50 kilometres, due to the high risk of flooding in those specific neighbourhoods, the entire segments should be reinforced according to the standard procedure. By using the multi-layered safety system at these segments, the flood risk (probability of flooding multiplied with the effect of flooding in casualties or monetary value) at these specific neighbourhoods can be targeted with local measures. This can decrease the flood risk of the safety standard segment without reinforcing the primary flood defence system (Rijkswaterstaat, 2018), as the effects are minimized due to clever decisions in layer 2 and 3.

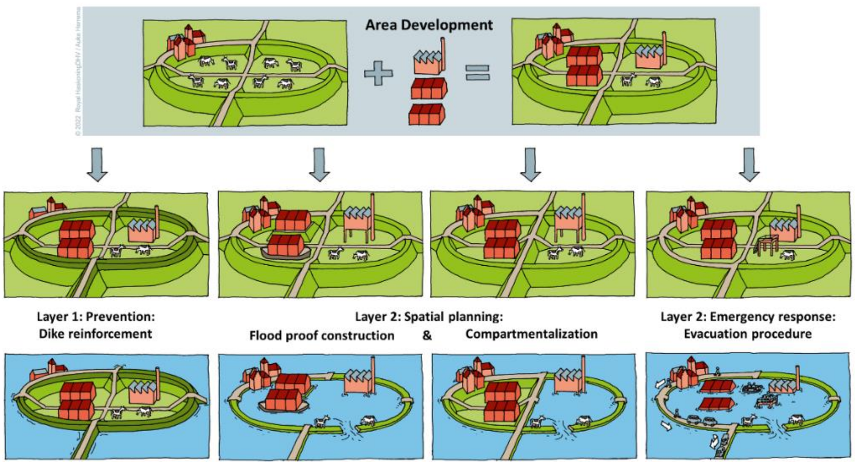

Figure 1 - Concepts of multi-layered flood safety and smart combinations. Image courtesy of Royal HaskoningDHV.

There has been little research and pilots into the possibilities of introducing smart combinations at Dutch safety standard segments. These have included the research by Te Linde et al. (2018) into the policy, legal, and governance aspects and Nannenberg (2020) into two neighbourhoods in dike ring 43, and several pilot studies at specific safety standard segments (Rijkswaterstaat (2018); Van der Most et al. (2017)). The smart combinations that have been proposed for the Netherlands in these studies are listed in Table 1.

Table 1 – Smart combinations discussed in previous studies, with corresponding studies indicated

Second layer smart combinations	Third layer smart combinations
Influencing the flood patterns (compartmentalizing or decompartmentalizing an area) (Asselman, Klijn & van der Most (2008); Nannenberg (2020); Hydrologic (2015))	Improving preventive evacuation (emergency plans, evacuation training, improving flood risk awareness) (te Linde, Streenstra, Kolen & Arts (2018); van der Most, et al. (2017))
Custom building (raising ground level, building on poles, wet and dry proof building, floating building, amphibian housing) (te Linde, Steenstra, Kolen, & Arts, 2018)	Improving planning, informing inhabitants, and giving training (van der Most, et al., 2017)
Constructing infrastructure that supports crisis management (evacuation routes and shelters) (van der Most, et al., 2017)	Development of shelters, increasing road capacity during floods, evacuation planning (te Linde, Steenstra, Kolen & Arts (2018); van der Most, et al. (2017))
Risk zoning, prohibiting building in areas that are at risk of flooding) (Kind, Bak, de Bruijn & van der Doef (2011); van der Most, et al. (2017))	Developing adaptive evacuation strategies (horizontal and vertical evacuation) with corresponding communication strategy (van der Most, et al., 2017)

Compared to other European countries, the implementation of these smart combinations is lacking in the Netherlands. The Dutch continue to have a strong capacity to resist flooding, compared to absorbing, recovering, transforming, or adapting to risks (Hegger, et al., 2016). In response to the large floods that occurred during the decades around the turn of the millennium, the EU Floods Directive was developed, which indicates that European member states should map, manage, and reduce flood risks that are posed in the countries (Raadgever & Hegger, 2018). This risk-based approach requires the member states to identify areas that are at risk of flooding, to create maps with flood extents and levels of risk, and to create flood risk management plans to minimize the risks. While the first requirements in determining risks are fixed, European countries have a lot of freedom to determine the policies and measures to minimize the risks they face (Raadgever & Hegger, 2018).

While the Dutch approach is now highly institutionalized, other countries have come up with all kinds of measures and smart combinations that are used to decrease the risks of flooding, by decreasing the effects that floods can have. A toolbox full of other types of measures – non-structural measures like temporary flood defences, land-use planning, and careful planning of new neighbourhoods – are more common in other parts of Europe.

For a paradigm shift towards more smart combinations in the Netherlands, the knowledge about the potential of these measures in the Dutch context should be improved. To make more effective use of the toolbox of potential measures for the Dutch safety standard segments, the knowledge gap about where and how these smart combinations can be implemented should be filled.

1.2. Problem statement

The problem addressed in this analysis is that the Netherlands focusses mainly on flood prevention, missing other options to improve flood resilience. As stated by Hegger et al. (2016), the Netherlands continues to have a strong capacity to resist flooding, compared to absorbing, recovering, transforming, or adapting to flood risks. Due to that, other opportunities to reduce flood risk are left unconsidered, possibly leading to decreases in flood resilience. While previous studies (see Table 1) have indicated smart combinations that could be introduced in the Netherlands, it is not yet known where they can be implemented and what the concept of smart combinations can contribute to reducing flood risk.

By filling the research gap of where smart combinations can work, and whether they can contribute to reducing flood risk, policy makers can take well-advised decisions on what measures will be taken to reduce flood risk in the Netherlands.

1.3. Research aim

This research aims to identify where and to quantify whether a potential flood risk reduction can be achieved by the implementation of smart combinations.

1.4. Research questions

Several research questions are used to structure the research. First, the safety standard segments that could allow for an effective implementation of smart combinations are determined using research question 1. To determine the quantitative effects of the smart combinations of decompartmentalization and improved evacuation procedures on flood risk, a flooding model is constructed and subsequently used in research questions 2 and 3.

1. Which safety standard segments in the Netherlands allow for flood risk reduction due to the implementation of smart combinations?
2. What conceptual flooding model setup delivers valid flood characteristics for a compartmentalized dike ring, using only a digital elevation model, dike material characteristics, and outer water levels?
3. What effects on flood risk can be achieved by implementing the smart combinations of decompartmentalization and improving evacuation?

1.5. Reader's guide

In chapter 2 a theoretical background of the norm criteria in the Netherlands is given, to provide a clear understanding for decisions that are made later in the analysis. Chapter 3 shows the methods that are used in the research, after which chapter 4 shows the results of the method. A critical discussion of these results is given in chapter 5. A conclusion is drawn in chapter 6, after which chapter 7 will close with several recommendations with further research.

2. Method to determine flood risks and standards

To understand the impacts that measures can have on the flood risks at different safety standard segments and their hinterlands, and to make well-advised decisions on the methods to reduce flood risk, first the current method to determine the flood safety standards of the segments must be understood. Up to and including 2016 the Dutch flood safety standards were defined as exceedance probabilities for dike rings: the probability of exceeding a discharge or water level that happens once in a specified period. For a standard of 1/100 years, the flood defence mechanisms were designed for a discharge that is exceeded once every 100 years. After 2017, the safety standard process changed to a flooding probability for safety standard segments. Each dike ring was split into one or more segments, for which the flooding probability and the corresponding risk is calculated (Huting & van den Berg, 2019). Every safety standard segment in the Netherlands has a standard that should be met, which is comprised of 4 criteria, of which the most stringent will be normative. These 4 criteria are the Local Individual Risk (LIR), the Societal Cost-Benefit Analysis (SCBA), the Group Risk (GR) and Vital Infrastructure (VI).

2.1. Vital Infrastructure and Group Risk

Vital infrastructure is essential infrastructure to the Dutch society: electricity, communication, transport (harbours and (rail)roads), gas, drinking water and vulnerable objects (van der Linden, et al., 2019). Failing of these infrastructures will lead to severe societal disruption and can even lead to hazards in the national security of the Netherlands (NCTV, 2019). Vital infrastructure is crucial for a flooded area, as damages in an area can lead to disruption of areas that are not directly affected by the flood. The indirect damage corresponding to disruption by floods can be multiple magnitudes larger than the direct damage and the vital infrastructure is necessary for disaster relief efforts. According to Van der Linden et al. (2019), vital infrastructures are made robust using location choices, design, and spatial planning. As these vital infrastructures are made robust themselves, they do rarely affect the norms of safety standard segments and are therefore barely used in the derivation of the norms. However, making specific areas robust does correspond to the idea of smart combinations.

A criterion that is of lesser importance for this research is the nation-wide requirement Group Risk. As it is undesirable from a societal perspective that one high discharge event leads to many casualties, this criterion limits the total amount of casualties that can occur with one flood. The FN-curve is a representation of the cumulative probability of the number of casualties shown for different return times. This curve indicates the probability of high numbers of casualties and therewith the societal disruption due to a flood (Huting & van den Berg, 2019). Several hotspot segments that significantly affect the Group Risk are determined in the Netherlands, for these hotspots the norm is increased by one class on top of the criterion that is normative at that segment. These normative criteria are generally the Local Individual Risk (LIR) and/or the Societal Cost-Benefit Analysis (SCBA), which will be elaborated more in depth in the upcoming paragraphs.

2.2. Local Individual Risk and Societal Cost-Benefit Analysis

Most safety standard segments have a standard corresponding to either the Local Individual Risk (LIR) or the Societal Cost-Benefit Analysis (SCBA). To calculate these two criteria, flood simulation models (i.e., Delft-FLS, SOBEK1D2D, D-Hydro, GIS tools) are run to determine the flood patterns in case a breach occurs. For each section of a dike, one representative breach location is chosen. The flood patterns along that section are assumed to be uniform – irrespective of the breach location – to limit the number of computations. Using test level and test level + 1 decimal height hydraulic conditions at the breach location, the temporal and spatial development of the flood over the hinterland is simulated. The output of the flood simulation models are maps with time series of flood data (inundation depth, flow speeds, rise rates and arrival times).

The maps containing flood data are input to a model that calculates the economic damages and the number of people affected – split between casualties and victims (i.e., SSM2017, HIS-SSM, or other GIS tools). Using the maximum inundation depth, maximum flow speeds, and maximum rise rates, the models calculate the corresponding mortality and victim rates over an area. With higher flow speeds and rise rates, more people will be in danger of falling casualty of a flood. Using other maps of road networks, land-uses, businesses, houses and inhabitants, the economic damages corresponding to the simulated flood can be determined (Huting & van den Berg, 2019).

2.2.1. Derivation Local Individual Risk

The mortality is used in the calculation of the Local Individual Risk, which is defined as the yearly probability of a person to die at a specific location due to a flood (Huting & van den Berg, 2019). The standard is split between the lower limit value and the alert value, which are the annual probability of a safety standard segment for which it marginally meets the flood risk criterion (lower limit) and the moment when flood defence managers should start planning interventions to prevent that the lower limit standard will be exceeded later (alert value) (Westerhof, 2019).

The standard according to the LIR ($P_{f,LIR}$) is the product of the maximum allowed Local Individual Risk LIR (= $1/100{,}000$ [yr^{-1}] for the alert value and $5/1{,}000{,}000$ [yr^{-1}] for the lower limit value) as stated by law, the evacuation percentage E [-] and the mortality M [-] (Slootjes & van der Most, 2016), and can be calculated with Equation 1.

$$P_{f,LIR} = \frac{LIR}{(1-E)*M} \tag{1}$$

The mortality is calculated on a grid for test level conditions (TL), with every cell within 100 meters from a body of water removed. To account for the maximum flood scenario, the test level + 1 decimal height hydraulic conditions (TL + 1D) are used to calculate the mortality corresponding to this maximum scenario. In this calculation, the maximum water depths, flow velocities, and rise rates that can occur due to different breach locations for TL + 1D along the dike ring are used to determine the mortality. A predetermined ratio between the flood scenario for test level conditions and test level + 1 decimal height conditions is used to determine the total mortality.

The mortality grid is overlaid with a neighbourhood map of the Netherlands, after which the median mortality value of all grid cells within a neighbourhood is determined to limit the effect of outliers. In some areas of the Netherlands the neighbourhoods can be large, resulting in a partial flood of the neighbourhood. This will affect the LIR value, and hence after the determination of the LIR an extra check is done whether the calculated LIR value is representative for the individual risk and, if needed, the value can be adjusted (Slootjes & van der Most, 2016). The neighbourhood with the highest LIR value is normative for the corresponding segment.

2.2.2. Derivation Societal Cost-Benefit Analysis

While the LIR calculation uses the casualties from the casualties and victims model, the SCBA requires the other two outputs: the economic damages and the victims. The SCBA is the balance between economic damages due to a flood and the costs corresponding to reducing the flood risk. Casualties and victims are monetized and added to the projected total damage in 2050 $D_{w,2050}$ [€]. Together with the investment cost for dike improvement $I(h_{10})$ [€], Equation 2 is used to determine the standard according to the SCBA, also including the ratio between test level conditions and test level + decimal height conditions like the method for the LIR. In similar fashion to the LIR, also a lower limit value and an alert value SCBA are determined.

$$P_{f,SCBA} = \frac{1}{38}\frac{I(h_{10})}{D_{w,2050}} \tag{2}$$

2.3. Safety standard classification

After determining the standards for the LIR ($P_{f,LIR}$) and the SCBA ($P_{f,SCBA}$), the highest of the two will be normative. The highest standard is then classified according to the scheme in Table 2. Any standard within the interval in the first column will be classified into the class in the second column. If the safety standard segment is determined to be a Group Risk hotspot, the corresponding standard can be raised by one class. A flood frequency analysis is used to convert the flood safety standard to a discharge or water level (Bomers, 2020).

Table 2 - Classification of standards into flood safety standard classes (Slootjes & van der Most, 2016)

Standard-interval [yr^{-1}]	Flood safety standard class [1/yr]
0 – 550	1/300
550 – 1,700	1/1,000
1,700 – 5,500	1/3,000
5,500 – 17,500	1/10,000
17,000 – 55,000	1/30,000
55,000 – 170,000	1/100,000

3. Methods

The methods used in this research are introduced in this chapter and are visualized in Figure 2. First the characteristics of the safety standard segments and their hinterland were analysed, to determine which features would allow for the implementation of smart combinations. Based on these characteristics, suitable safety standard segments were chosen. To determine the quantitative effect of smart combinations on flood risk a conceptual flooding model was set up, which was calibrated and validated using a case study area that would allow for the implementation of smart combinations. In research question 3, the effects of decompartmentalizing and improving evacuation procedures on flood risk were determined.

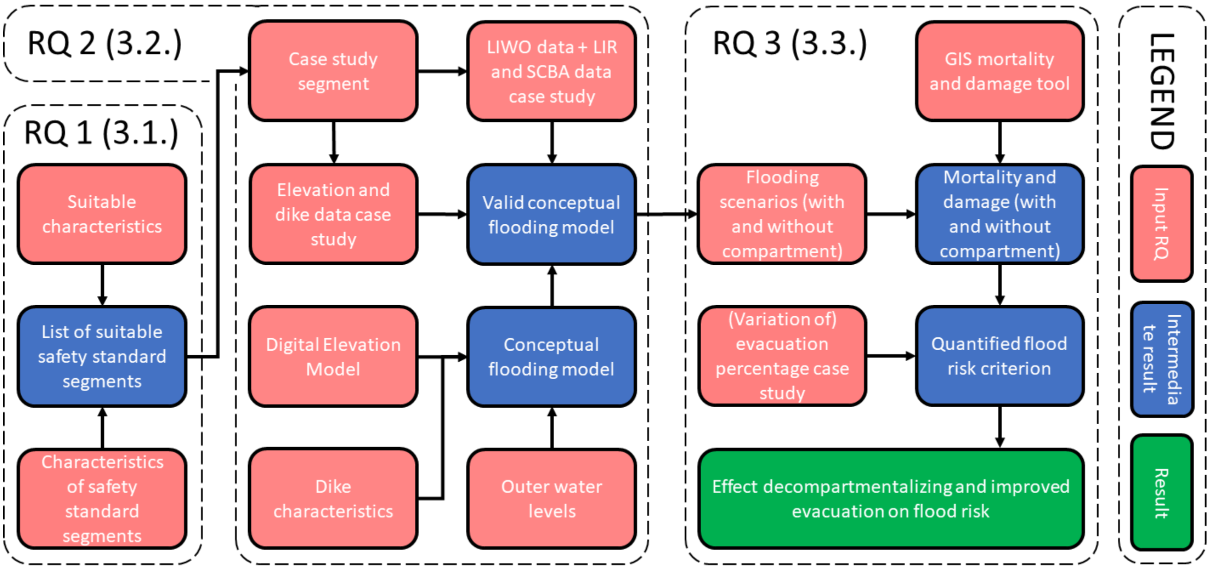

Figure 2 - Methods research. Each box with a dashed outline indicates a research question (RQ), with the corresponding section of the report indicated between brackets (3.#). The inputs and intermediate results are also indicated, see legend on the right.

3.1. Determining suitable safety standard segments for smart combinations

To answer which safety standard segments would allow for the implementation of smart combinations, first the characteristics that will allow for an effective implementation were determined. The characteristics were found based on literature and are discussed in 3.1.1. After that, the method to determine the suitable safety standard segments and the data that was used will be elaborated.

3.1.1. Suitable characteristics safety standard segments

Based on previous studies, the characteristics of safety standard segments that allow for the effective implementation of smart combinations were determined, and these will be discussed in this section. The standard criteria discussed in Chapter 2 allow for different possibilities with smart combinations. The standard criterion that is of lesser importance (Group Risk) was left out of the analysis, as this criterion does not focus on local areas and measures but on a nation-wide requirement on flood risk. Literature indicated that in general smart combinations can be applied in areas that are governed by the Local Individual Risk. According to Te Linde et al. (2018), 58 segments of the Dutch primary flood defence system would be suitable for the introduction of smart combinations, at all these the LIR is normative.

This could be explained with the calculation of the LIR shown in 2.2.1. The calculation of the LIR includes the mortality and the evacuation fraction, which varies spatially. As shown by Westerhof

(2019), the LIR is most sensitive to these two variables. As the neighbourhood with the highest LIR value is normative for the safety standard segment, specific measures aimed at this neighbourhood can significantly affect the flood risk. Irrespective of costs, the LIR can be reduced by limiting the number of casualties and/or increasing the evacuation percentages in these specific areas within the dike ring. This fits in well with the aim of smart combinations. The mortality in a region can be reduced with all layers of the multi-layered flood safety system, and the evacuation fraction is mainly an emergency response, so this can be increased in the third layer.

At segments where the SCBA is normative, smart combinations are less likely to be effective. This is due to multiple reasons, the first one being the costs. Literature showed that in general the introduction of smart combinations in SCBA-normative segments does not lead to the desired reduction of costs, and hence smart combinations will not be desirable from this point of view (Asselman, Klijn, & van der Most (2008); Hydrologic (2015)).

An example is the research into the compartmentalization of Zwolle, a city along the IJssel in the Netherlands, and located within dike ring 53. Within this dike ring, the largest capital cost of a dike breach is in the north, in and around Zwolle. As the SCBA is normative at the different safety standard segments around it, research was done into the option of compartmentalizing the city of Zwolle, such that water could not flow into the city. Hydrologic (2015) has shown that despite a monetary reduction in risks, the reduction in costs of the primary flood defence is negligible, as such the compartmentalization of Zwolle is not cost-effective.

Also, by introducing optimistic cost-estimates of the smart combination of increasing the ground level of entire neighbourhoods, Te Linde et al. (2018) found that in only 3 safety standard segments the costs of raising ground levels were lower than the budget for dike reinforcements, which were all areas with less than 100 inhabitants. Further analysis with more realistic cost-estimates revealed that even in those three cases the raising of ground level in residential areas did not improve the SCBA. The pilots with smart combinations in Marken, the IJssel-Vechtdelta and Dordrecht were also deemed too expensive. In each of the pilots, the LIR and the SCBA led to the same standard class, so both criteria are normative. Hence, for the smart combinations to work, the mortality, evacuation fraction and the budget should all be optimized, which turned out to be unfeasible (Rijkswaterstaat (2018); Hydrologic (2015)).

