Flood preparedness of hospitals in the Netherlands

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Preface

This thesis was written in partial fulfilment of the master's degrees in Civil Engineering (CE) and Construction Management & Engineering (CME) at the Delft University of Technology and is the result of a research internship at HKV Lijn in Water. The two programmes have been combined in an Individual Double Degree (IDD). The added value of integrating two theses is that their contents can contribute to each other, leading to a combined result that is believed to be of greater value than when conducted as separate researches.

In addition, this thesis marks the end of just over seven years of studying at the Delft University of Technology. During these seven years, I have acquired a lot of technical knowledge from the field of civil engineering, which has sparked my enthusiasm for what is technically feasible. At the same time, I have learnt to always regard technical developments in their human and environmental context. This insight is invaluable to me and was made possible through my IDD.

I would like to express my gratitude to my graduation committee: Bas J., Marian, Maria, Yared, Saba and Bas K. Their multidisciplinary views have greatly contributed to this thesis. Thank you for thinking along with me and providing feedback. I particularly enjoyed the joint meetings. I would also like to thank HKV and its employees for their welcoming, helpful and interested attitude. I enjoyed getting to know everyone and learning about all the interesting projects from the Water & Climate group. Specifically, I would like to thank Dorien, who regularly checked in on me and provided feedback on my work. Lastly, I want to thank my family and my girlfriend. They have always been an enormous support throughout my studies and have encouraged me to pursue this IDD.

Luuk den Ouden
Delft, November 2024

Summary

Introduction and research questions
Hospitals are part of the vital and vulnerable infrastructure in the Netherlands. Failure of such infrastructure may have severe consequences on a national scale. The Dutch flood risk management approach aims to prepare hospitals for floods through spatial adaptation. However, the current policy does not prescribe concrete guidelines for consistent decision-making and implementation of flood strategies to increase flood preparedness of hospitals. The engagement of stakeholders in this process is also arbitrary. Hospitals are required to have disaster preparedness plans, but the contents are not prescribed. In practice, hospitals are often unaware of flood risk and, if considered, hospitals do not have the knowledge or tools to make substantiated decisions on flood strategies.

The stated problems resulted in the main research question: How can flood preparedness of hospitals in the Netherlands be assessed and improved? The main aim of this research is to quantitatively assess the flood preparedness of hospitals to enable comparison between flood strategies and to make recommendations on which stakeholders should be engaged for the implementation of flood strategies and how this can be achieved.

Methodology
First, a literature study was conducted. In the literature, flood preparedness of hospitals is defined as the anticipation and mitigation of flood disasters to reduce the loss of human life. The literature study also identified four flood strategies that hospitals can implement to improve their flood preparedness: "shelter in place with additional measures", "shelter in place without additional measures", "accept" and "preventive evacuation". Additional measures may consist of spatial adaptation of the hospital, increasing stocks and staffing, making emergency plans or discharging patients. Two hospitals were selected as cases: the Reinier de Graaf Gasthuis (RdGG) and Erasmus Medical Centre (EMC). Flood scenarios that threaten these hospitals were retrieved from the National Water and Floods Information System (LIWO). A first round of interviews (called phase 1 interviews) was held with employees of these hospitals and a flood expert. In a second round of interviews (called phase 2 interviews), (former) doctors of the VieCuri Medical Centre (VCMC) with flood experience were interviewed.

The phase 1 interviews, combined with the literature and a tour at the selected hospitals, were used to identify flood preparedness indicators. Each indicator represents a set of hospitals facilities and processes that are critical to the continuity on healthcare. The selected indicators were evaluated through the phase 2 interviews. The flood preparedness indicators, flood scenarios and phase 1 interviews were used to assess the flood preparedness of the RdGG. Critical flood levels were assigned per hospital facility and for the suppliers. The flood impact per scenario was subsequently derived by verifying whether the critical flood levels were exceeded, which would result in failure. The hospital facilities were grouped per flood preparedness indicator. It was assumed that if any of the hospital facilities belonging to a flood preparedness indicator fails, that specific indicator fails. If any of the indicators fail, it is assumed that the continuity of healthcare has failed (see Figure 1). This series

system was used to quantify the flood impact of each flood scenario in terms of fatalities among patients and types of costs to a hospital. These two factors depend on the flood strategy implemented by a hospital. The result is an overview of the availability of each flood preparedness indicator per flood scenario and the number of fatalities and types of costs per flood strategy. The phase 2 interviews were used to evaluate mortality rates and the classification of patients.