The SCBA is most sensitive to the damage functions used in the calculation (Westerhof, 2019). Smart combinations do not affect these functions themselves, only some minor parts of the inputs, and will therefore influence the SCBA less. Hence, for this research, the potential of smart combinations at segments where the SCBA is normative would not be considered further.

The fourth standard criterion is the Vital Infrastructure (VI). At segments where the VI is normative, the vital infrastructures – e.g., electricity, drinking water, etc. – the objects that are of importance are made robust themselves. As this way of implementing local measures to protect a certain area or object corresponds to the very idea of smart combinations, segments where the Vital Infrastructure is normative will be suitable for smart combinations, irrespective of any other characteristics the dike ring might possess. Comparatively, the characteristics of the hinterland of segments where the LIR is normative vary a lot and affect the applicability of smart combinations, ranging from marine to fluvial systems. As mentioned in Slootjes & Van der Most (2016) and Te Linde et al. (2018), not all safety standard segments where the LIR is normative therefore allow for the implementation of smart combinations. The characteristics of the flood defence and the hinterland can greatly influence the LIR standard (Nannenberg, 2020) and were therefore deemed to be of importance in the effectiveness of smart combinations.

The local topography at a safety standard segment influences the flood patterns (Vergouwe, 2012). With elevation differences and obstacles blocking the flow, the flood water will be directed towards lower areas and around obstructions. In these lower areas, water will accumulate, leading to larger water depths at these locations. Due to the variation in flow velocities, maximum water depths, rise rates and land-use, the percentage of people affected will differ over the area, leading to variation in LIR values. Neighbourhoods with high LIR values can be seen as LIR-hotspots, which are of importance for this research.

At safety standard segments that have one or more LIR-hotspots, as opposed to an even spread of LIR values over the neighbourhoods, smart combinations can be most effective, as the smart combination can target one specific area. In the calculation of the LIR – explained in Chapter 2 – the mortality values are calculated per neighbourhood. If one neighbourhood has a high LIR value and all the other neighbourhoods along the segment do not, that one neighbourhood – regardless of size or population – will be normative for the entire safety standard segment. By taking a local measure in or around this neighbourhood, the flood risk can be reduced specifically and effectively. Therefore, LIR-normative segments that are dominated by one or more specific locations in their hinterland are more interesting for smart combinations. This matches the conclusions of Slootjes & van der Most (2016), a quickscan by HKV and Asselman et al. (2008) which concluded that smaller areas within a dike ring are easier to protect with local measures than dike rings where the LIR is homogeneous over the whole area.

Asselman et al. (2008) further indicates that the slope of the surface and the current compartmentalization of the area can allow for areas with higher rise rates than others. Line elements such as dikes and elevated (rail)roads can either shelter an area or make for faster rise rates, as the water will be pushed into one compartment. These faster rise rates lead to higher mortality rates, therefore increasing the LIR. Spatial planning measures can be applied in these areas to reduce mortalities. The implementation of spatial planning measures and emergency measures can benefit from the use of current elevation differences. By using existing structures such as land masses and elevated line elements through the landscape, the costs of implementing a new flood safety measure can be reduced (Asselman et al., 2008).

Also, the shape of the dike ring affects the applicability of smart combinations in an area. In elongated areas, compartmentalization can be interesting as the secondary dikes do not have to be long. In less rectangular – i.e., rounder – areas, these measures would be more difficult and expensive to implement. A ratio of length of safety standard segment over area of the corresponding hinterland would indicate how much dike is needed per area of hinterland. Another advantage of this metric is that it shows the necessity of a dike. The more dike is needed for an area, the more interesting a smart combination can be, the option of reinforcing a dike is more expensive with longer stretches of dike.

3.1.2. Determining suitable safety standard segments

The criteria discussed in the previous section could be used to select suitable safety standard segments for smart combinations. First, the segments where the LIR or the VI is normative were selected from the 207 safety standard segments in the Netherlands. After that, for each selected LIR segment it was determined whether a LIR hotspot is present in the hinterland using the LIWO map of the current flood risks in the Netherlands (Rijkswaterstaat, 2022). Segments that have a LIR hotspot were included, segments that do not were excluded from the analysis.

The other criteria – e.g., shape, etc. – do only indicate the degree of suitability of smart combinations and were therefore not used to select suitable segments. These were used to select a case study in Section 3.2.5., but not to determine a list of suitable safety standard segments.

3.2. Setting up and validating model

To quantify the effects of decompartmentalizing and improved evacuation procedures, a conceptual flooding model was set up. This model could be used to calculate water depths and rise rates for compartmentalized dike rings, based solely on a digital elevation model, dike material characteristics, and outer water levels. The output of the model could be used to calculate the mortality and LIR standards for the modelled safety standard segments. The standards in the Netherlands have been determined using different models – e.g., Sobek, Delft-FLS, etc. – that calculate the flooding patterns over an area. To overcome possible unavailability of models and to limit the set-up time and the post-processing time, a conceptual model is set up.

To ensure quick implementations for different areas, the model was constructed solely based on digital elevation maps and outer water levels, used in ArcGIS Pro and Excel. To construct this model, a few assumptions were done and validated, the validity of these assumptions will be elaborated in the results section (4.2.2.). These assumptions are:

- The flow velocities of the flooding water are assumed to be zero.
- The water level in a compartment rises from the bottom upwards, the lowest points will be flooded first. Therefore, the flood does not start at a breach location but at the lowest locations within the first compartment, and flow directions are unaccounted for.

3.2.1. Breach development

The input for the model is the inflow into the first compartment, where the outer water levels and the breach dimensions dictate the volume of water entering the system. The hydraulic boundary conditions were determined using literature, such as the Dutch Ministry of Infrastructure and Water Management (2007) and area-specific literature like Mourik (2011) that describe the theoretical background of hydraulic boundary conditions in a certain area. The width of the dike breach over time was calculated with the Verheij-van der Knaap formula for breach development, see Equation 3 (Verheij, 2003).

$$B(t) = 1.3\frac{\sqrt{g}\,(h_{out} - h_{in})^{1.5}}{u_c}\log\left(1 + \frac{0.04\,g}{u_c}t\right) \qquad (3)$$

In which:

B = breach width (m)
g = gravitational acceleration (9.81 m/s^2)
h_{out} = water level outer side dike (m+NAP)
h_{in} = water level inner side dike (m+NAP)
u_c = critical flow speed (m/s)
t = time (h)

For Equation 3, was assumed that h_{out} and h_{in} are constant, to simplify the calculation. Using the actual water level difference over time would result in unrealistically high values of breach dimensions, previous studies have also assumed constant water levels (e.g. Verheij (2003) and Westerhof (2019)). The value for the critical flow speed u_c is 0.2 for sand-core dikes and 0.5 for clay-core dikes (Verheij, 2003). Note the differences in time dimensions in the equation. To reduce calculation times, but to ensure a relatively continuous output, the timesteps used in the calculation were in minutes: $\Delta t = 1/60$ h.

3.2.2. Inflow from outer body of water

The water level development $h(t)$ and the breach width B were used in Equation 4 to determine the inflow of water through the breach. The parameters and variables in Equation 4 are visualized in Figure 3. As a breach occurs, the top of the primary flood defence has been decreased with the depth of the breach.

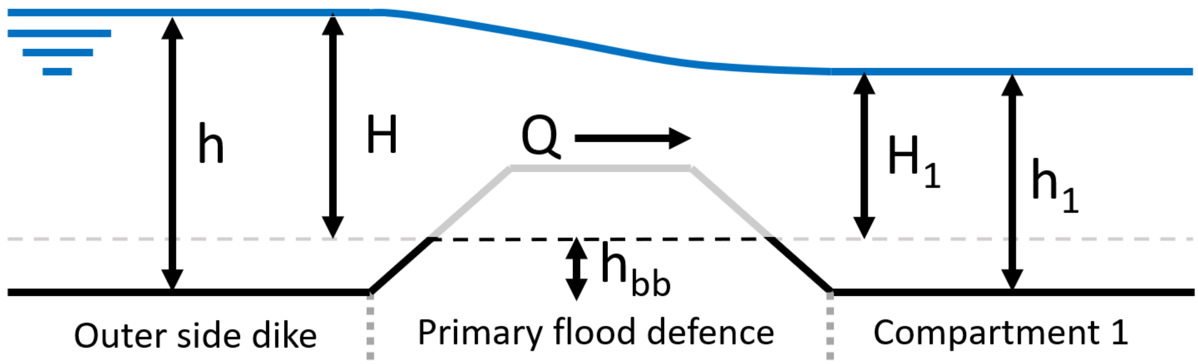

Figure 3 - Parameters Equation 4

With a high-water level in compartment 1 ($H_1 > 2/3\,H$), the head difference is small leading to decreases in flow speeds, and the equation switches from a free flow weir to a submerged weir. In the calculation of whether a free flow or a submerged weir situation occurs, the water level in compartment 1 of the previous time step is used ($h_1(t-1)$).

$$Q(t) = \begin{cases} m\,B\,[h(t) - h_{bb}]\sqrt{2g\,(h(t) - h_{bb})}, & H_1 \leq 2/3\,H \\ m\,B\,[h(t) - h_{bb}]\sqrt{2g\,(h(t) - h_1)}, & H_1 > 2/3\,H \end{cases} \tag{4}$$

In which:

Q = discharge through breach (m^3/s)
m = discharge coefficient (-)
h = water level outer side dike (m+NAP)
H = head above the bottom of the breach outside dike (m)
h_{bb} = bottom level of the breach (m+NAP)
H_1 = head above the bottom of the breach within first compartment (m)
h_1 = water level in compartment 1 (m+NAP)

The discharge coefficient m was obtained from Nortier & van der Velde (1961) and lies between 0.9 and 1.3 (-). Equation 4 puts out a volume per second, to convert this to a volume per minute, the output was multiplied by 60. Taking the cumulative of the equation over time results in the total inflow of water into the dike ring. These volumes flowing into the dike ring first fill up the first compartment, and after that the next compartments. Therefore, the volumes and water levels up to the threshold were determined first. No flow back into the outer water body was modelled, once the discharge wave/high water has passed, the water level does not decrease to initial conditions again. The model was built to find the maximum water level in a compartment and the rise rate, which did not require exact outflow patterns, and these were therefore deemed unnecessary to include. For other applications, this could have been included.

Using the Raster Calculator and Zonal Statistics tools in ArcGIS, a relationship between the volumes and water levels within the area was determined. With the Extract by Mask tool, elevation maps of the different compartments within a dike ring were extracted from the digital elevation map AHN4 DTM 5m (Actueel Hoogtebestand Nederland, version 4). The Raster Calculator was used to calculate the water level at each grid cell with a specified level compared to NAP (with intervals of 10 cm: $\Delta h = 0.1$ m). The intervals of 10 cm were chosen to limit the number of computations, but to ensure a high enough level of detail.

Calculating the sum of all water levels at all grid cells with the Zonal Statistics and multiplying that with 5x5 m^2 – corresponding to the resolution of the digital elevation model – the volume corresponding to a water level was obtained. The relation between volume and water levels was then manually inserted into Excel. The INDEX() and LOOKUP() Excel-functions were used to find the corresponding to the cumulative volume found with Equation 4.

3.2.3. Flow over compartmentalizing dike

Once a certain threshold is reached, a compartmentalizing dike will overflow, leading to flows from a compartment (x) to the next ($x+1$). After the level of the dike is reached, the flow of water over the compartmentalizing dike was calculated with Equation 5. Figure 3 is then reduced to the schematization in Figure 4.

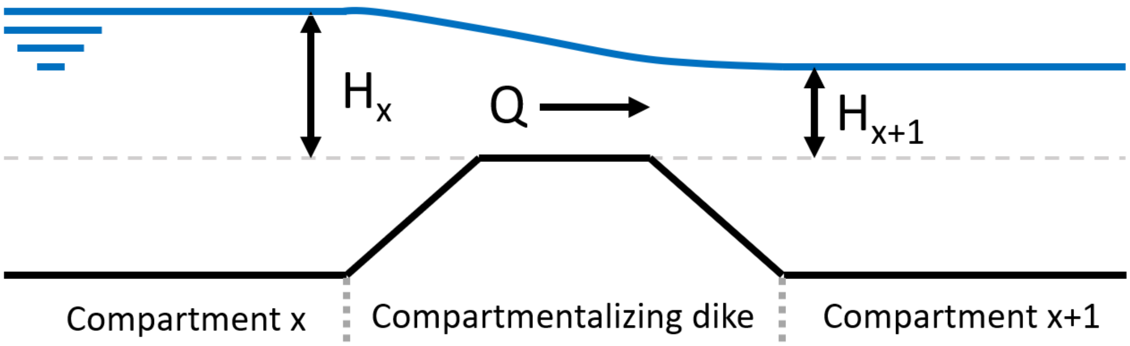

Figure 4 - Parameters Equation 5

With a relatively high-water level in a compartment $H_{x+1} > 2/3\, H_x$, the equation switches from a free flow weir to a submerged weir, like Equation 4.

$$Q_{x+1}(t) = \begin{cases} \frac{2}{3} mL \sqrt{\frac{2}{3} g} H(t)_x^{3/2}, & H_{x+1} \leq 2/3\, H_x \\ mLH_{x+1}\sqrt{2g\big(H_x(t) - H_{x+1}(t)\big)}, & H_{x+1} > 2/3\, H_x \end{cases} \tag{5}$$

In which:
Q_{x+1} = discharge over the compartmentalizing dike to the next compartment (m^3/s)
L = length of compartmentalizing dike that gets overflown (m)
H_x = head above the compartmentalizing dike in a compartment (m)
H_{x+1} = head above the compartmentalizing dike in the next compartment (m)

The elevation level of the compartmentalizing dike does not necessarily have to be equal over the whole stretch of dike. To account for that, an elevation profile along the dike was determined using the Stack Profile tool in ArcGIS was determined. The obtained elevation data was split into several bins, to develop a stacked profile. If the water level in a compartment is higher than the lowest edge of a bin, that bin is representative for the entire stretch of dike and is used in the calculation. The discharge obtained with Equation 3 was then subtracted from the volume of water in the first compartment. If there are multiple compartments after each other, this procedure of overflowing will be repeated.

3.2.4. Rise rate

The rise rates of the water levels in the different compartments are essentially the difference in water levels divided by the time it takes to get to a new water level, see Equation 6. As the model outputs a timeseries of water levels, at intervals of 10 cm ($\Delta h = 0.1$ m), the rise rate of a water level in a compartment could be determined. The multiplication by 60 is added to obtain a rise rate r in meters per hour.

$$r = 60\frac{\Delta h}{\Delta t} = 60\frac{0.1}{\Delta t} = \frac{6}{\Delta t} \quad (6)$$

In which:

r = rise rate (m/h)

Δh = intervals at which water levels and their corresponding volumes are calculated in GIS (m)

Δt = time interval required to get to the next water level (min)

Excel was used to calculate the amount of timesteps t – the number of minutes – that a water level occurs in a compartment. For every water level it was determined how long (Δt) it takes to move to the next water level $h + 1$. Based on this, a rise rate map could be constructed. As the water level difference between the inner and the outer side of the dike decreases over time, the head difference lowers, resulting in decreasing inflow volumes over time. Due to that, the first moment that a grid cell inundates is the moment at which the highest rise rate could be observed. Therefore, there is a relation between the rise rate and the moment a grid cell inundates – or the ground level: a lower ground level compared to NAP at a cell means an earlier moment of inundation. A trendline was drawn in Excel between ground levels (representing the moment inundation occurs) and the rise rates. This relationship was used in ArcGIS to calculate the rise rate map based on the elevation map from the AHN using the Raster Calculator.

3.2.5. Case study area

To validate the model, the model will be calibrated and tested for a case study area that allows for the implementation of smart combinations. Therefore, first a case study area had to be determined from the list of suitable safety standard segments determined with the first research question. Several criteria were set up, for which the safety standard segment that scored a high score on all these parameters was chosen as case study area. First, the shape of the area – which shows the necessity of a dike, as mentioned in Section 3.1.1. – was determined with Equation 7.

$$S = \frac{L_{segment}}{A_{ring}} \quad (7)$$

In which:

S = ratio between length and size of dike ring area (km/ha)

$L_{segment}$ = length safety standard segment (km)

A_{ring} = surface area dike ring (ha)

Next to that, to determine in which areas the most progress can be made with the measures, two other parameters were constructed, which are used to make distinctions between the safety standard segments. The two upcoming parameters do not affect the LIR, it was just used to determine case study areas in which the most progress can be made regarding casualties. The first parameter considered the number of people living within the dike ring, the more people living in the area, the more people can potentially be affected by a flood. Therefore, a metric was introduced of the ratio between the number of casualties due to a flood and the total number of inhabitants within that dike ring area, see Equation 8. This metric indicates the mortality of a flood in a dike ring.

Another complication next to the number of inhabitants of an area is the size of the flood. With smaller breaches the dike ring may flood partially, rendering the total number of people and the size of the dike ring of lesser importance. To overcome these limitations of the ratio between inhabitants and casualties, another parameter was introduced: the number of casualties per victim of a flood, which can be calculated with Equation 9. This metric specifically addresses the inhabitants that are affected by the flood, people from areas that are not flooded within the hinterland are excluded from this metric. A higher ratio indicates that the flood possesses characteristics that are more deadly, thereby increasing the effect of a flood measure.

$$M = \frac{C}{I} \tag{8}$$

$$R = \frac{C}{V} \tag{9}$$

In which:
M = ratio between the number of casualties and the total number of inhabitants (-)
C = number of casualties due to a flood (people, retrieved from van der Doef et al. (2014))
I = number of inhabitants of the dike ring (people, retrieved from van der Doef et al. (2014))
R = ratio of casualties per victim of a flood (-)
V = number of victims due to a flood (people, retrieved from van der Doef et al. (2014))

The parameters were calculated for all safety standard segments that were determined to be suitable, see the segments that have the highest scores on all three parameters in Appendix 2. The safety standard segment that scores high on all three aspects is segment 27-2 – Tholen en St. Philipsland 2, which location is shown in Figure 5.

Figure 5 - Location safety standard segment 27-2 – Tholen en St. Philipsland 2

The normative neighbourhood in safety standard segment 27-2 is Scherpenisse (BU07160200, shown in Figure 7), which has a high LIR value if a breach occurs at the breach location shown in Figure 6. As can be seen in the figure, the elevation in the area has some clear higher elevated lines running across the area, which are regional barriers or old sea dikes that are now inland.

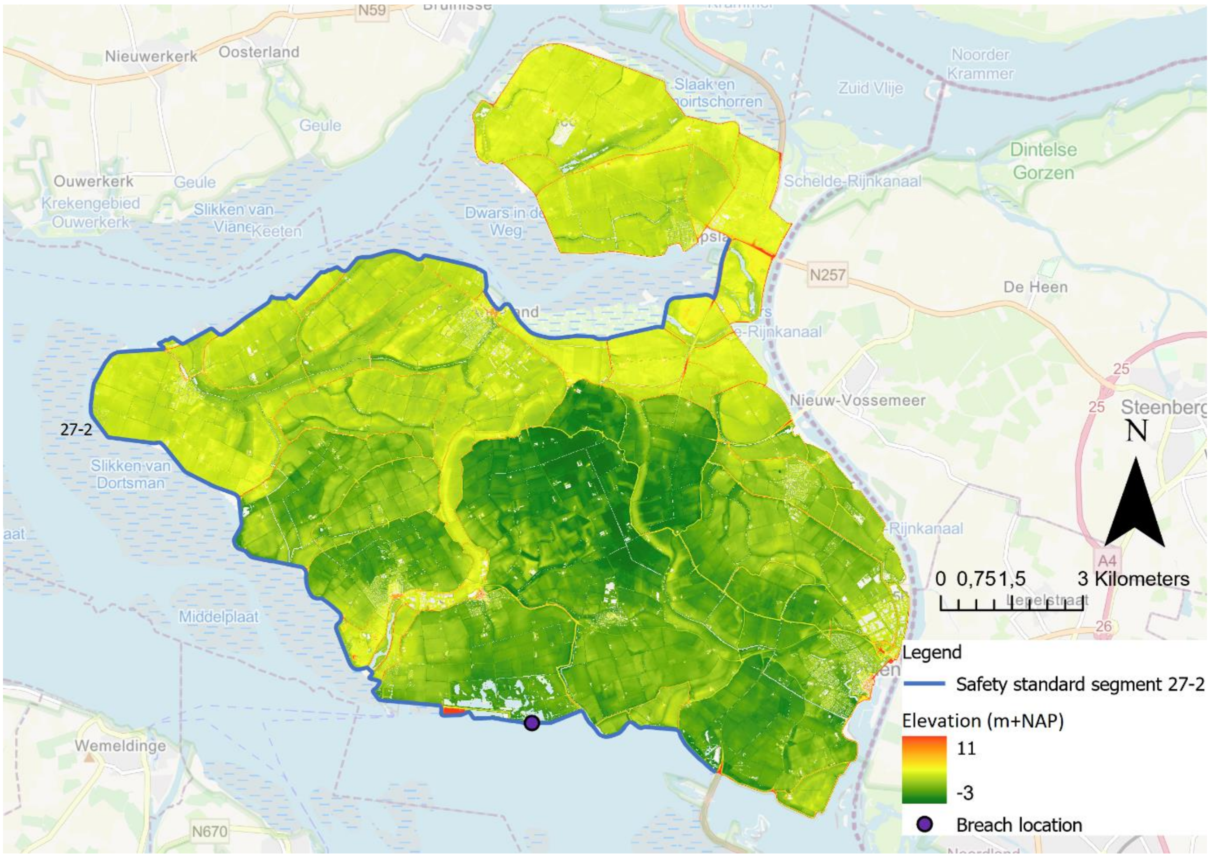

Figure 6 - Elevation map dike ring 27, safety standard segment 27-2 and the corresponding normative breach location

The two compartments that get filled up due to a breach at the breach location are highlighted in Figure 7. These two compartments were modelled in the conceptual model, as this breach location does not lead to flow to other compartments than these two. The inflow at the breach location leads to large water depths and rise rates due to the regional barrier indicated in purple in Figure 7 and shown in Figure 8.

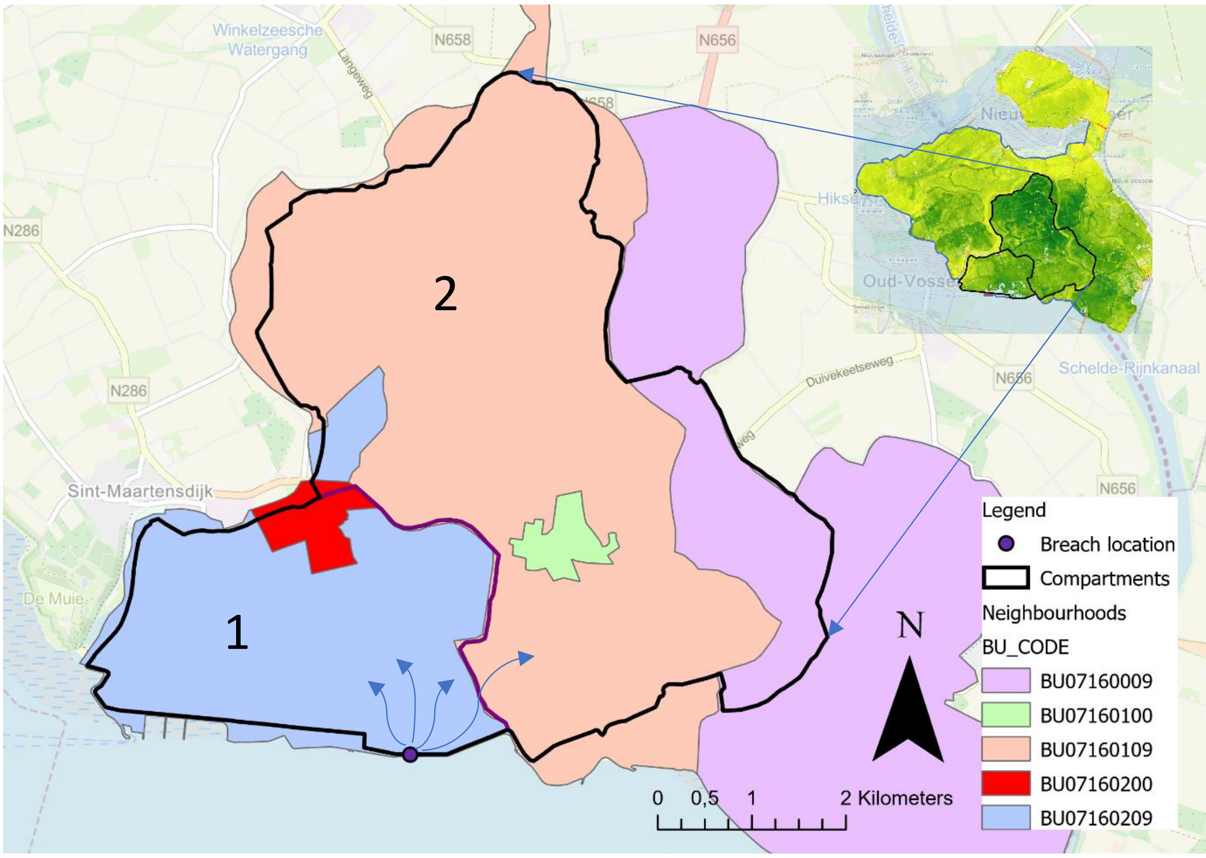

Figure 7 - Study area within dike ring 27, indicating the first and second compartment and the neighbourhoods that will be considered. BU07160200 is the normative neighbourhood for a flood at the breach location

The presence of this dike separates the area that gets flooded in two, see compartment 1 and 2 in Figure 7. The first compartment fills up quickly, while the second one only starts to fill up after the water level in compartment 1 reaches the level of the compartmentalizing dike. The first compartment is relatively small in surface area, which leads to high rise rates, and a corresponding high mortality and Local Individual Risk.

Figure 8 – Compartmentalizing dike, with compartment 1 on the right side, and compartment 2 on the left side. Location photograph shown in Appendix 3.

3.2.6. Calibration model to match the case study area

First, the hydraulic boundary conditions at the breach location. The Eastern Scheldt has several characteristics that affect the hydraulic boundary conditions that should be used: the tidal influence is much larger than any fluvial effects that might occur and the Eastern Scheldt Barrier can be closed during storm conditions to regulate the water levels (Dutch Ministry of Infrastructure and Water Management, 2007).

For the stability of the vegetation cover a closed Eastern Scheldt Barrier is assumed, while for the other failure mechanisms such as a dike breach the barrier is assumed to be open (Dutch Ministry of Infrastructure and Water Management, 2007). According to Mourik (2011), the sinusoidal hydraulic conditions of the storms superimposed on the tidal range can be represented by a trapezoid, with test level 3.8 m+NAP, low level 0 m+NAP, and the cap 10 centimetres below test level (Dutch Ministry of Infrastructure and Water Management, 2007). The modelled hydraulic TL conditions are shown in blue in Figure 9, where the hydraulic conditions observed during a storm are given in orange.

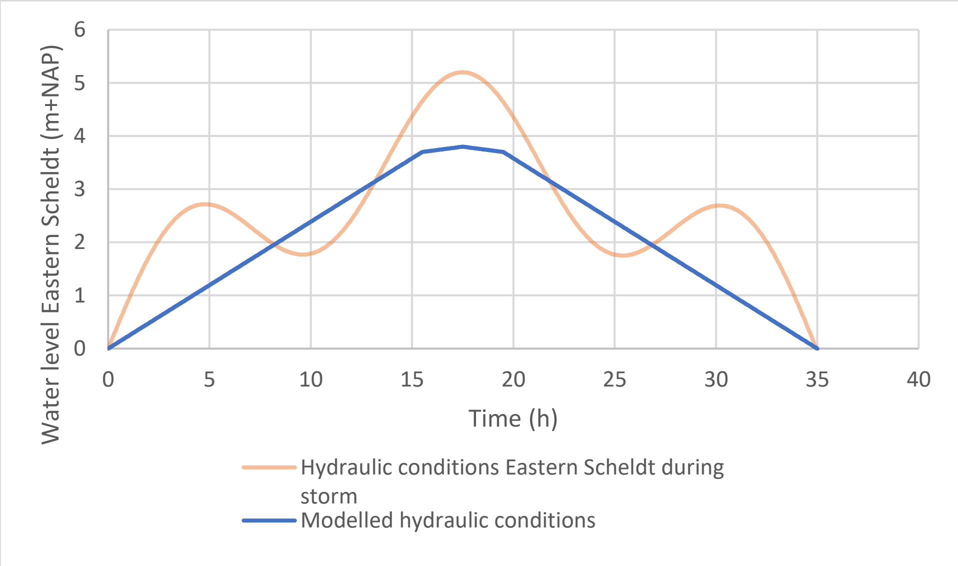

Figure 9 - Hydraulic conditions Eastern Scheldt during storm

It cannot be expected that the dike segment breaches during low water, so for the model it was assumed that the moment of breaching is at 2 m+NAP, or after 8 hours. At this moment of breaching, the initial breach is assumed to be 10 meters wide. After that, the breach width increases according to the Verheij-van der Knaap formula in Equation 3. The critical flow speed u_c is 0.2 m s^{-1} for the sandy dikes along the Eastern Scheldt and for the level difference $h_{out} - h_{in}$ a value of 1.5 m was used, as this was also used in the model used for the LIWO data. This led to the breach development over time that is shown in Figure 10, which uses the breach moment at 8 hours, so moment 0 h in Figure 10 matches with 8 h in Figure 9.

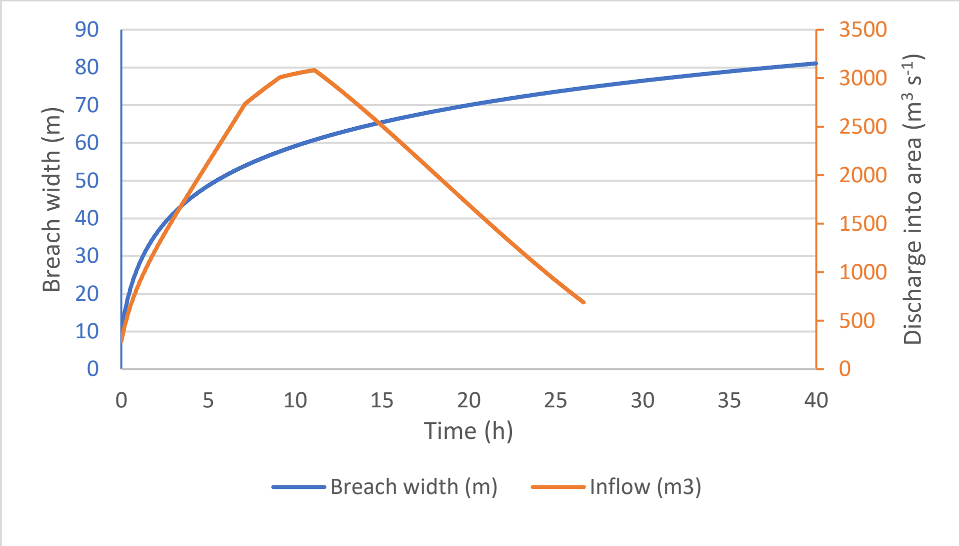

Figure 10 - Boundary conditions model

To determine the discharge into the first compartment, the hydraulic conditions and breach width over time are used, together with the discharge coefficient m that is equal to 0.9 according to Nortier and Van der Velde (1961) and the bottom level of the breach h_{bb} which is -1.75 m according to the LIWO (2022). The resulting discharge into dike ring area 27 is given in orange in Figure 10. The trapezoidal shape of the hydraulic conditions in Figure 9 is also apparent in Figure 10. After the high-water conditions have passed, the inflow into the area stops.

During the initial stages of the flood, the first compartment will fill up, up to the level of the compartmentalizing dike. To determine the level of overflow, an elevation profile along the compartmentalizing dike has been drawn with AHN4 DTM, shown in Figure 11. Starting at the northern tip towards the sea dike at 4.5 km, the dike increases towards to the level of the sea dike at 4.5 km.

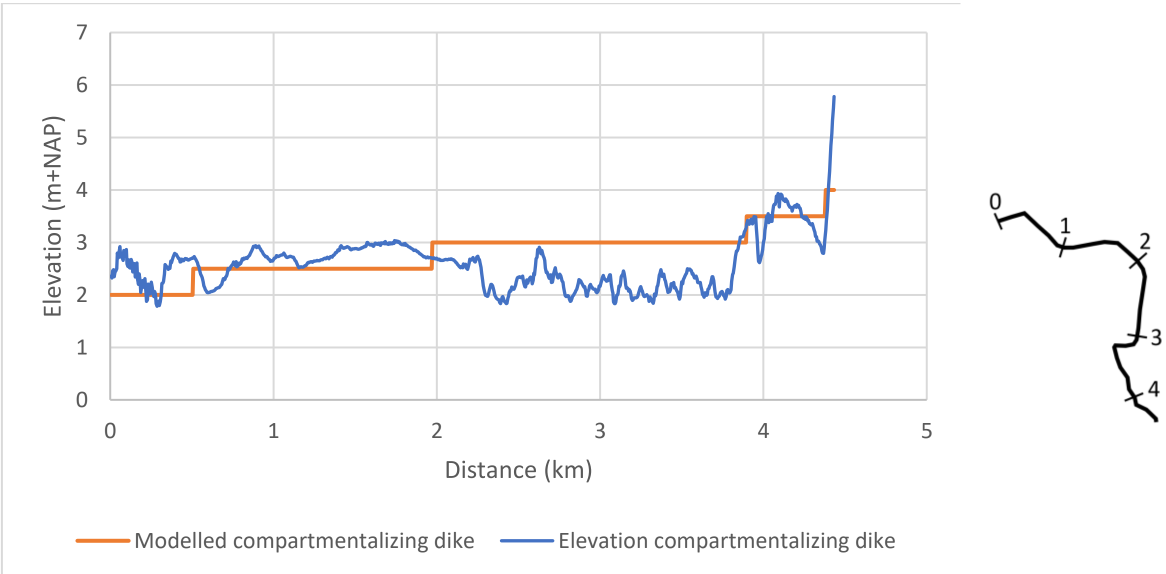

Figure 11 - Elevation profile and modelled elevation profile compartmentalizing dike (compartmentalizing dike and distance shown on the right)

Based on Figure 11 it is estimated that the lowest point of overflow is approximately 2 m+NAP, with a width of 500 meters in total. If the water level in the compartment exceeds 2 meters above NAP, the overflow formulas will be applied, and water will flow into the second compartment. It is assumed that the compartmentalizing dike does not breach. The modelled elevation profile is indicated in orange in Figure 11.

3.2.7. Determining flood risk using the model results

Once the water depths and rise rates were determined with the model, the regular standard derivation could be applied to determine the LIR and/or SCBA. As Section 3.1.1. has indicated that only segments where the LIR is normative are suitable for smart combinations, only the LIR was calculated in this analysis. A tool in ArcGIS that is based on the damage and casualty formulas from HIS SSM (Rijkswaterstaat, 2004) could be used to determine the mortality per grid cell. Using the water depth map, the rise rate map and the flow velocity map that equals zero, the mortality over the area could be calculated for test level conditions (TL). This mortality accounts for a percentage of the final mortality, as the maximum scenario (TL + 1D) accounts for a certain percentage as well (60% TL and 40% TL + 1D for safety standard segment 27-2). After that, the grid cells within 100 meters of a body of water are excluded from the analysis. Using the combined mortality maps and the Zonal Statistics As Table tool in ArcGIS Pro, the median mortality per neighbourhood was determined.

This median mortality per neighbourhood was used as input for the LIR calculation in Excel. As shown in Chapter 2, the LIR calculation includes the evacuation percentage as well, where the evacuation percentage given in the factsheets could be used (Slootjes & Wagenaar, 2016). The calculated value for $P_{f,LIR}$ was then used to calculate the standard.

3.2.8. Model validation

To ensure that the model that is set up was valid – whether it could be stated that there is a large certainty that the model was able to deliver the intended results – a validity check was done. The intended results of the model considered are the correct water depths and rise rates, which are used to calculate the median mortality per neighbourhood and the corresponding Local Individual Risk. Therefore, three aspects were validated, first the assumptions mentioned in the first paragraph of Section 3.2. The first assumption on whether the flow velocities could be assumed to be zero is validated using the data from the LIWO. The mortality of the case study area was determined twice, once using all three inputs: water depth, rise rate, and flow velocities, and once using only water depth and rise rate, thereby assuming that the flow velocity is zero. With a small difference in mortality between the two compositions of inputs, the assumption would be considered valid. To validate the second assumption on the rise of water bottom up, the flood patterns over time between LIWO and the model are compared.

Secondly, the results of the model were compared to the LIWO data. The obtained water depth map and rise rate map of the model were compared to the maps found in the LIWO. Thirdly, it was validated whether the results of the model could be used to calculate the mortality, and to determine whether these values correspond to the flood risk standards found in the official Dutch standard derivations. The mortality corresponding to the LIWO data and corresponding to the model was calculated using a GIS tool and was compared. After that, the median mortality of the model results and the corresponding LIR was determined and compared to the standard criteria in Slootjes & Wagenaar (2016), see Table 3.

Table 3 - Alert and lower limit standards official standard derivation

	Alert standard (1/yr)	Lower limit standard (1/yr)
LIR according to Slootjes & Wagenaar (2016)	16,600	8,300

3.3. Determining effects smart combinations

With a validated model, the effects of the smart combinations of decompartmentalization and improved evacuation procedures could be determined.

3.3.1. Effects decompartmentalization

To determine whether the decompartmentalization of an area allows for reductions of flood risk, the decompartmentalized area was modelled as well. There are multiple ways in which an area can be decompartmentalized: removal of the compartmentalizing dike, lowering the crest level at a specific location to the level of the hinterland, and lowering the whole dike with a certain height. As flow speeds and directions are assumed to be zero in the model, the removal of the dike or the lowering of the crest level at a specific location will render equal results, these two situations will be modelled as one large compartment. Lowering the dike is another situation, this still includes multiple compartments, but the moment of overflow towards a next compartment changes. The threshold after which overflow occurs will be lowered to model the effects of lowering the compartmentalizing dike.

The calculation of the mortality and LIR values for the lowering of the dike were equal to the original situation, only the threshold for overflow over the compartmentalizing dike was adjusted. The situation in which the dike is removed or cut through was modelled as one large compartment, the area got modelled as if there is no separating line element in between the two original compartments. The hydraulic boundary conditions and the breach development are equal for both new situations, as they are independent of the conditions in the compartment(s) over time. The accompanying inflow $Q(t)$ however differs, as the water level in a compartment affects the amount of inflow.

The model was run with the new configurations of compartmentalizing dikes, resulting in water depth maps and rise rate maps. With the water depths and rise rates, the LIR was calculated, and could be compared to the current situation, to determine whether a lowering of the mortality and standards was possible.

3.3.2. Effects improved evacuation procedures

For the improved evacuation procedures, the theoretically possible reduction of flood risk was determined. At safety standard segment 27-2, the evacuation percentage has been determined to be 6% (van der Doef, van Buren, Wagenaar, & Slootjes, 2014). This conservative estimation of preventive evacuation is due to the short warning times before a flood arrives at the case study area. According to Slootjes & Wagenaar (2016), dike ring 27 is estimated to have lower evacuation percentages due to the Eastern Scheldt barrier as the normative hydraulic conditions in the Eastern Scheldt only happen in case of an emergency close of the barrier, which cannot be predicted. In fluvial systems, the discharge wave can be predicted well in advance of its arrival, due to observations upstream. However, at the marine system of the Eastern Scheldt, this is much more difficult. Storms at the North Sea are highly unpredictable in speed and directions, and for a flood to occur, the tide should also be high. However, the 6% used in the standard determination is more conservative than other estimations found in literature.

The effect of the less conservative evacuation percentage on the flood risk was quantified first. This was done for two scenarios: once for the current situation and once for the decompartmentalized situation. The mortality values from the current situation and the decompartmentalized situation were used, combined with an evacuation percentage of 26% for the evacuation percentage. These were input for Equation 1 to calculate the lower limit and the alert value LIR standards.