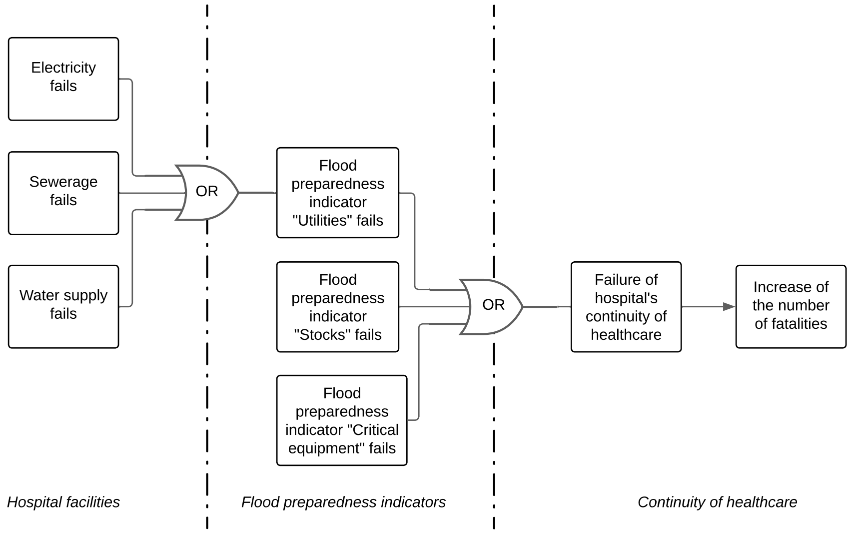


Figure 1: Scheme of the proposed series system for continuity of healthcare at hospitals containing examples of hospital facilities and flood preparedness indicators.

Based on the literature and phase 1 interviews, stakeholders that could be engaged for the implementation of flood strategies were identified and organised per flood strategy. The stakeholders' power, influence and attitude regarding the implementation of each flood strategy was determined to obtain recommended actions for stakeholder engagement. Subsequently, the current and desired level of stakeholder engagement was mapped. These steps resulted in an overview of which stakeholder should be engaged per flood strategy. The phase 2 interviews were used to obtain recommendations on how these stakeholders can be engaged.

Results

Six different flood preparedness indicators were selected that together describe flood preparedness of hospitals. The characteristics of the flood strategy ″preventive evacuation″ significantly differ from the other flood strategies. Therefore, a different set of flood preparedness indicators is selected for this and the other flood strategies. For preventive evacuation, the following flood preparedness indicators are selected:

- Availability of modes of transport for patients
- Having prepared emergency management plans
- Availability of sufficient and qualified personnel

For the flood strategies ″shelter in place with additional measures″, ″shelter in place without additional measures″ and ″accept″, the flood preparedness indicators below are selected:

- Availability of critical equipment
- Having sufficient supplies in stock
- Availability of utilities
- Having prepared emergency management plans
- Availability of sufficient and qualified personnel

The methodology for quantitatively assessing hospitals' flood preparedness was applied to the RdGG and EMC. Four flood scenarios threaten RdGG. Two scenarios threaten the EMC For all scenarios it was found that the continuity of healthcare is disrupted. Figures 2 and 3 provide an overview of the costs and fatalities per flood strategy for the RdGG and EMC respectively. Comparing these figures, it becomes apparent that the number of fatalities for the EMC is much higher than for the RdGG for every flood strategy. For the RdGG, more expensive flood strategies result in less fatalities. For the EMC, this is only true if the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept" are regarded. "Preventive evacuation" is more costly than "accept", but results in more fatalities.