After that, the theoretical potential flood risk reduction was determined. A sensitivity analysis of the LIR standards to the evacuation percentage (from 6% to 96%) was done to see the effect of improved evacuation procedures on the LIR criterion.

Figure 12 – Evacuation route from Tholen to Bergen op Zoom via the N286, location photograph shown in Appendix 3

4. Results

The results of the research questions are elaborated in this chapter.

4.1. Suitable safety standard segments

Several criteria for the effectiveness of smart combinations have been put forward in the method. The first one is that safety standard segments where either the LIR or the VI is normative are most suitable for smart combinations. From the LIR normative segments, only segments are included where a LIR hotspot occurs. Appendix 1 indicates whether a LIR hotspot occurs per LIR-normative segment, Figure 13 only includes the segments that contain a hotspot.

The segments where the VI is normative are 6-7 Friesland-Groningen – Groningen 3 that protects the gas installations in Groningen and 30-4 Zuid-Beveland West 4 that protects the nuclear power station in Borssele, both are indicated in red in Figure 13. All safety standard segments highlighted in Figure 13 are suitable for smart combinations.

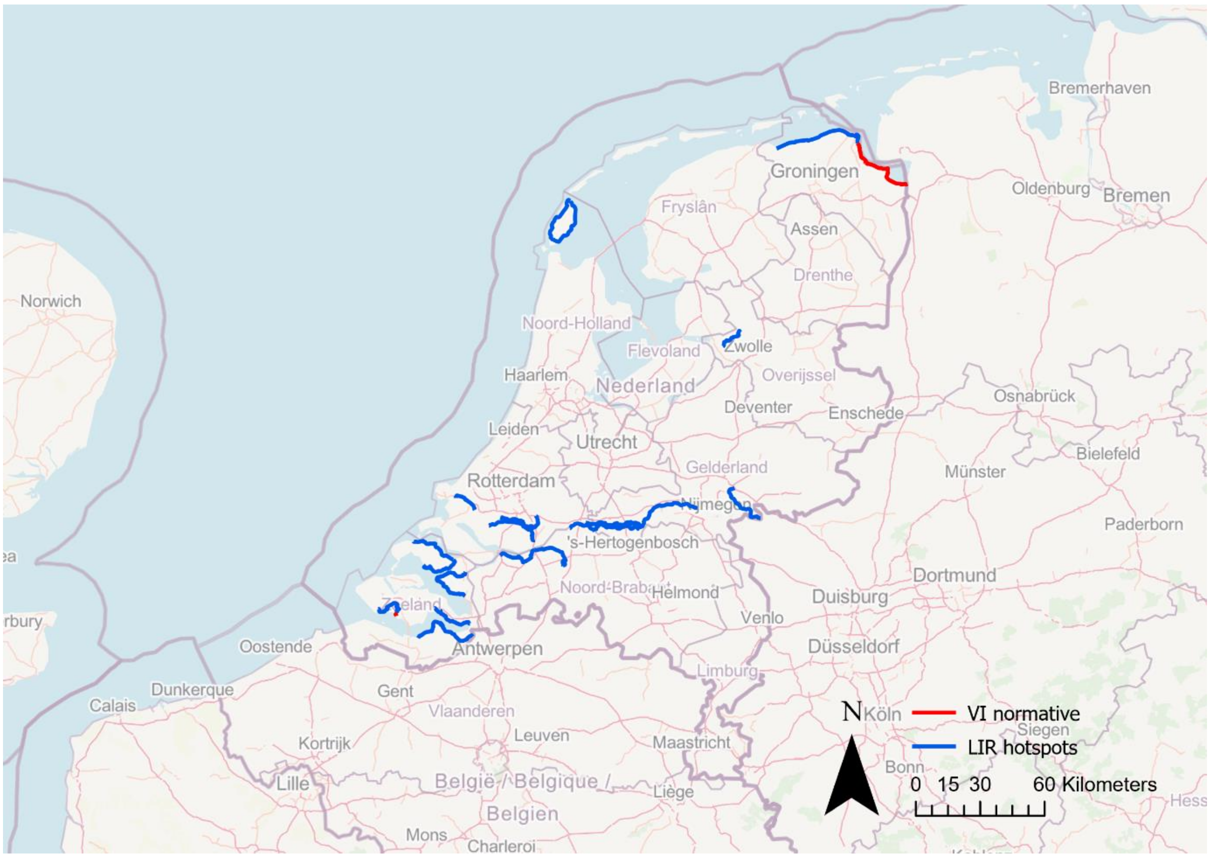

Figure 13 – Safety standard segments suitable for smart combinations. The segments are listed in Appendix 1.

4.2. Model results and validation

In this section, the results of the calibrated model based on safety standard segment 27-2 will be shown, after which the validity of the model is discussed.

4.2.1. Model results

With the model that is set up, the water levels over time were calculated. The breach at the first compartment resulted in water levels in compartments 1 and 2 over time, as shown in Figure 14.

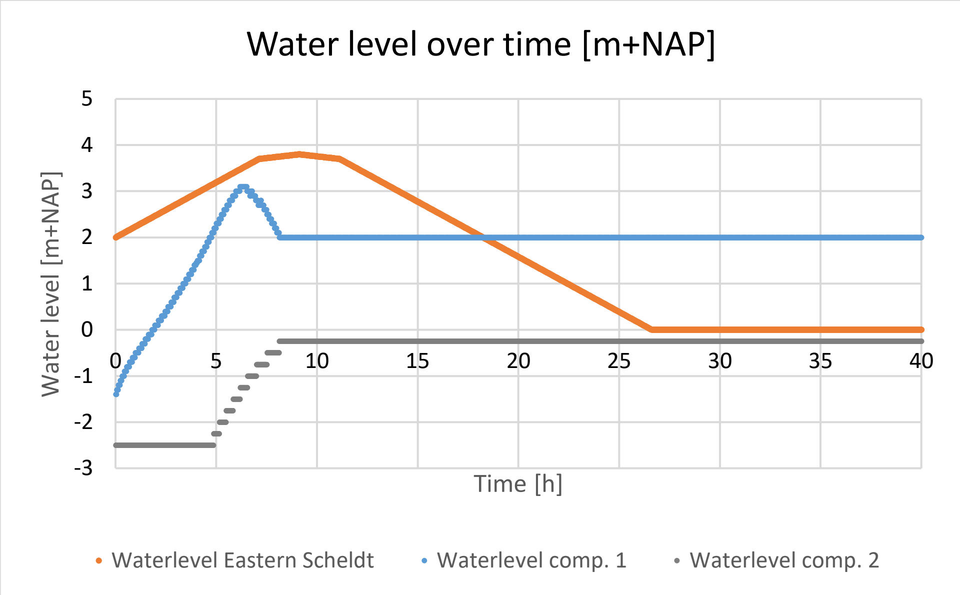

Figure 14 - Water levels over time in the Eastern Scheldt, in the first compartment and in the second compartment

During the first period after the exceedance of the elevation level of the compartmentalizing dike, the inflow into the first compartment is still larger than the outflow towards the second compartment, hence there is an overshoot over the threshold of 2 meters. After that, the water level decreases as the outflow increases, eventually leading to a constant water level of 2 meters in the first compartment and corresponding constant water level in compartment 2. The maximum water levels at a location are of importance to the mortality, therefore the maximum water level per compartment was used from Figure 14. As mentioned in 3.2.2., the water level does not decrease once the boundary condition is lower than the water level in the first compartment, as it was deemed unnecessary for the aim of this model.

For the calculation of the mortality and LIR, the rise rates over the area were determined as well. With the calculation of the difference in water level divided by the number of timesteps a water level occurs, the rise rate could be determined with Equation 4. As explained in the method, there is a relation between the ground level and the rise rate, which is shown in Figure 15.

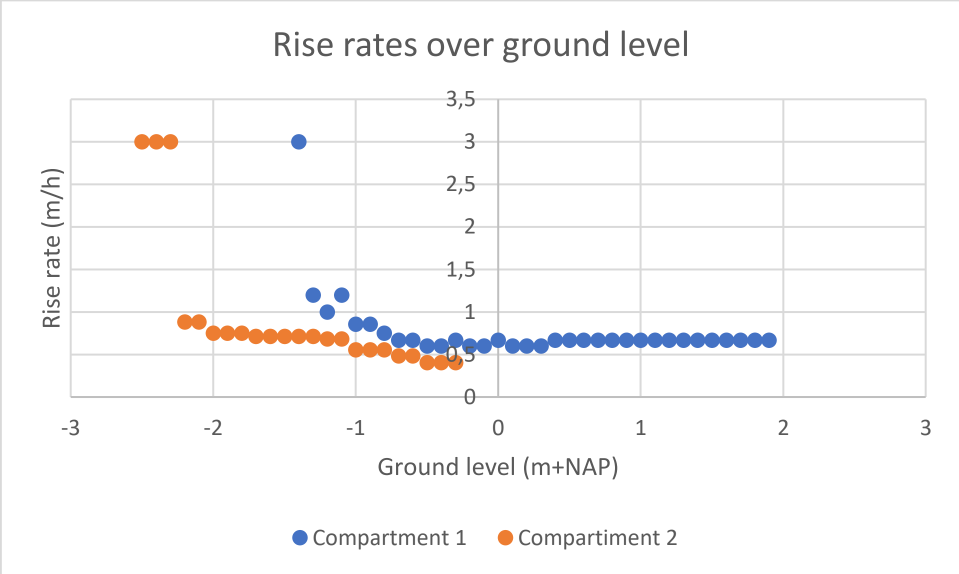

Figure 15 - Rise rates over ground levels in the different compartments

Using a trendline fitted through the datapoints in Figure 15, a relation between the AHN4 DTM map and the rise rate could be calculated using the Raster Calculator tool in ArcGIS Pro. The maximum water levels and the rise rates over the area are given in Figure 16 and Figure 17.

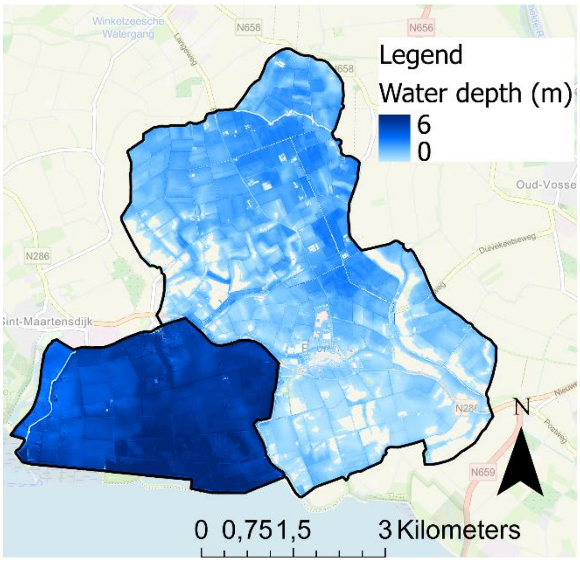

Figure 16 - Water depth (m)

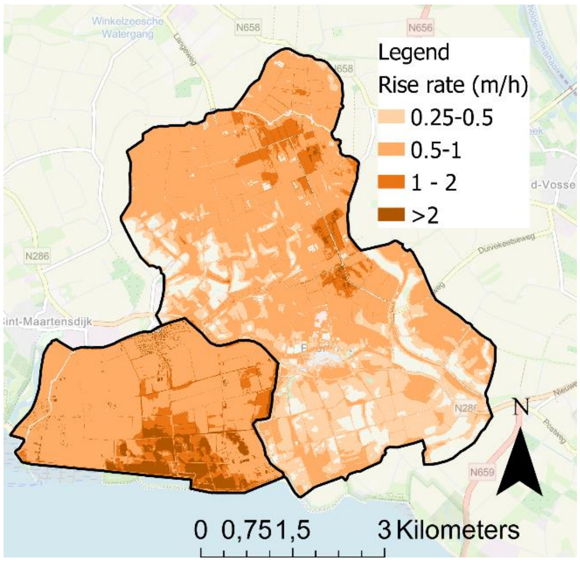

Figure 17 - Rise rate (m/h)

The two maps shown were input for the mortality calculation, which led to a mortality map. Combining the mortality map for test level conditions with the mortality map of the TL + 1D hydraulic conditions and deleting the grid cells within 100 meters of a body of water, the total mortality map was obtained, which is shown in Figure 18. The redder an area, the higher the percentage of people that will die in case of a flood if they are at that specific location.

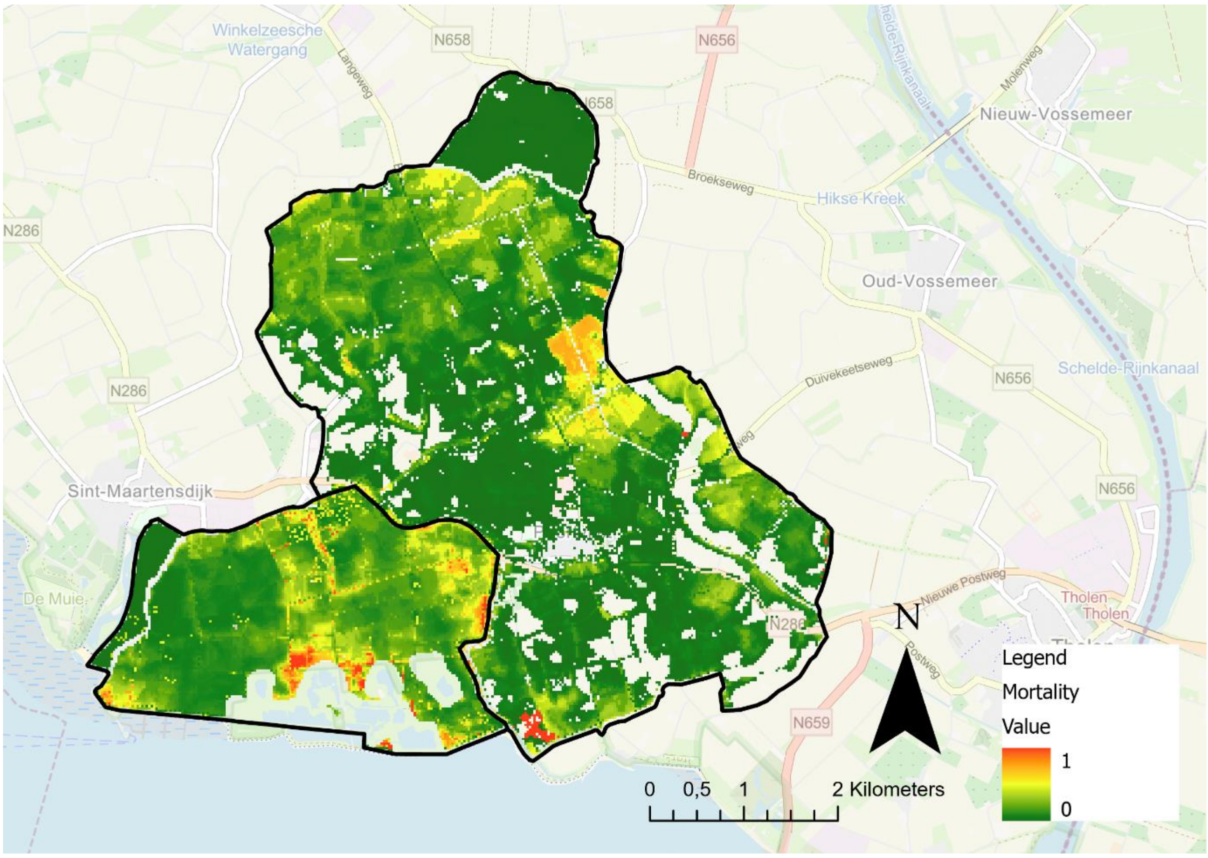

Figure 18 - Mortality (-)

4.2.2. Model validation

In this section, the validity of the model – and its results – will be checked. First, the check whether the assumptions to construct the model were valid, after that the model results will be discussed. The two assumptions mentioned in the method are given below.

- The flow velocities of the flooding water are assumed to be zero.
- The water level in a compartment rises from the bottom upwards, the lowest points will be flooded first. Therefore, the flood does not start at a breach location but at the lowest locations within the first compartment, and flow directions are unaccounted for.

To test the effects of no flow speeds in the model, the flooding data from the LIWO was used. The water depth, rise rate, and flow speeds corresponding to the normative breach location of safety standard segment 27-2 were obtained. These three were input for the mortality tool in ArcGIS Pro. The GIS tool was run twice: once with all three inputs and once with only the water depth and the rise rate in the area, assuming that the flow speed is zero. The difference in mortality is shown in Figure 19.

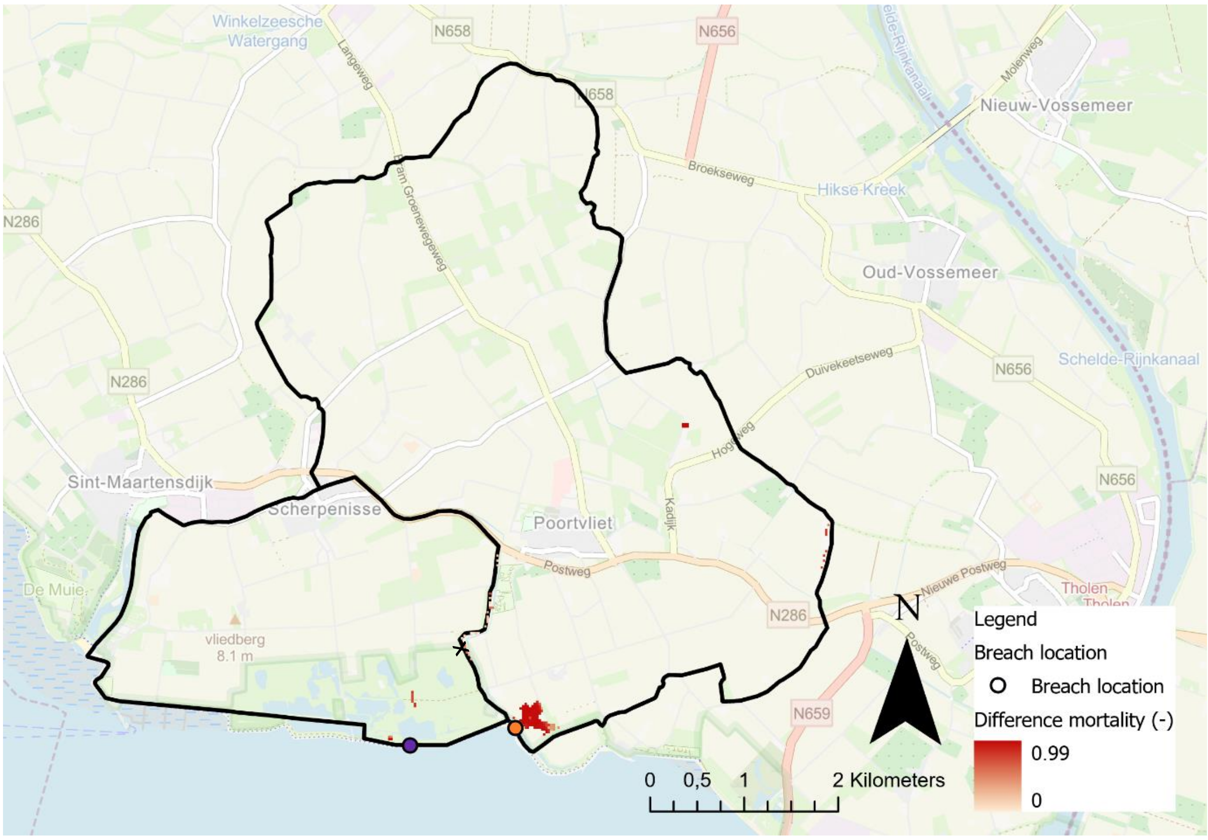

Figure 19 – Absolute difference mortality with and without using flow velocities (based on LIWO data). The purple breach location is the normative breach location, the orange breach location is only considered in the maximum scenario. The x indicates a small waterway through a culvert that is usually closed.

The only slight differences are visible at locations where the different breaches are modelled (TL and TL + 1D effects) and at locations where overflow takes place. The area with the highest difference in mortality – in the south of the second compartment – is due to the inclusion of the maximum scenario, which also includes other breaches – see the orange breach location. At that location, another breach in the primary flood defence is modelled for the maximum scenario. The normative breach (at the purple dot in Figure 19) that is considered is located within 100 meters from a body of water and is therefore excluded from the mortality and LIR calculation, hence there are no effects of the flow velocities visible there.