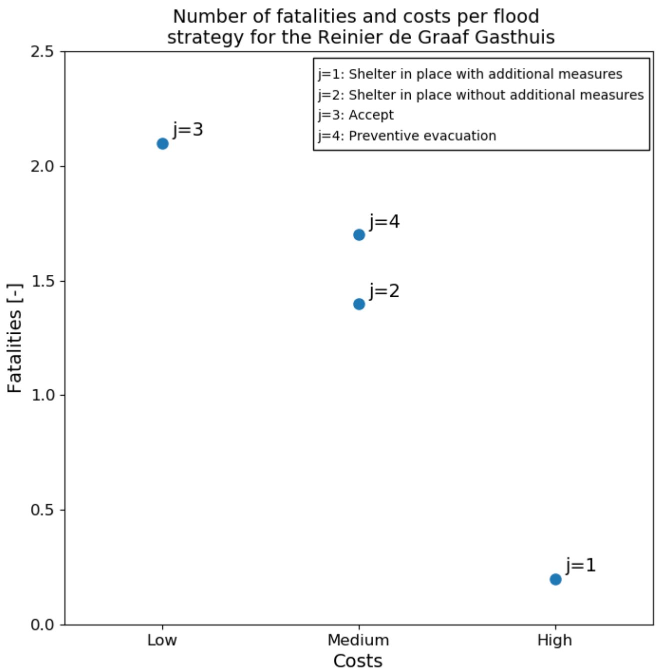


Figure 2: Number of fatalities at the RdGG caused by the flood scenario "Precipitation 1000", "Precipitation 100", "Precipitation 10" or "Regional 100" and costs per flood strategy.

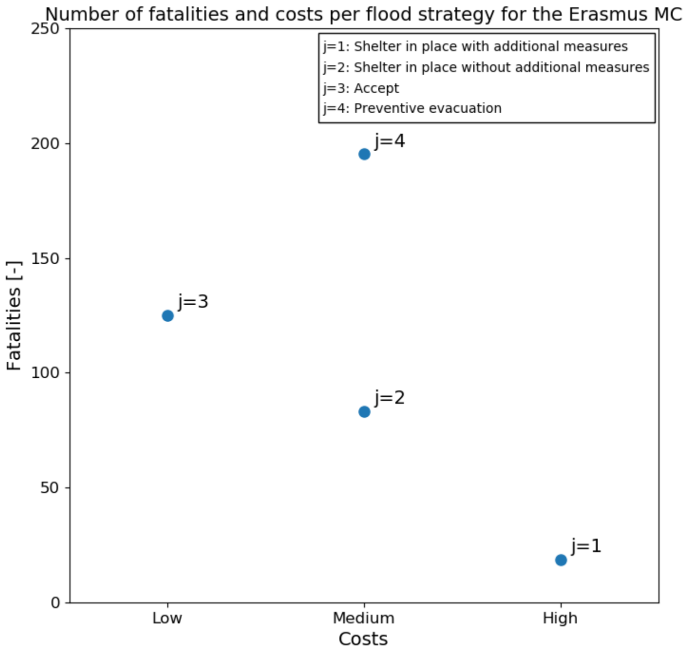


Figure 3: Number of fatalities at the EMC caused by the flood scenario ”Parksluizen 1” or ”Parksluizen 2” and costs per flood strategy.

Table 1 contains the overview of which stakeholders should be engaged for the implementation of each flood strategy. During the phase 2 interviews two medical expert with flood experience at hospitals shared their view on how relevant stakeholders could be engaged. No consensus was found on a single ”best” method. Instead, two methods were proposed: enforcing engagement through legislation and creating awareness. These two methods for stakeholder engagement contain aspects that are also mentioned in the literature (Olejniczak et al., 2020): using the law, an incentive or providing information to steer decisions. According to the experts, the advantage of enforcing engagement through legislation is that, in theory, success is guaranteed once the legislation comes into force. However, the experts also mentioned that the costs of enforcement, the duration of implementing new laws and the experience that hospitals already have to meet many obligations are downsides. The stated advantage of creating awareness is that broad support is created, resulting in willingness to be engaged. However, this method is said to be unpredictable and requires a lot of time to succeed.

Table 1: Overview of which stakeholders should be engaged per flood strategy.

Stakeholder	Shelter in place with additional measures	Shelter in place without additional measures	Accept	Preventive evacuation
Hospital Executive Board	●	●	○	●
Hospital personnel	●	●	○	●
Hospitals receiving patients	○	○	○	●
Patients	○	○	○	○
Ambulance services	○	○	○	●
Suppliers	●	●	○	○
Utility companies	●	●	○	○
Water boards	●	●	○	●
Municipalities	●	●	○	●
Safety regions	●	●	○	●

Engaged: ●
Not engaged: ○

Discussion
The flood preparedness of the RdGG and EMC have been assessed and recommendations on which stakeholder should be engaged and how this could be achieved were made. The most important remarks regarding the applicability and limitations of this research are discussed.