These very small deviations led to a maximum difference of 1% median mortality for a neighbourhood (BU07160109), which is not even the normative neighbourhood at this safety standard segment. The normative neighbourhood (Scherpenisse) even had no change in the median mortality. Therefore, it is concluded that the assumption of flow speeds of zero is valid.

The second assumption about the rise of water from the bottom upwards – neglecting the exact breach location and flood patterns – can also affect the results. Especially in the second compartment, the areas lowest compared to NAP are on the opposite side of the compartment compared to the overflow location. It is physically not possible that water ends up at these lowest locations, without first flowing through the higher elevated areas. The water will accumulate in the lowest areas, but not originate there. So, the first timesteps of a compartment filling up will not resemble reality. After a few timesteps, when there is a compartment-wide flood coverage, the calculation will more closely resemble the current – compartmentalized – situation. Therefore, it is concluded that the assumption does not affect the maximum water levels in a compartment, only the rise rate of the lowest areas increases a little. This is however at grid cell-spatial scales (5x5m), so it will not affect the median mortalities of a neighbourhood.

Now, the water depth map and rise rate map of the model will be compared to the data from the LIWO. The water level progression over time in Figure 14 seems to match the arrival times shown in the LIWO data. The water level in the first compartment increases to one meter above the lowest points of the compartmentalizing dike, up to 3.2 meters above NAP. This seems like a rather high value, but it matches the water level of 3 m+NAP found in the LIWO and therefore fits the purpose of remodelling the results in the LIWO well. The water level in the second compartment seems logical according to this analysis. However, the water depths found in the LIWO data are much higher in the second compartment (a difference of 1.59 m on average). This is due to the boundary condition used in this model, the inflow is not only dependent on the outer water levels, but also on the water level in the compartment. In the LIWO, the inner water levels are not considered and the storm duration is longer, this will be elaborated in Section 5.3.1. The other input for the mortality calculation is the rise rate through the area. This rate map matches with the rise rate shown in the LIWO as well.

Both water depth- and rise rate maps are used in the calculation of the mortality. The normative neighbourhood resulted in the same median mortality, but as can be seen in Figure 20, mainly in the second compartment there is an average decrease in mortality (-0.8% difference on average). This is due to the lower water depth that was determined for this area compared to the data in the LIWO. As the average difference over the whole neighbourhood is 0.8%, and the median difference is even smaller, it is determined that the model is still suitable for calculating the mortality before and after decompartmentalizing the area.

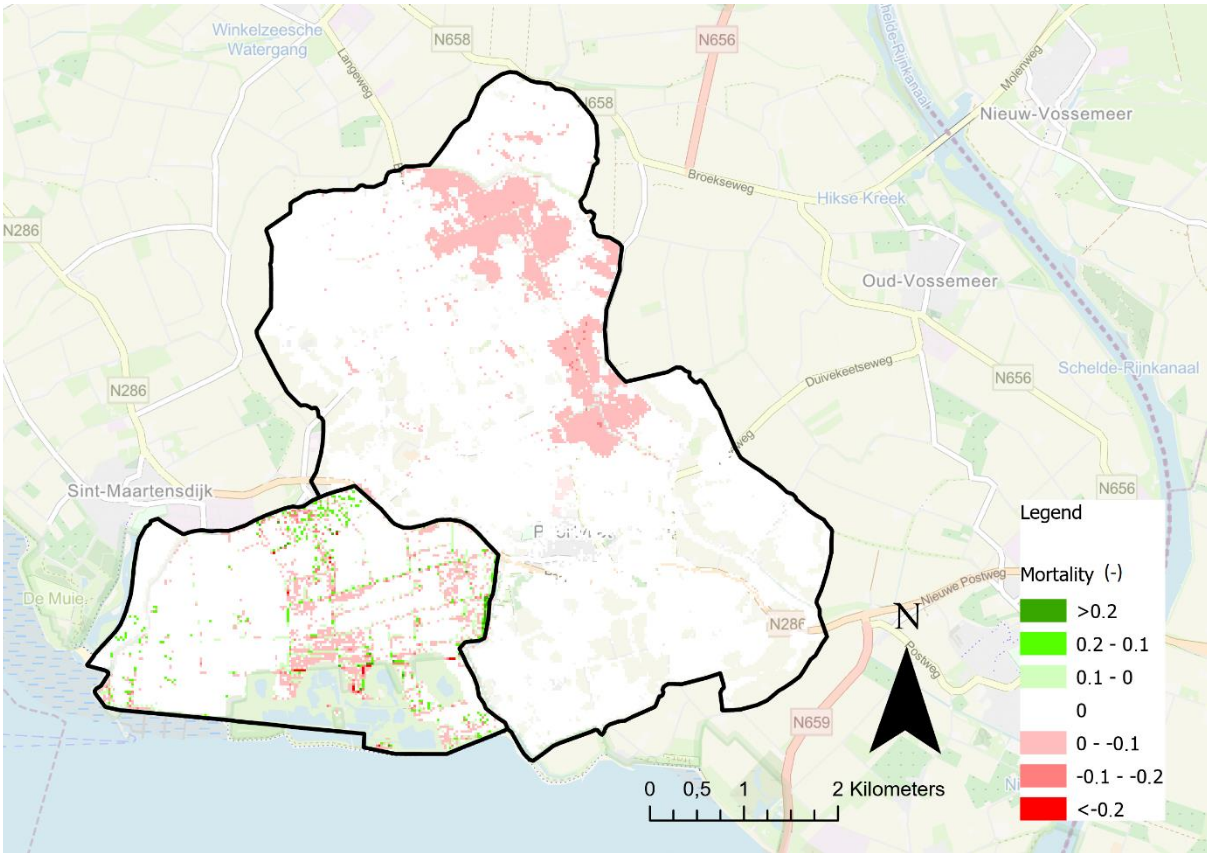

Figure 20 - Difference LIWO mortality and model mortality (L-M: LIWO minus Model) (positive means model mortality is larger, negative means LIWO has a larger mortality)

The median mortality per neighbourhood that intersects the area is calculated using the Zonal Statistics tool in ArcGIS and is compared to the LIR standards in literature. Using the highest median mortality and the expected evacuation percentage of 6% obtained from Slootjes & Wagenaar (2016) and Ons Water (2022), Equation 1 was used to find the Local Individual Risk, that could be compared to the data used in the standard derivations in Dutch law.

Table 4 - Alert and lower limit standards model and official standard derivation

	Alert standard (1/yr)	Lower limit standard (1/yr)
LIR model 27-2	16,742	8,371
LIR according to Slootjes & Wagenaar (2016)	16,600	8,300

Both modelled standards differ less than 1% from the standards used in the standard derivations, therefore the model is considered valid for the assignment. Next to that, the same neighbourhood – Scherpenisse (BU07160200) – is normative. As the LIR values that are calculated with the output of the conceptual model match with the standards found in literature, it is concluded that the model can deliver the intended results with a high degree of certainty and is therefore considered valid for this assignment.

4.3. Quantification effects smart combinations

The results of the third research question on the effects of decompartmentalizing and improving the evacuation percentage in safety standard segment 27-2 are elaborated in this section.

4.3.1. Quantification effects decompartmentalization

With the established model, the new scenarios with the implementation of smart combinations could be modelled. Following the same procedures, except for the lowering of the elevation profile of the compartmentalization dike by 1 and 2 meters, the mortality over the area could be calculated when the dike was lowered by a certain amount. The resulting mortality maps are shown in Figure 21 and Figure 22.

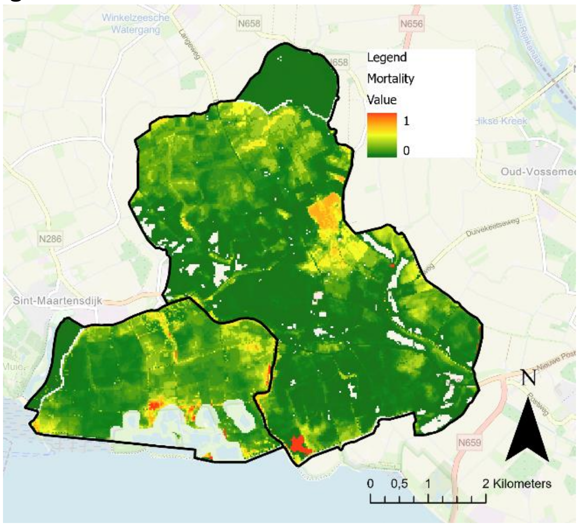

Figure 21 - Mortality after lowering the compartmentalizing dike with 1 meter

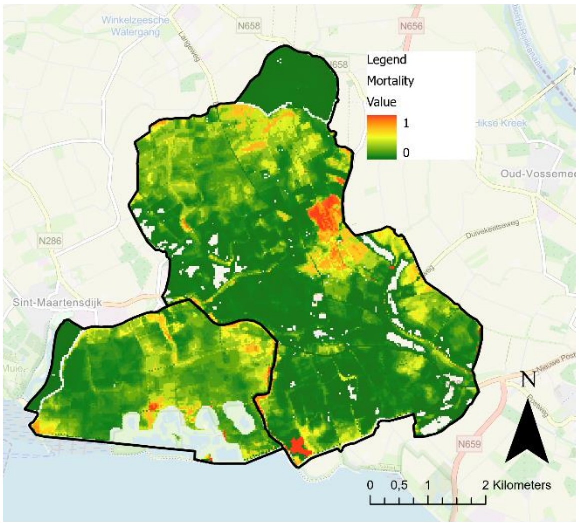

Figure 22 - Mortality after lowering the compartmentalizing dike with 2 meters

A cut through or the entire removal of the compartmentalizing dike results in a mortality map as shown in Figure 23.

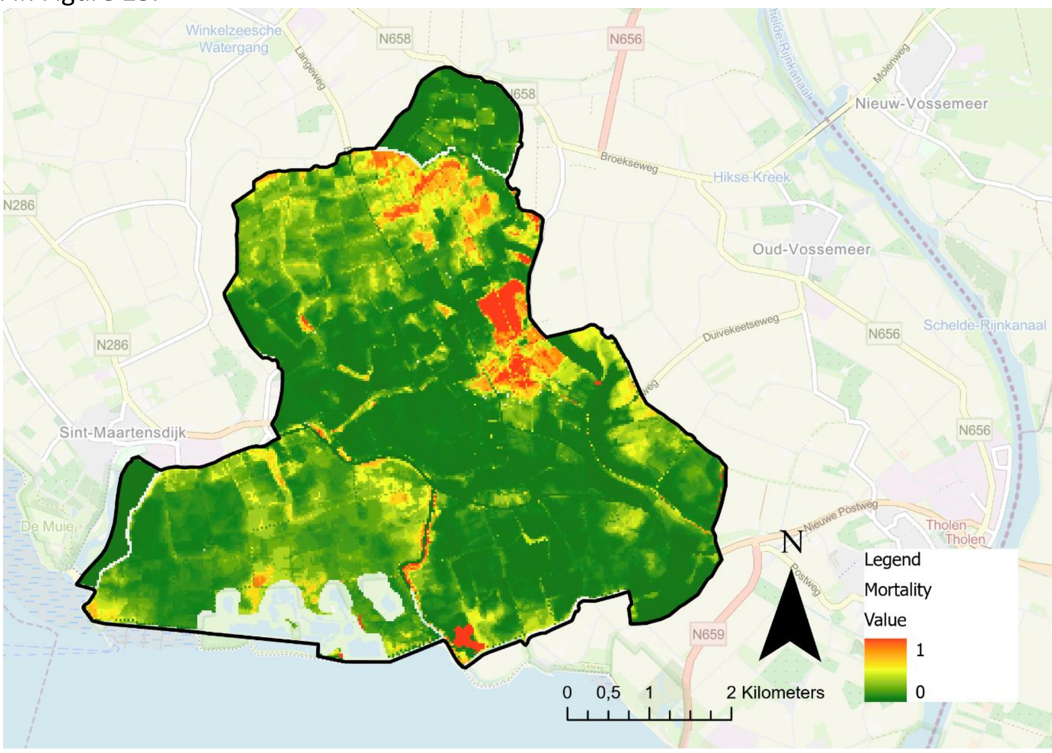

Figure 23 - Mortality decompartmentalized area

The three ways to decompartmentalize result in reductions of the alert value of the LIR of 5% (1 m lowering), 16% (2 m lowering) and 26% (entire decompartmentalization) respectively. This is due to the reduction of the flood risk in the neighbourhood BU07160200 (Scherpenisse). The area is still the normative neighbourhood of the safety standard segment 27-2, but the mortality has gone down. Comparatively, the (median) mortality in the neighbourhood in the north-east has increased by 10% (BU07160100) and 18% (BU07160109), but these mortalities are still lower than the mortality in the normative neighbourhood of Scherpenisse, therefore the LIR standard is not affected by these increases in mortality.

Another result of the model is that there is a much larger volume of water flowing into the area, and hence the water covers the entire area, resulting fewer empty spaces in the mortality map. Although the water reaches almost all areas of the project area, the mortality in these areas is low, due to the small water depth.

Next to the implementation of a decompartmentalization in this area, the evacuation procedures can be adjusted. During the analysis, it was found that the evacuation percentage for the dike ring was very conservative, due to short prediction times of floods in the area (Ons Water, 2022). The effects of improving this third layer safety measure will now be discussed.

4.3.2. Quantification effects evacuation procedures

The less conservative estimation of an evacuation percentage of 26% for Zeeland's safety standard segments results in decreases in LIR alert- and lower limit values, see Table 5.

Table 5 - Alert- and lower limit standards for different scenarios, with the corresponding standard class. Blue indicates a lowering of the standard class

	Alert value | alert value class (1/yr)	Lower limit | lower limit class (1/yr)
Compartmentalized, 6%	16,742 | 10,000	8,371 | 10,000
Compartmentalized, 26%	13,394 | 10,000	6,704 | 10,000
Decompartmentalized, 26%	9,885 | 10,000	5,403 | 3,000

A combination of this improvement of evacuation procedures and decompartmentalization leads to a class reduction of the lower limit. A sensitivity analysis of the evacuation percentage – given in Figure 24 – shows that the LIR can be reduced significantly with the inclusion of improved evacuation procedures, where also the alert value becomes lower than 5,500 such that the standard class lowers. Each 10% increase in evacuation percentage results in a flood risk reduction of roughly 10%, which can be explained by the linear dependency between the LIR standard $P_{f,LIR}$ and the evacuation percentage E in Equation 1.

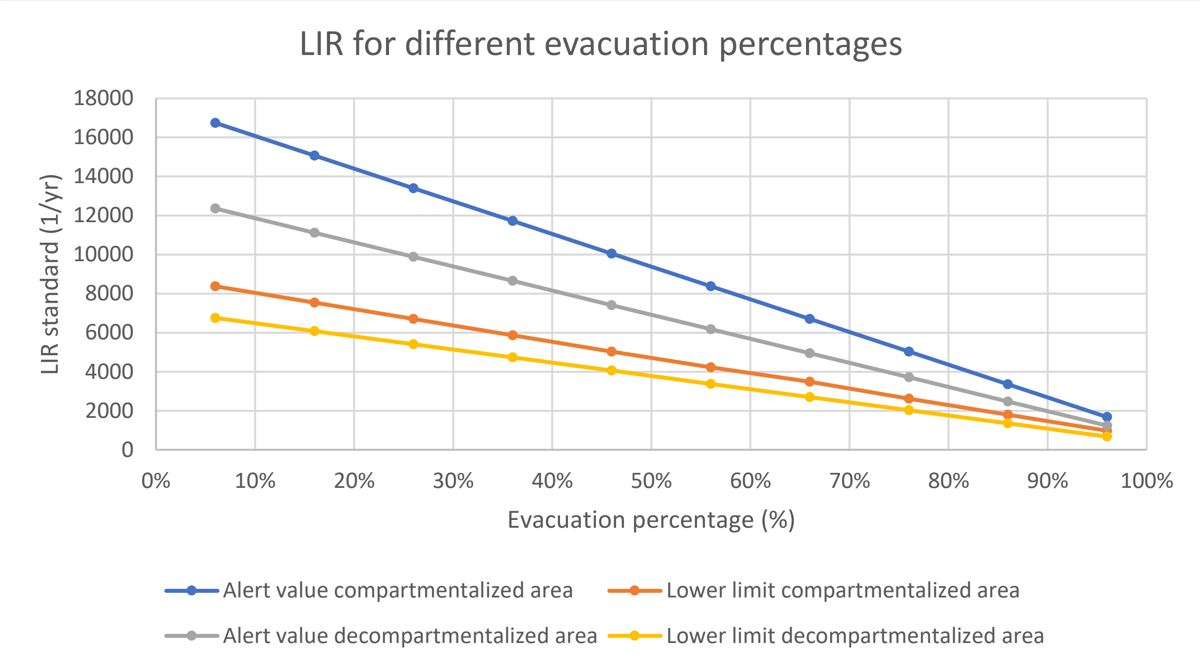

Figure 24 - LIR for different evacuation percentages

In the neighbourhoods within the storm-stricken area, there are several aspects that should be considered for evacuation. The first being the number of people that would potentially have to be evacuated before a flood occurs. The number of people living in each neighbourhood in 2014 is given in Figure 25, and this adds up to 3,425 people in total, including the neighbourhood that overlaps only little with the project area (BU07160009).

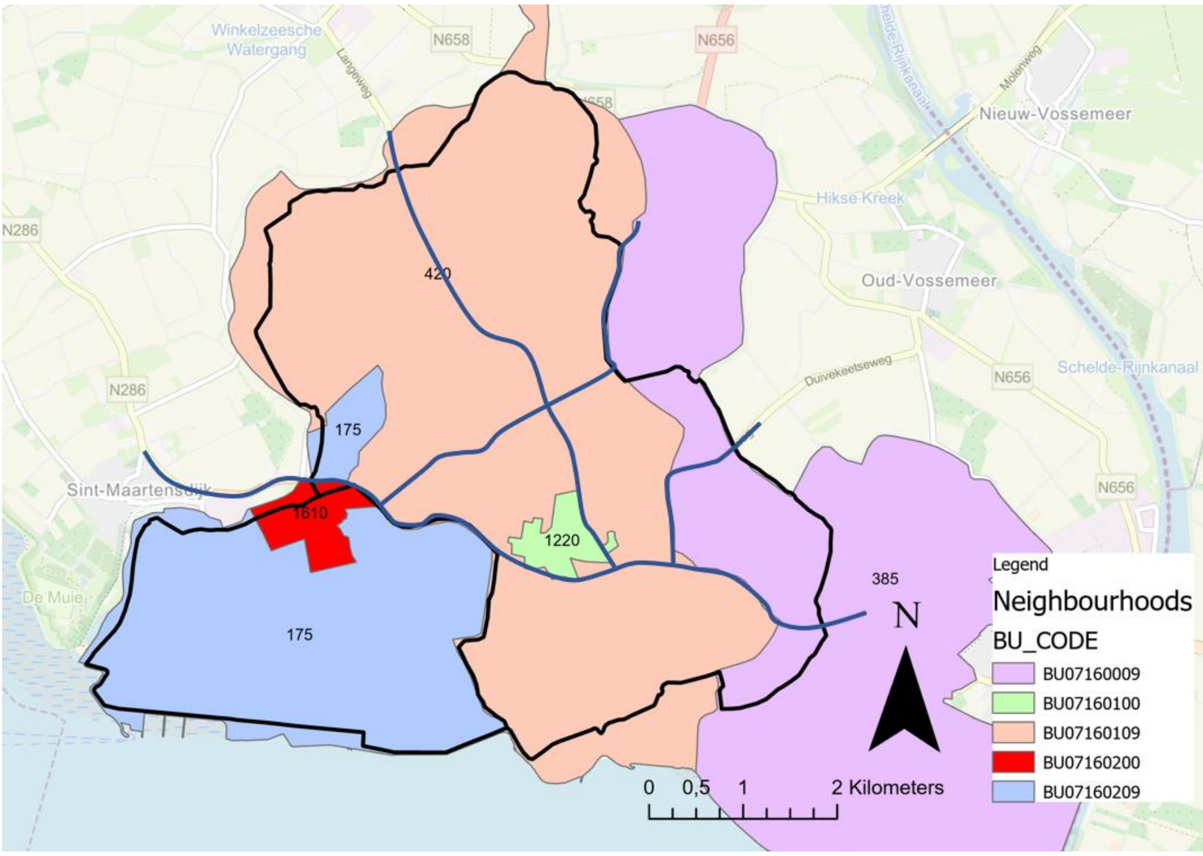

Figure 25 - Number of inhabitants neighbourhoods

The highest number of residents is in the normative neighbourhood (Scherpenisse). These people have two options: to evacuate outside of the dike ring, or to evacuate towards a shelter inside the area. Scherpenisse is located close to a section of the compartmentalizing dike that is around 1 meter higher – 3 m – than the point of overflow at 2 meters. The second option is to relocate to outside of the dike ring. There are 4 routes to do this from Scherpenisse, which are also indicated in Figure 25 in blue. The design of these routes can be optimized to improve the room to relocate to other areas within dike ring 27, or outside of that.

By combining the improvement of evacuation routes with decreasing the decision-making time, the flood risk can be reduced. Once this moment happens, the scripts on how to approach the evacuation procedure for the area should be complete and must be practiced regularly.

5. Discussion

In this section, the results from Chapter 4 will be discussed and compared to existing literature on the topic. After that, the results will be generalized and the assumptions, limitations, and sensitivity of the model and standard derivation will be discussed. Lastly, non-technical aspects and side effects of smart combinations will be discussed.

5.1. Comparison to previous studies

The first research question is based on literature, so the findings will largely correspond to other conclusions found in previous studies. Rijkswaterstaat (2018) came to a shortlist of 58 segments that would prove to be suitable for the smart combination of vertical evacuation. The 24 segments that were found in this analysis are almost all in the list by Rijkswaterstaat as well. All LIR-normative segments are included, only the two segments where the VI is normative were not considered in the analysis of Rijkswaterstaat (2018). So, this study has narrowed down the suitable segments from Rijkswaterstaat and extended to include other types of segments as well.

The factsheets that elaborate the standard derivations per safety standard segments in the Netherlands indicate one segment where smart combinations could be applied: segment 6-7 Friesland-Groningen – Groningen 3 where local measures can be taken to protect gas infrastructure (van der Doef, van Buren, Wagenaar, & Slootjes, 2014). This notion corresponds to the findings of this study, as the vital infrastructure is normative here. Next to that, the factsheets mention 3 pilot studies where smart combinations have been tested: 13b-1 Marken, the IJssel-Vechtdelta and 22-1 Eiland van Dordrecht 1 which includes the Wieldrechtse Zeedijk that acts as a compartmentalizing line element. These pilots were initiated due to specific different reasons, which could not be extrapolated to serve as a basis for wider applications of smart combinations. Smart combinations in these areas were deemed relatively expensive and therefore abandoned. The SCBA is normative in all these pilot studies, and therefore the results of the pilot correspond to the findings of this study.

An analysis by Nannenberg (2020) showed that decompartmentalizing of a neighbourhood in Tiel resulted in a lower standard class. This was done for safety standard segments 43-6 and 43-7, which are also on the list of suitable safety standard segments in this analysis, see Appendix 1. The alert value could be decreased from 18,798 years to 16,898 years, a reduction of 10%, even lowering the standard class. The results of the analysis of Nannenberg (2020) match with the results of this analysis.

Based on literature, LIR-normative segments were determined to be suitable and SCBA segments were excluded from the analysis. However, monetized casualties and victims can also be the main contributor of the SCBA. It could be that these types of SCBA-normative segments will also be suitable for smart combination. This option has however not been verified and has not been discussed in previous studies. More research could be done to test whether these segments would allow for smart combinations.

Later in the analysis, it was found that another criterion could also have been included to determine the effectiveness of smart combinations, this is the size of the neighbourhoods that are normative. A large neighbourhood is more difficult to protect with local measures. We will come back to the neighbourhood aspect in Section 5.2.1.

The results of the decompartmentalization indicate a decrease in maximum median mortality and LIR with decreasing decompartmentalization. The three scenarios of decompartmentalizing indicate a gradual decrease of the median mortality from the current situation to the complete removal of the dike. The lowering with 1 meter results in 5% decrease of LIR, a lowering of 2 meters results in 16% decrease, and the modelled removal of the dike results in a decrease of 26% of the current LIR criterion in the area. The complete removal of the dike – or lowering the crest level at one specific location – especially results in a significant result. This finding corresponds to the results of Nannenberg (2020), as compartmentalizing a neighbourhood and decompartmentalizing another neighbourhood resulted in a flood risk reduction, for one scenario even a standard class reduction was found.

The results of the improvement of the evacuation procedures also indicate reductions of the flood risk in the area. While the decompartmentalization has negative effects on the LIR in other neighbourhoods, improving evacuation does not, the LIR criterion can be lowered over the whole area. Each increase of evacuation percentage results in a decrease of the Local Individual Risk. To reduce the LIR standard class for the alert value, an evacuation percentage of 73% should be achieved. It is however debatable whether such high evacuation percentages are possible in this area, or anywhere else. While the evacuation percentage of 6% in the study area is very conservative due to the Eastern Scheldt Barrier, it cannot be stated that improved evacuation percentages can reach more than 26%. The methods to improve the evacuation rate – setting up emergency plans, evacuation training, improving flood risk awareness – can be applied, but due to the highly unpredictable moment of high water in the Eastern Scheldt it cannot be stated with certainty that the evacuation rate can be raised by tens of percentage points. Safety standard segment 27-2 is on a shortlist of 19 segments of Rijkswaterstaat (2018) for which evacuation percentages can significantly be improved, therefore taking local measures like constructing mounds could potentially achieve a large risk reduction, but that is not certain. For this research project – to determine the effects of improved evacuation on the LIR – the area could be used. The sensitivity analysis in Figure 24 has shown that improved evacuation can significantly decrease the flood risk in an area, even decreasing the standard class.

5.2. Generalization results

The results of this research can be generalized in two ways: to other safety standard segments and to other measures. Both aspects will be elaborated in this section.

5.2.1. Generalization other measures

The results of the analysis of the decompartmentalization and improved evacuation can be generalized to other second- and third-layer flood safety measures. Table 1 is shown below again, of which all smart combinations will be discussed, based on the findings of this research.

Table 1 - Examples of smart combinations considered in literature

Second layer smart combinations	**Third layer smart combinations**
Influencing the flood patterns (compartmentalizing or decompartmentalizing an area)	Improving preventive evacuation (emergency plans, evacuation training, improving flood risk awareness)
Custom building (raising ground level, building on poles, wet and dry proof building, floating building, amphibian housing)	Improving planning, informing inhabitants, and giving training
Constructing infrastructure that supports crisis management (evacuation routes and shelters)	Development of shelters, increasing road capacity during floods, evacuation planning
Risk zoning, prohibiting building in areas that are at risk of flooding)	Developing adaptive evacuation strategies (horizontal and vertical evacuation) with corresponding communication strategy

The measure of influencing the flood patterns has been applied in this analysis, resulting in 26% reduction in LIR with the implementation of decompartmentalizing. The effects of compartmentalizing are expected to be larger, as a new compartmentalizing dike around the neighbourhood of

Scherpenisse will render the mortality in the area zero, assuming the compartmentalizing dike does not breach. The median mortality of the other neighbourhoods will increase a little, due to the displacement of the volume of water towards the other neighbourhoods, hence LIR hotspots are required for this smart combination to be effective. As it is uncertain what the exact flow patterns will be, the effects of compartmentalizing Scherpenisse on the LIR can only be estimated. By assuming that the neighbourhood with the second highest median mortality (BU07160209) becomes normative if Scherpenisse is compartmentalized, and that the mortality within that neighbourhood will not change much due to the compartmentalization of Scherpenisse, the normative LIR value becomes 12,564 years. This result is like the decompartmentalization of the area, with the reduction of 26% to 12,356 years. The largest difference is that another neighbourhood becomes normative, from Scherpenisse to BU07160209 – Verspreide huizen Scherpenisse.

Based on the results of this analysis, the effects of custom building cannot be deduced. The effects of constructing infrastructure that supports crisis management are interconnected with the possibilities of improved evacuation, and therefore the effects will be comparable to the improvement of evacuation procedures. For the effects of the last second layer safety measure – risk zoning – I refer to Bakker (2022).

Regarding the third layer safety measures, the effects will all be like the results of the improvement of preventive evacuation, except the improvement of vertical (responsive) evacuation. This form of emergency response does not affect the LIR, as vertical evacuation does not affect the LIR (Slootjes & van der Most, 2016).

5.2.2. Generalization other safety standard segments

Next to the generalization to other measures, also a spatial generalization to other areas will be discussed. To allow for an insight into possibilities of smart combinations in other areas, another neighbourhood configuration is modelled. The current configuration can for example coincidentally allow smart combinations, while another configuration would have resulted in completely different results. To map this variation and to say something about the possibilities of measures in other areas, another neighbourhood configuration is modelled.

The current neighbourhood configuration at the project area was expected to have a large effect on the results as there are relatively few and they are large. Due to the sizes of the neighbourhoods the median mortalities get spread out over a large area, and as a result the found lowering of risks in this analysis may not be applicable to other areas with smaller neighbourhoods. Any locations with high mortality values in a large neighbourhood get spread out. A random square grid was created, shown in Figure 26, for which the median mortality per polygon was determined using the Zonal Statistics As Table tool.

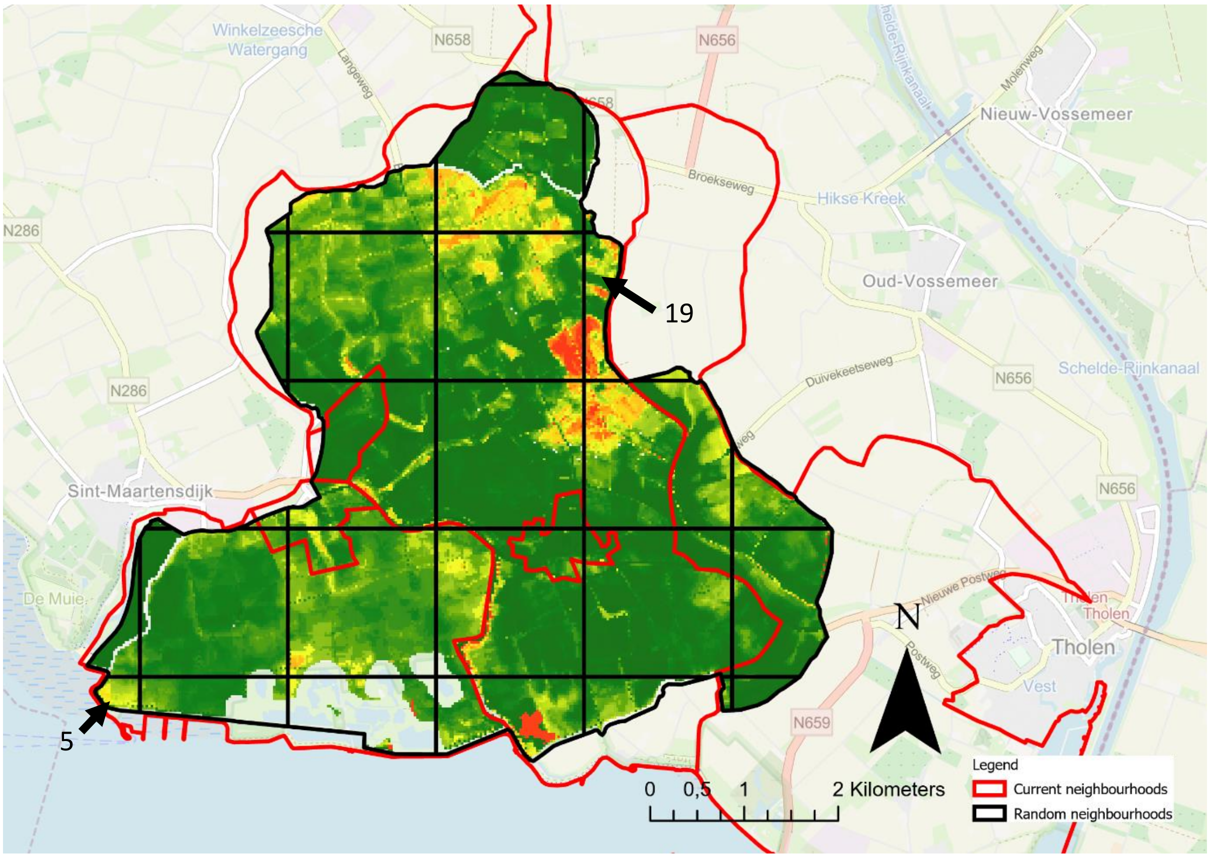

Figure 26 - Current and random neighbourhood configuration over the mortality of the decompartmentalized area, fictional neighbourhoods 5 and 19 are indicated

The maximum median mortalities for different scenarios of compartmentalization are given in Table 6. The corresponding neighbourhood in which the highest median mortality is observed is also given in the table.

Table 6 - Median mortality for the random neighbourhood configuration

	Current situation	1 meter lowering of the comp. dike	2 meters lowering of the comp. dike	Complete decomp.
Normative neighbourhood	5	5	5	19
Highest median mortality	0.16	0.15	0.14	0.16

There are several things to note in Table 6. First, it can indeed be observed that the highest median mortality in the fictional neighbourhood configuration lowers with several decompartmentalizations. However, with a complete decompartmentalization of the area, another neighbourhood becomes normative (from 5 to 19, both are indicated in Figure 26), leading to an increase of mortality again. While the original normative neighbourhood (5) has a decrease in mortality and risk, the increase in water depth in the second compartment leads to a higher mortality in this area, and most severely in one specific neighbourhood (19).

The results have shown that the LIR criterion is sensitive to the configuration of neighbourhoods in an area. Careful consideration of the measure chosen and the way in which it should be implemented is needed. Every area has its specific characteristics and limitations for the implementation of second-layer smart combinations. The spatial planning aspect of measures is highly variable in each area considered, and to construct the correct measure the optimal implementation for that specific area should be calculated. The results cannot be extrapolated directly to other areas, but each area has its specific optimum implementation of smart combinations.

Improving evacuation procedures is less variable between different safety standard segments, as the methods in which this can be improved are more straight forward. As indicated in the results section, there are four aspects to the estimation of the preventive evacuation percentage. Only in areas in which the shelters and evacuation routes are not optimized, the LIR standard can be improved.

There are 24 safety standard segments where smart combinations can be effective. At both Vital Infrastructure-normative segments the spatial planning smart combinations will work. The measures from the third-flood safety will not be as useful in these two areas as the gas installations and the nuclear power plant are not affected by the emergency response as defined in Section 1.1. The measure of improving emergency response systems can be applied in more than just segments where there is a LIR-hotspot, but the potential is highest in areas where there is currently a conservative estimated evacuation percentage – e.g., at marine safety standard segments (Ons Water, 2022) – see the evacuation percentages of the suitable safety standard segments in Appendix 2. The segments with the lowest evacuation percentages have the highest potential to improve the evacuation procedures. The segments that have the most conservative evacuation percentages used in the standard derivation (0-20%) are 5-1, 5-2, 17-1, 20-2, 21-1, and 26-3, which are all located at the sea.

The 22 LIR-normative segments all have some form of a LIR-hotspot in the area, which makes smart combinations suitable for these areas. From the results of this analysis, it is concluded that while the optimal implementation will differ for each segment, smart combinations such as decompartmentalization and improving evacuation procedures can effectively be used to reduce flood risks in 24 safety standard segments.

5.3. Sensitivity and limitations

As a conceptual model is defined as a representation of key elements which purposely excludes any design complexity, some factors must be omitted. These omissions have led to some limitations of the model where the model can deviate from real flood events. Two assumptions have already been discussed and validated, but in this section some other limitations of the model will be discussed.

5.3.1. Sensitivity model and maximum scenario

In this paragraph, the sensitivity of the results to the different parameters used in the analysis is discussed. As indicated by Westerhof (2019), the breach development $B(t)$ has a significant impact on the results of the standard calculations. Therefore, the sensitivity of the results to the breach development formula in Equation 3 is determined and shown in Figure 27.

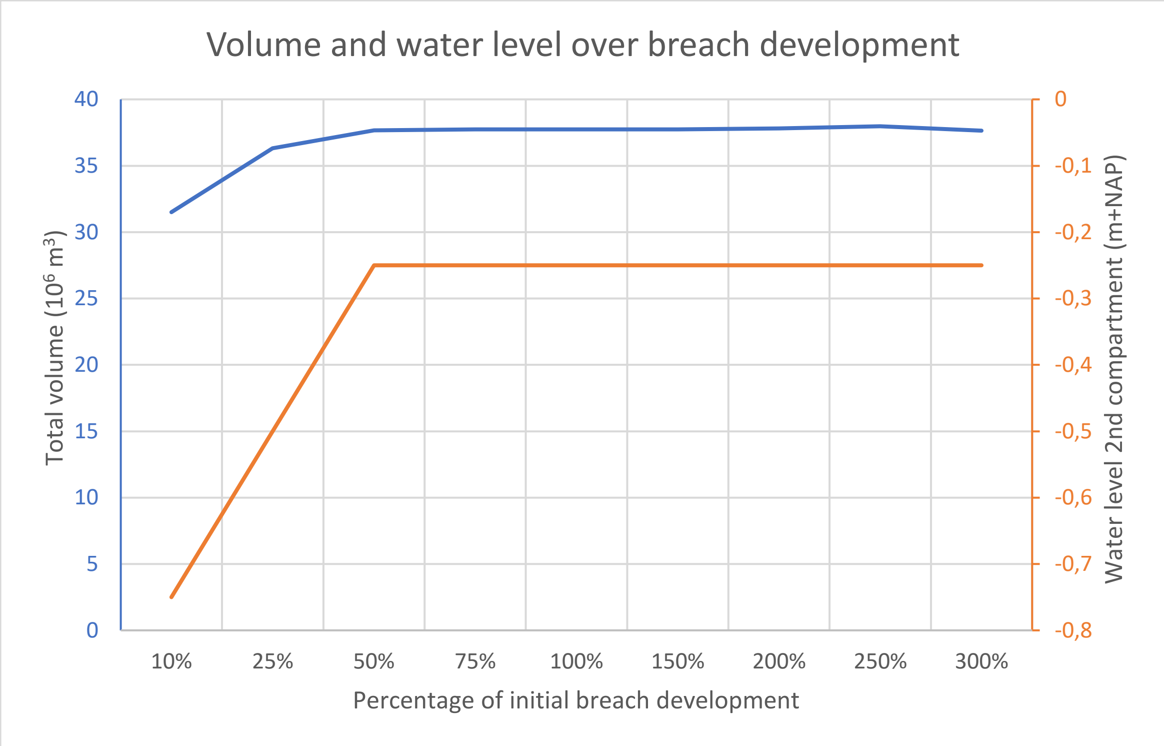

Figure 27 - Volume and water level over relative breach developments

The total inflow volume in Figure 27 does not change much with changing breach developments, only if less than 50% of the used breach development is modelled. This is due to the water level in the first compartment. As the compartment fills up quickly, the head difference between the Eastern Scheldt and the first compartment will decrease quickly, leading to lower inflow volumes.

This finding also indicates the difference between the volume in LIWO and the volume from this model that was mentioned in section 4.2.2., and the difference in water depth of 1.59 meters between the LIWO and model data in the second compartment. It is unknown which breach development formula is used to obtain the data in the LIWO, nor which overflow formulas were used, but they will be different from the calculation used in this analysis.

Once the compartmentalizing dike has been cut or removed, the water level in the hinterland will however not rise as quickly, extending the period of a large difference in head for longer and therefore the total inflow will increase. The data obtained from the model supports this thesis. Figure 28 indicates the water levels for different breach developments compared to the used development in the model, and the corresponding final volume of the model. With smaller breach sizes, the storm duration limits the volume of water that enters the dike ring. It could be that the storm duration modelled in the LIWO is also longer than the boundary conditions in the model that is set up. This would also explain the large water level difference in the second compartment. However, as the boundary conditions used in the model are obtained from literature, this is not considered a flaw of the model.

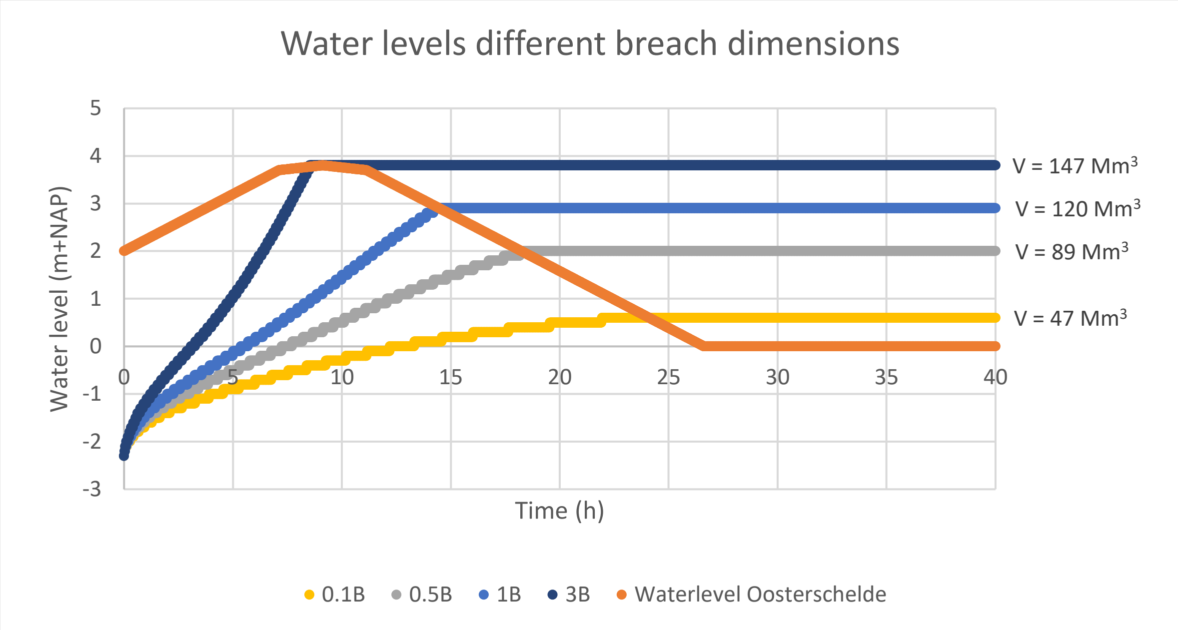

Figure 28 - Water levels decompartmentalized area with different breach dimensions

The total inflow volumes are significantly larger with the decompartmentalized area, due to the persistence of larger head differences at the breach location. The inflow Q is linearly dependent on the head difference between both sides of the primary dike, as can be seen in Equation 4, and hence the inflow volumes will differ a lot. As discussed 4.3.2., despite the increase in inflow volume into dike ring area 27, the mortality will decrease. Therefore, the results will not be affected by the dependency on the inflow volumes.

Another choice during the setting up of the model was the moment of breaching of the primary dike. Like the breach dimensions, the moment of breaching during the flood wave does not significantly affect the volume that flows into the area. During the complete rise of the water level in the Eastern Scheldt (0-16.8 h in Figure 14), it does not matter at which moment the dike breaches, as the total volume flowing into the dike ring does not differ more than 1% from any other moment during that period. No matter which moment the dike breaches, the first compartment fills up within 5 hours, like Figure 14. The further in time the dike breaches, the larger the water level difference and the quicker the first compartment fills up, resulting in only small differences in water inflow with variable breach moments.

While generally the maximum flooding scenario (TL + 1D) for an area accounts for 20% of the mortality, in this region the maximum scenario accounts for 40%. Therefore, it can have quite an influence on the current scenario, but also a dampening effect on the possible effects of newly introduced measures such as smart combinations. The median mortality and corresponding normative neighbourhood for different percentual contributions of the maximum scenario to the compartmentalized (original) model is given in Table 7.

Table 7 - Percentage of mortality map corresponding to the maximum scenario (TL + 1D), for the current situation

Contribution TL + 1D	0%	20%	40%	60%	80%	100%
Normative neighbourhood (BU-)	07160209	07160200	07160200	07160200	07160200	07160200
Median mortality	0.013	0.045	0.077	0.108	0.123	0.141

The use of the maximum scenario for the area does increase the median mortality in the area. The model does put out the correct data, as the median mortality of 0.077 matches the data in the LIWO.

The mortality of the maximum scenario is also used for the results of the decompartmentalized area, as the maximum scenario could not be modelled with the ArcGIS Pro/Excel model, as other breaches that end up in the second compartment were not included in the model due to time limitations. For both extremes (0% and 100% of the mortality) the median mortality does barely change compared to the current situation, according to Table 8.

Table 8 - Percentage of mortality map corresponding to the maximum scenario (TL + 1D), for the decompartmentalized area

Contribution TL + 1D	0%	20%	40%	60%	80%	100%
Normative neighbourhood (BU-)	07160109	07160200	07160200	07160200	07160200	07160200
Median mortality	0.012	0.036	0.062	0.087	0.112	0.139

In between the two extremes the effects of decompartmentalizing will be dampened, as the normative mortality is increased by the maximum scenario. With a contribution of 20% maximum scenario, the effects of decompartmentalizing would be larger, as the further from 0% or 100%, the larger the effects of the maximum mortality will be. Lastly, for a percentage of 0% another neighbourhood is normative, comparing Table 7 and Table 8.

The maximum scenario TL + 1D was not calculated with the model. If more compartments of dike ring 27 were included in the model, this could have been done. For this analysis it was decided that the maximum scenario from the LIWO of the current area would suffice. The flood patterns of the maximum scenario would have been slightly different, as the flood patterns from the other breach locations would have changed with the decompartmentalized area. The volume flowing into dike ring 27 would be spread over a larger area without the compartmentalizing dike, therefore reducing the rise rate and possibly the maximum water level. The flow velocity would barely be affected, as the highest flow velocities are mainly observed at the breach location, which would not change. Based on this, it is estimated that the maximum scenario would result in a slightly smaller mortality than used in the analysis, lowering the standard a little more compared to the found results for decompartmentalization.

5.3.2. Limitations model

First, with the omitted flow directions and flow velocities that are assumed to be zero, the water does not flow from a breach location towards the lowest areas. Rather, the water rises from the lowest points of the area upwards. In some areas – such as the second compartment in segment 27-2 – the lowest areas are not located close to the breach location. Therefore, the initial stages of the modelled flood will differ from an actual flood event. In larger dike ring areas or areas with larger elevation differences, this effect may be larger. For determining maximum water depths and rise rates this conceptual model can be used, for other applications – e.g., determining flood patterns, etc. – the limitations of the model should be considered.

Second, the assumption that the flow velocities are zero can lead to limitations. While for safety standard segment 27-2 it was determined that the assumption is valid (see Section 4.2.2.), areas with larger elevation differences can have specific areas where the flow velocities are large. However, the casualty functions used in the mortality only increase if a flow velocity of 2 m/s is exceeded (Rijkswaterstaat, 2004). These flow velocities are rare, and usually mainly occur at the breach locations. It is however possible that some safety standard segments have more locations that have high flow velocities, which do not get spread out because of the neighbourhood configuration like in segment 27-2.

The third limitation is the determination of rise rates for the lowest areas of the compartments. In Figure 15, the lowest areas in each compartment have significantly higher rise rates than the others. Due to the small surface area of these low-lying spots, the water rises quickly if a volume of water enters the compartment. It is not known whether these high rise rates are realistic, nevertheless the corresponding mortality in these low-lying spots is large. The effects of these spots on the LIR standard are however limited, as the median mortality per neighbourhood is determined, which limits the effect of these outliers. The outliers can multiple magnitudes larger, and it will not affect the median mortality, therefore this limitation of the model will not affect the results of this analysis.

In this system, the outliers do not have an effect as the neighbourhoods are large, these outliers are therefore not a limitation for this situation. However, when applying the model in other areas with smaller neighbourhoods, the effect of small areas with high mortality values can be larger, as shown in Section 5.2.2. For future research, the outliers can be removed to ensure that the results are not affected by some unrealistically high rise rates. The limitations of the model discussed in this section do not affect the results of this analysis.

5.3.3. Limitations standard derivation

Limitations of the model were determined before modelling commenced, however, after using the model to determine flood characteristics and corresponding standard also other limitations of the standard derivation itself were found. These will be discussed in the upcoming paragraphs.

During the setting up of a model, decisions must be made on what will be included in the model, and in what way different characteristics of the dike and hinterland are modelled. All these decisions will affect the results in a way, making these decisions important to know and understand. To repeat the setting up of a model for a dike ring to obtain the same results on water depth, rise rate – and, if applicable, on flow velocities – therefore requires a well-documented step-by-step approach. The process of the standard derivations is however highly untransparent and undocumented, which makes it hard to replicate results. It takes a lot of reverse engineering – and therefore time and money – to set up a model that can replicate the results found in LIWO or literature. The lack of proper documentation of the derived standard for safety standard segment 27-2 made it harder to set up a model that matched the LIWO, which has happened in other previous studies as well (e.g. Westerhof (2019); Nannenberg (2020)). With better documentation of the decisions made, models and results can be replicated quicker, and more time can be spent on finding results for certain problems in areas.

The model has been calibrated to meet the data in the LIWO, using parameter values listed in the LIWO and literature. Based on that, it was concluded that the compartmentalizing dike does not breach when faced with a flood and that it does not have any holes. This assumption listed in the LIWO can have major influence on the results of the analysis. While a breach at the primary flood defence is modelled, it is assumed that the compartmentalizing dike around compartment 1 will not breach and can withstand all the forces that are going to act on it. In the case of a breach in the compartmentalizing dike – regardless of the moment of breaching – the scenario will more closely resemble one of the scenarios in which decompartmentalization has been applied. The breach will result in a lower water depth and rise rate in the first compartment, and thus the median mortalities and risks will decrease. If the compartmentalizing dike would not have been assumed to be stable, the effects of decompartmentalizing would be smaller.

The same goes for a waterway (location indicated in Figure 19, with an x), which can be open during the case of a flood but is usually closed. The waterway leading from the culvert beneath the dike is up to 20 meters wide at some locations, see Figure 29. For the calculation – in this analysis and in the LIWO data – it is assumed that the culvert beneath the dike is permanently closed.

Figure 29 – Waterway leading to the culvert in the compartmentalizing dike. On June 13th, 2022 – when the picture was taken – the culvert that is visible at the end of the waterway was also closed. The location where the picture is taken is indicated in Appendix 3

It would be useful to have documentation of not only the derivation of the standard per safety standard segment, but also to have documentation of the implications of certain decisions that have been taken in the process, such as the closed culvert underneath the compartmentalizing dike. This overview of decisions, their implications, and sensitivities makes it better to understand the results that are shown in the LIWO.

In the derivation of the standards, the rise rates over an area are determined, which are independent of the moment that the largest rise rate occurs. Now, the moment a grid cell inundates is assumed to be the moment at which the highest rise rate occurs. Therefore, the rise rate is always highest at the lowest locations in a compartment, as the inflow volume gets divided over a small area. This does not necessarily have to be true, according to Figure 14. The increase in water level speeds up between 3 and 4 hours after the moment of breaching, so the rise rate at all locations that are already flooded are a little higher than in the rise rate map indicated. These differences are however small – difference in rise rate of 0.07 m/h – and will therefore not affect the results. The method also does not consider the deadliest moment of a rise rate. A rise in water depth from 0 to 10 centimetres for example is less dangerous than an increase from 30 to 40 centimetres, with equal flow velocities (Da Vieira, Andrade Simões, & Sousa Fontes, 2019). The standard derivations only consider the maximum rise rate over the whole flood-period, without considering the deadliest moment (Slootjes & van der Most, 2016). Therefore, it can also be seen as a minor flaw of the Dutch standard derivations.

Next to the flood characteristic of the rise rate, the determination of the flow velocity makes for a major complication in the calculation of the standards. As shown in this research, a conceptual model that does not put out flow velocities can give comparable results to a more sophisticated flooding model. This raises the question whether flow velocities should be considered in the standard derivation at all, if simpler models can be used that result in similar mortalities. In the mortality calculation, only flow velocities that exceed 2 m/s do result in large increases in mortality. In general, the areas where the velocities reach these speeds are located at or close to a breach location. The normative breach location is however arbitrarily chosen somewhere along a dike section for which the strength and loads are considered homogeneous, which makes the location of the high flow velocities along a primary flood defence variable and uncertain. The generally low flow velocity and uncertainty in the location of high flow velocities along a primary flood defence can make the flow velocity redundant in the calculation of the standard.

After determining the damage and/or the mortality, there are three other aspects that were found to be debatable in the standard derivation. For the LIR calculation in Equation 1 the median mortality per neighbourhood is used, this usage of neighbourhoods to determine the median mortality does affect the LIR, as shown in 5.2.2. The configuration of neighbourhoods in safety standard segment 27-2 does affect the LIR, high mortality areas in large neighbourhoods get understated, while high mortalities in smaller neighbourhoods get emphasized. The usage of the median value limits the effects of outliers, but it does not overcome the problem of neighbourhood size.

After the median mortality is determined, it is input for the LIR calculation. During the analysis, it was found that this calculation procedure is an elaborate system of steps that does allow for improvements of automation. The manual procedure of determining the LIR per segment and then the multiplication with the difference compared to the LIR of 1/100,000 or 5/1,000,000 in Equation 1 takes time and allows for human errors. By automizing the steps, the Local Individual Risk can even possibly be reduced for different segments, and the manual steps can be reduced.

Once the LIR standard has been determined, the calculated value will be classified into a standard class, see Table 2. This seemingly arbitrary classification into standards has a major effect on the standard and the money spent on flood safety in the Netherlands. While decompartmentalization of segment 27-2 results in a significant mortality and risk reduction of 26%, a standard class reduction from 1/10,000 to 1/3,000 was not possible. For this class reduction, the flood risk should have decreased with 2/3 of the current value of 1/16,600. Comparatively, the analysis by Nannenberg (2020) showed that a flood risk reduction of 10% at safety standard segment 43-6 was already enough to lower a standard class (18,798 years to 16,898 years). A wide range of derived standards between two classes does not reflect the actual flood risk, as a calculated LIR standard of 1/6,000 years and one of 1/17,000 years end up in the same class, despite the latter being almost thrice as large.

5.4. Non-technical aspects smart combinations

The research has shown that the implementation of smart combinations is technically capable of reducing the mortality in an area, thereby reducing the LIR. There are however more aspects that should be met, to be able to implement the measures in the area. According to Te Linde et al. (2018), there are three factors that should be met, first there should be a support base and mutual trust between the stakeholders that everyone will support a common goal of flood safety. Smart combinations containing measures from the third multi-level safety system will not face much opposition from surrounding areas, surrounding areas may even benefit from the improvements in evacuation procedures, by improving their own approaches. Within the affected area, the support of people to any improvements to decrease the mortality is expected.

Decompartmentalizing an area can however result in more opposition from surrounding areas. By decompartmentalizing dike ring 27, the median mortality in BU07160109 and BU07160100 will increase by 18 and 10%. The decompartmentalization of the area can therefore result in resistance from these two areas. These two neighbourhoods are however much less densely populated than the area that is normative for this stretch of dike. Hence, less people will be in danger of falling victim to a flood. Clear communication with the people in the two neighbourhoods will be key to allow for mutual trust and understanding of why a possible decompartmentalization will be implemented.

Second, the technical feasibility – whether the benefits reducing the dike reinforcement costs compensate for the costs of the measures in layer 2 and 3 – of smart combinations. As evaluated by van Buuren et al. (2015), the pilots of Marken and the IJssel-Vechtdelta both did not render suitable locations for smart combinations. While the first criterion of Te Linde et al. (2018) was met – there was a political support base for smart combinations – due to the urgent safety issues, however the technical feasibility was not researched beforehand. After more research into the possibilities, it was rendered too expensive, or it was not able to be connected to other investments. At Marken, the number of inhabitants was too small to lead to large reductions of costs and at the IJssel-Vechtdelta the construction and maintenance of the compartmentalizing dikes were determined to be higher than the benefits (van Buuren, Ellen, van Leeuwen, & Van Popering-Verkerk, 2015). At both safety standard segments, the SCBA is normative, hence the costs of the measures are of importance.

The third aspect put forward by Te Linde et al. (2018) is the demonstrability and enforceability of the measures proposed. This aspect focusses on whether the correct institutional, financial, and legal criteria can be met. For smart combinations to work, the money and regulations should be aligned with the new paradigm. If this is not possible, the implementation will fail.

5.5. Side effects of the smart combination-measures

Next to the accomplishment of the standard criteria, other factors of interest for Waterboards and municipalities can be achieved using smart combinations. A factor that is affected is the constant reinforcements of dikes, or other defence systems. For example, as shown by Deltares (2011), land subsidence is a major factor in strengthening dikes. Especially in the lower areas of the Netherlands, land subsidence over several years leads to the lowering of the dikes compared to the water levels. Measures in the third layer of the multi-layered flood safety approach are not affected by these regular maintenance procedures, as they are lesser affected by outside factors. The effect of evacuation procedures would counteract the effects of land subsidence and could be used to cancel each other.

The implementation of smart combinations can also lead to reductions of material use. As constructing and reinforcing long stretches of dike requires a significant volume of clay, sand, and other materials, the flood defence in the Netherlands puts a strain on raw materials. By implementing smart combinations, this footprint can be reduced. An example at safety standard segment 27-2 is that the decompartmentalization results in an excess of materials. These can be used in other projects where materials are needed. That way, Waterboards do not have to deplete material sources.

There are also some downsides to the use of smart combinations. There can be a hesitancy of the people in the area, as it is a new concept. The people in the second compartment of the flood at safety standard segment 27 will see their mortality rates increasing with the removal of a dike. Next to that, the evacuation rate of the second compartment can also decrease, due to the shorter time between the breach and the arrival of flood water in this compartment. It will require some convincing, but the improvements in views and other aspects can allow for a support base. In this area it helps that the normative neighbourhood of Scherpenisse has significantly more inhabitants than the neighbourhoods in the second compartment combined. The Group Risk at safety standard segment 27-2 is therefore reduced.

6. Conclusion

The results of the research questions have shown several aspects that would allow for an effective implementation of smart combinations. Based on literature, it is found that the implementation of second- and third layer flood safety measures would be most promising at safety standard segments where either the LIR or Vital Infrastructure is normative. A next distinction was found at the safety standard segments where the LIR is normative, there should be a LIR-hotspot – a normative neighbourhood in which the mortality is much higher than in the other neighbourhoods – for smart combinations to be effective. These characteristics are found in 24 safety standard segments: two VI-normative segments and 22 LIR-normative segments.

To model the effects that smart combinations can have on smart combinations, a conceptual model was set up. The model that was set up uses a digital elevation model, dike material characteristics, and outer water levels, and calculates the inflow of water into different compartments of a dike ring. Using the Verheij-Van der Knaap formula for breach development of the primary dike, inflow formulas through the breach, and overflow formulas over compartmentalizing dikes, the water depths and rise rates over the flooded areas could be determined.

To validate the model, a case study was chosen based on several quantitative parameters that considered dike length and mortality: safety standard segment 27-2 – Tholen en St. Philipsland 2. For this area, the model was used to determine the water depths and rise rates in two compartments of dike ring 27, which were input for the standard method to determine the mortality. First, the two main assumptions that were made to set up the model were validated. The assumption that flow velocities could be assumed to be zero was found to be valid due to the limited effect that the flow velocities found in the LIWO had on the (median) mortalities, only at the breach locations the flow velocities affect the mortality. The second assumption that the water rises from the lowest locations upwards was found to be valid for this assignment, as only the first timesteps that water flows into a compartment do not resemble a real flood event. The aim of this model is to find the maximum water levels, which is not affected by these first timesteps. The model was found to be valid and could be used to model water depths and rise rates after the compartmentalizing dike would be removed.

It was hypothesized that the smart combinations of decompartmentalization and improved evacuation procedures could decrease the flood risk at safety standard segment 27-2. A complete decompartmentalization of the area could decrease the LIR in the normative neighbourhood with 26%. Other options to decompartmentalize include the lowering of the compartmentalizing dike by 1 or 2 meters, which resulted in reductions of the LIR by 5 and 16%, respectively. With a fictional neighbourhood configuration, it was found that other divisions of neighbourhoods could have resulted in the largest reduction of mortality and LIR by lowering the compartmentalizing dike with 2 meters. Therefore, it was concluded that the results cannot be extrapolated directly to other areas, but each area has its specific optimum implementation of smart combinations.

The improvement of evacuation procedures could decrease the flood risks even more. A sensitivity analysis of the LIR to the evacuation percentage showed that improvements in evacuation procedures lead to the reduction of the risk. By achieving the average estimated evacuation percentage of 26% for Zeeland, the lower limit LIR value could be lowered by one class. Further improvements lead to class reductions of the alert value as well. Each 10% increase in evacuation percentage results in roughly 10% decrease of flood risk.

The aim of identifying where and quantifying whether potential reductions in mortality and flood risk can be achieved at different safety standard segments in the Netherlands has been fulfilled. The smart combinations can be considered as an alternative or addition to reinforcing the primary flood defence in areas where the LIR is normative due to one or a few neighbourhoods along the safety standard segment, with a high mortality or with a low evacuation percentage and in areas where the VI is normative. At 24 safety standard segments in the Netherlands, smart combinations have the potential to decrease flood risk.

The quantification of effects has indicated that the smart combinations of decompartmentalizing can reduce rise rates and water depths in areas with high LIR values, thereby reducing the LIR. Next to that, the LIR can be reduced by improving evacuation procedures. By combining the second- and third-layer flood safety measures, the mortality and risk in the normative neighbourhood in the case study area could be reduced. This research has shown that – while the optimal implementation will differ for each segment – smart combinations such as decompartmentalization and improving evacuation procedures can effectively be used to reduce flood risk at 24 safety standard segments, as an alternative or addition to the standard procedure of reinforcing dikes.

7. Recommendations

This research has focussed on two aspects: where smart combinations are suitable and how much it can contribute to reducing the flood risk in a specific safety standard segment. Part of the knowledge gap has been answered, but new questions have been raised. In this section, the remaining questions and other recommendations for future research will be discussed. First, the recommendations regarding smart combinations themselves are mentioned, after a few recommendations about the improvement of the model and the standard derivations will be issued.

7.1. Recommendations for smart combinations

The research has shown that it is technically possible to reduce mortality and flood risk at a safety standard segment. However, before these measures can be implemented, more questions should be answered. Not only research questions, but also policy questions regarding the implementation of the concept. The model used in this analysis did come with its limitations, and the results should therefore be handled with care. Before any policy decisions should be taken, a 2D hydraulic model should calculate the exact flood patterns, using flow directions and velocities as it is possible that the used model will have missed certain high mortality areas where flow speeds would have increased due to the decompartmentalization.

Next to that, the technical implementation of measures does differ between areas, and will therefore have to be calculated before anything is implemented in a certain area. As shown with the random configuration of neighbourhoods, a slightly different configuration can have a large impact on which measure can be used and to which extend that measure can be effective. The results found in this analysis cannot be extrapolated directly to any other area. Therefore, it should be determined which measure can work in an area, and what flood risk reductions can be achieved, using more sophisticated models.

At the safety standard segments that were deemed suitable in this analysis, also more attention should be paid to the policy decisions required to implement the concept. The three aspects put forward by Te Linde et al. (2018) and discussed in section 5.4. – a support base and mutual trust, technical feasibility, and demonstrability and enforceability – should be researched thoroughly per safety standard segment. The stakeholders and interests are variable for each area considered, and therefore can lead to different implementations of smart combinations.

To get a clear framework for policy makers in the Netherlands, a multicriteria analysis that uses a comparison between dike reinforcements and smart combinations can be used to determine what type of measures would fit best within the safety standard segment. In this analysis, no comparison is done to compare the dike reinforcements and smart combinations, only the suitability of smart combinations in the Netherlands was considered. Before smart combinations are implemented it should be compared to the current method of reinforcing dikes. For different areas, different interests will play a role, and therefore the different aspects – costs, risks, mortality, other values like nature, etc. – should be considered in the multicriteria analysis and be given weights to compare which measures are suitable in a certain area.

Lastly, it is recommended that it should be verified whether safety standard segments where the SCBA is normative due to the monetization of casualties and victims are indeed unsuitable for smart combinations. In this analysis, all SCBA-normative segments were excluded at once, without considering the differences between each SCBA. As it turns out that the mortality can be reduced using the smart combinations, the flood risk of SCBA segments where monetized casualties and victims are normative can possibly also be reduced, as mentioned in 5.1.

7.2. Recommendations for developed model

While the impact of smart combinations per area should be calculated with a 2D hydraulic model that can deliver accurate results based on physical laws, there is a potential with the conceptual model that was used in this analysis. The model allows for quick implementations and calculations of areas, requiring little input data, while it delivers accurate results for the assignment it was built for: to determine the water depths and rise rates over different compartments of a dike ring. To test for potential other areas in which the spatial planning measures can be used, this model can be expected to deliver results that can give predictions of what would be possible in an area. It would be interesting to determine what this conceptual model can contribute to running quick calculations for complex scenarios of possibilities with smart combinations or other measures. It is recommended to set up this model for another dike ring and determine whether it can deliver accurate in other areas as well.

Next to that, some aspects of the model can be improved. In Section 5.3.2., several limitations that could be addressed to improve the model are mentioned. First, the flood patterns that do not match reality during the initial stages of a flood. As the flood is not modelled to start at a breach location but is modelled as if it starts from the lowest point, the initial flood patterns do not match with a real flood in the area. Especially in the second compartment of safety standard segment 27-2 in this analysis, the lowest points are far from the point of overflow over the compartmentalizing dike, making it unrealistic that the actual flood would occur in this way. A proposed method to improve this is to let the model only fill up the low areas close to the breach or to the point of overflow, and only extend further if these first low areas are filled up.

Another flaw of these initial stages of flood patterns are the rise rates of the lowest areas of the compartment. As shown in Figure 15, the rise rates for the lowest locations are much higher than the rise rates of other locations. Due to the usage of the median mortality in the large neighbourhoods in dike ring 27 the outliers did not affect the results, but for other areas an improvement of the model could be to delete these outliers. A flaw of the model at the final stages of the flood wave is that the model does not consider outflow towards the outer water body. This was unnecessary for the application in this assignment, but for other applications it might be included. The last recommendation regarding the model is to research whether flow velocities could be assumed to be zero in other areas as well.

7.3. Recommendations for standard derivations

During the analysis, several oddities in the standard derivations were found which could be improved. First, the documentation of the standard derivations – choices made during the derivation, etc. – should be recorded. Like previous research by Westerhof (2019) and Nannenberg (2020), setting up the models to match the quantifications found by Slootjes & Wagenaar (2016) in the standard derivations was time-consuming and uncertain. To save time and resources when setting up new models, it would be beneficial if the standard derivations for all segments are documented. This is important for the calculation of the LIR, because the results depend on a lot of steps before a final value is determined. This documentation can also include sensitivities and implications of the assumptions that are made during the derivation, such that the standards that end up in the law can be understood better.

While the LIR is linearly dependent on the preventive evacuation percentage, the research into this percentage per safety standard segment is limited, it is only based on a few characteristics like marine/fluvial flooding and other conditions. The uncertainty due to that leads to conservative estimates of evacuation percentages, for each segment considered in Appendix 2 it was indicated in literature that the value used in the standard derivation was at the low end of the bandwidth. By conducting more research into the evacuation percentage, a more valid analysis can be done regarding the flood risk at a safety standard segment.

Two aspects of the calculation of the mortality that can be researched are to include the deadliest moment of the rise rate and/or to exclude (parts of) the flow velocities. Currently, the highest rise rate observed at a location is used in the calculation, while that moment does not have to be the deadliest moment of rising water, the effect of this can be researched. The second aspect of the flow velocities is about the inclusion of flow velocities in the mortality calculation, during the analysis it was found that the flow velocity in at safety standard segment 27-2 did not influence the (median) mortality. Next to that, the flow velocity was only high at the breach locations – which are arbitrarily chosen within a dike section for which the strengths and loads are considered homogeneous, making this location uncertain. The uncertainty in breach location does not make the flow velocities at the breach location reliable, an option would be to exclude the flow velocities within a certain radius from the breach location. A more radical approach of excluding the flow velocity from the standard derivation can open new opportunities to use less sophisticated models that are able deliver valid water depths and rise rates without requiring a lot of input data and set-up time. The opportunities to limit the inclusion of flow velocities can be researched in future studies.

The mortality that is used in the LIR calculation is sensitive to the neighbourhood configuration that is chosen for an area, as shown in 5.2.2. The configuration of neighbourhoods in safety standard segment 27-2 results in very large areas in which the mortality gets spread out and any areas with high mortality values get overlooked and neglected. It is debatable whether these hotpots should be neglected, and therefore a recommendation is to determine the effects of using neighbourhoods on the LIR values.

To conclude, the efficiency of the LIR calculation can be improved. During the analysis, it was found that the calculation is an elaborate system of steps that allow for improvements of automation. By automizing the steps, the Local Individual Risk can even possibly be reduced for different segments, and the manual steps that must be taken can be reduced. Research can be done into options to automize the process.

The last step in the standard derivation is to classify the calculated standard values into several standard classes, which were found to be debatable. The different ranges do not capture the variability of the standards, as calculated standards that are thrice as large as other standards are classified into the same class, resulting in the same flood safety standard class. It is recommended that the classification system gets re-evaluated to determine a new classification system, other options for a classification system like a more even spread of classes or a percentage within a class could be researched to allow for a less arbitrary division of classes.

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Appendices

Appendix 1 – Suitable safety standard segments

All LIR-normative segments are shown in Table 9, for which it is indicated which segments have a LIR hotspot. The segments that are suitable for smart combinations are bold and indicated in the fifth column; these are shown in Figure 13.

Table 9 - Safety standard segments, with normative aspect (LIR or VI), with indicated where a LIR hotspot occurs, and whether the segment is suitable for smart combinations in bold

#	Name safety standard segment	Normative aspect	LIR hotspot	Suitable?
1-1	Schiermonnikoog Duin	LIR	No	No
1-2	Schiermonnikoog	LIR	No	No
2-1	Ameland Duin	LIR	No	No
2-2	Ameland	LIR	No	No
3-1	Terschelling Duin	LIR	No	No
3-2	Terschelling	LIR	No	No
4-1	Vlieland Duin	LIR	No	No
5-1	**Texel Duin**	**LIR**	**Yes**	**Yes**
5-2	**Texel**	**LIR**	**Yes**	**Yes**
6-5	Friesland-Groningen - Groningen 1	LIR	No	No
6-6	**Friesland-Groningen - Groningen 2**	**LIR**	**Yes**	**Yes**
6-7	**Friesland-Groningen - Groningen 3**	**SCBA/VI**	**Vital Infrastructure**	**Yes**
10-2	**Mastenbroek 2**	**LIR**	**Yes**	**Yes**
12-1	Wieringen 1	LIR	No	No
13-2	Noord-Holland - Kust 2	LIR	No	No
14-3	Zuid-Holland - Nieuwe Waterweg	LIR	No	No
14-10	Zuid-Holland - Kust 6	LIR	No	No
17-1	**IJsselmonde - Zuid**	**LIR**	**Yes**	**Yes**
20-2	**Voorne-Putten 1**	**LIR**	**Yes**	**Yes**
21-1	**Hoekse Waard 1**	**LIR**	**Yes**	**Yes**
23-1	Dijkring 23	LIR	No	No
24-3	**Land van Altena 3**	**LIR**	**Yes**	**Yes**
25-4	Goeree-Overflakkee Grevelingen	LIR	No	No
26-3	**Schouwen-Duiveland 3**	**LIR**	**Yes**	**Yes**
26-4	**Schouwen-Duiveland 4**	**LIR**	**Yes**	**Yes**
27-1	Tholen en St. Philipsland 1	LIR	No	No
27-2	**Tholen en St. Philipsland 2**	**LIR**	**Yes**	**Yes**
27-4	Tholen en St. Philipsland 4	LIR	No	No
29-1	Walcheren 1	LIR	No	No
29-2	Walcheren 2	LIR	No	No
29-3	**Walcheren 3 - Ritthem**	**LIR**	**Yes**	**Yes**
29-4	**Sloehavengebied**	**LIR**	**Yes**	**Yes**
30-2	**Zuid-Beveland West 2 - Hansweert**	**LIR**	**Yes**	**Yes**
30-3	Zuid-Beveland West 3	LIR	No	No
30-4	**Zuid-Beveland West 4**	**VI**	**Vital Infrastructure**	**Yes**
31-1	**Zuid-Beveland Oost 1**	**LIR**	**Yes**	**Yes**
31-2	Zuid-Beveland Oost 2	LIR	No	No
32-1	Zeeuwsch Vlaanderen 1	LIR	No	No
32-2	Zeeuwsch Vlaanderen 2	LIR	No	No

32-4	**Zeeuwsch Vlaanderen 4**	**LIR**	**Yes**	**Yes**
34-1	**West-Brabant 1**	**LIR**	**Yes**	**Yes**
34-2	**West-Brabant 2**	**LIR**	**Yes**	**Yes**
36a-1	Keent	LIR	No	No
38-1	**Bommelerwaard-Waal**	**LIR**	**Yes**	**Yes**
39-1	Alem	LIR	No	No
40-1	Heerewaarden - Waal	LIR	No	No
40-2	Heerewaarden - Maas	LIR	No	No
41-3	Land van Maas en Waal - Maas	LIR	No	No
42-1	Ooij en Millingen	LIR	No	No
43-5	**Betuwe, Tieler en Culemborgerwaarden 5**	**LIR**	**Yes**	**Yes**
43-6	**Betuwe, Tieler en Culemborgerwaarden 6**	**LIR**	**Yes**	**Yes**
48-1	**Rijn en IJssel 1**	**LIR**	**Yes**	**Yes**
52-2	Oost-Veluwe 2	LIR	No	No
52a-1	Veessen-Wapenveld	LIR	No	No

Appendix 2 – Quantified parameters optimal safety standard segments

For the suitable safety standard segments listed in Appendix 1, the parameters from Section 3.2.5. are quantified and listed in Table 10. The last column indicates the evacuation percentage, which is not part of the quantified parameters, but is discussed in Section 5.2.2.

Table 10 - Quantified parameters per suitable safety standard segment

#	Name safety standard segment	Casualties per 10.000 inhabitants M	Casualties per 1.000 victims R	Length per area S [km/ha]	Evacuation percentage
5-1	Texel Duin	2.10	1.2619	0.0022	0%
5-2	Texel	9.41	2.3126	0.0021	0%
6-6	Friesland-Groningen - Groningen 2	0.15	3.7924	0.0001	29%
6-7	Friesland-Groningen - Groningen 3	0.000	0.0000	0.0000	N/A – VI
10-2	Mastenbroek 2	8.75	6.2808	0.0015	44%
17-1	IJsselmonde - Zuid	0.83	1.7906	0.0021	8%
20-2	Voorne-Putten 1	9.14	3.2040	0.0007	8%
21-1	Hoekse Waard 1	7.70	1.7005	0.0012	8%
24-3	Land van Altena 3	45.01	5.4392	0.0010	46%
26-3	Schouwen Duiveland 3	33.33	16.2342	0.0010	6%
26-4	Schouwen Duiveland 4	0.60	1.0081	0.0011	20%
27-2	Tholen en St. Philipsland 2	154.98	58.2777	0.0027	6%
29-3	Walcheren 3 - Ritthem	172.90	36.6120	0.0004	20%
29-4	Sloehavengebied	0.00	0.0000	0.0006	20%
30-2	Zuid-Beveland West 2 - Hansweert	162.18	163.7118	0.0002	20%
30-4	Zuid-Beveland West 4 - Borssele	0.000	0.0000	0.0000	N/A – VI
31-1	Zuid-Beveland Oost 1	197.35	32.7050	0.0026	20%
32-4	Zeeuwsch Vlaanderen 4	3.86	8.5697	0.0005	29%
34-1	West-Brabant 1	0.10	0.3615	0.0003	29%
34-2	West-Brabant 2	0.08	0.1513	0.0003	29%
38-1	Bommelerwaard-Waal	64.33	3.7897	0.0027	56%
43-5	Betuwe, Tieler en Culemborgerwaarden 5	9.48	2.1676	0.0004	56%
43-6	Betuwe, Tieler en Culemborgerwaarden 6	14.12	4.1430	0.0008	56%
48-1	Rijn en IJssel 1	24.83	3.2099	0.0007	56%

There are two segments in Table 10 that score a relatively high value for each of the three parameters: 27-2 and 31-1. As the number of casualties compared to the number of victims is almost twice as high, safety standard segment 27-2 is chosen.

Appendix 3 – Locations pictures report

The locations of the pictures in the report are shown in Figure 30.

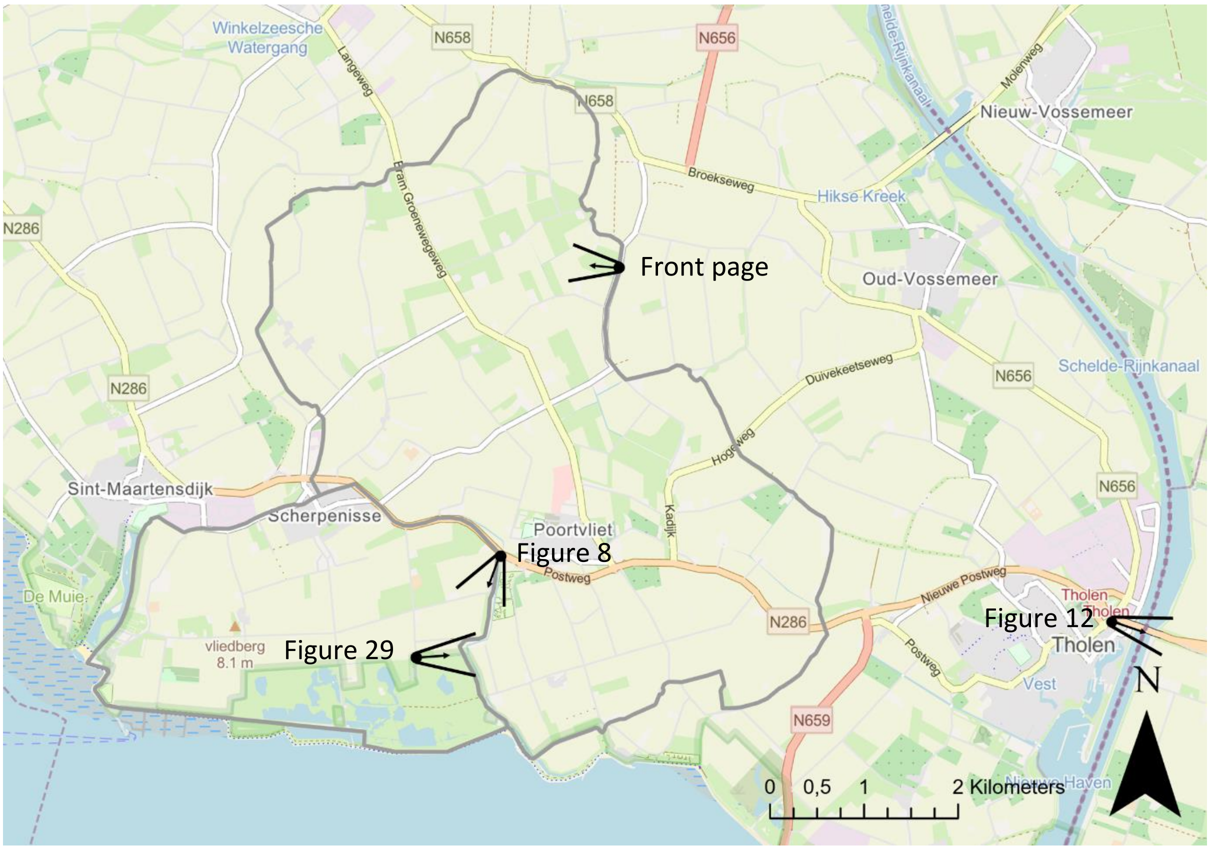

Figure 30 - Locations pictures front page, Figure 8, 12, and 29. Dot indicates location and arrow indicates direction of photo