Two different equations were proposed to calculate the number of fatalities. One equation was proposed for the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept". The outcomes of this equation are influenced most by the assumed duration of the flood and the mortality rate. A different equation was proposed for "preventive evacuation". This equation is most sensitive to the mortality rate for successful and unsuccessful preventive evacuation.

The two selected hospitals have varying characteristics. Because the methods from this research could be applied to these hospitals, they are expected to be applicable to other hospitals too. However, by studying only two hospitals, the applicability of the method that was developed could only be verified to a limited extent.

This research has made a number of scientific contributions. First, this studies proposed six flood preparedness indicators that also take into account the dependency of hospitals on services that are externally supplied. Furthermore, this research provides a detailed overview of fatalities and cost estimations per flood strategy to facilitate decision-making of flood strategies. This research also makes recommendations on which stakeholders should be involved per flood strategy. In addition, medical experts who have experience hospital floods were asked for their view on how stakeholders could be engaged. These expert opinions are a first step towards creating a policy where relevant stakeholders are actively engaged for the implementation of flood strategies at Dutch hospitals.

Conclusion
Essential hospital functions can be categorised based on the flood preparedness indicators. The availability of these indicators during floods can be used to quantitatively assess flood preparedness in terms of fatalities and types of costs. The results of the assessment can be used to compare flood strategies that can be implemented to contribute to flood preparedness. For the RdGG and EMC, "shelter in place with additional measures" yield the least amount of fatalities and is therefore the "best" flood strategy. Stakeholders were identified per flood strategy, which showed that for every flood strategy, except for "accept", at least the Executive Board of a hospital, hospital personnel, water boards, municipalities and safety regions should be engaged to realise the implementation of flood strategies. Experts with lived experience recommended to engage stakeholders through legislation or creating awareness. In conclusion, flood preparedness has been assessed, enabling decision-making regarding flood strategies. By engaging the right stakeholders for the implementation of these flood strategies, the flood preparedness of hospitals in the Netherlands can be improved.

For future research, it is recommended to add more cases to verify whether the proposed methods are generally applicable to Dutch hospitals. To estimate the number of fatalities per flood strategy more accurately, it is recommended to calibrate the fatality equations based on historical flood events at hospitals. Lastly, it is recommended to analyse the vulnerability of the regional healthcare system to supplier failure during floods. It is suggested to consider all scenarios that can flood suppliers and to prioritise suppliers that distribute supplies to multiple hospitals.

Contents

Acronyms

AHN	Actueel Hoogtebestand Nederland
CBS	Central Agency for Statistics
CE	Civil Engineering
CME	Construction Management & Engineering
DPRA	Delta Programme for Spatial Adaptation
EMC	Erasmus Medical Centre
HV	high voltage
HWBP	Flood Protection Programme
HSI	Hospital Safety Index
IC	intensive care
IDD	Individual Double Degree
LCPS	Landelijk Coördinatie Centrum Patiëntenspreiding
LIWO	National Water and Floods Information System
LNAZ	Landelijk Netwerk Acute Zorgketens
MV	medium voltage
PDPC	Pandemic & Disaster Preparedness Center
PIA matrix	power-interest-attitude matrix
RdGG	Reinier de Graaf Gasthuis
RWS	Rijkswaterstaat
SQ	sub-question
VCMC	VieCuri Medical Centre
WTS	Wet tegemoetkoming schade bij rampen

1. Introduction

1.1 Context

Functions such as electricity, drinking water, telecommunications, transport and healthcare are part of the vital and vulnerable functions in the Netherlands. Failure of these functions may result in severe consequences on a national scale (Kennisportaal Klimaatadaptatie, n.d.). One of the causes for failure of these functions that has to be anticipated in the Netherlands is floods. There are several types of floods in the Netherlands, illustrated in Figure 1.1. For this research, breaches of primary and regional flood defences (type 6 and 5), high water at the outer dyke area (type 7) and extreme precipitation (type 1) are considered. Approximately 47% of the Netherlands is protected against floods by primary flood defences. 62% of the Dutch population (in 2022), or 10,9 million people, lives in this threatened area. If the regional flood defences fail, approximately 20% of the Netherlands could be flooded. An additional 4% of the Netherlands is outer dyke area that can be flooded, housing 75.000 people. Extreme precipitation can occur throughout the Netherlands. Floods of this type usually occur due to high-intensity rainfall or large-scale and long-lasting rain events (Mens et al., 2024).

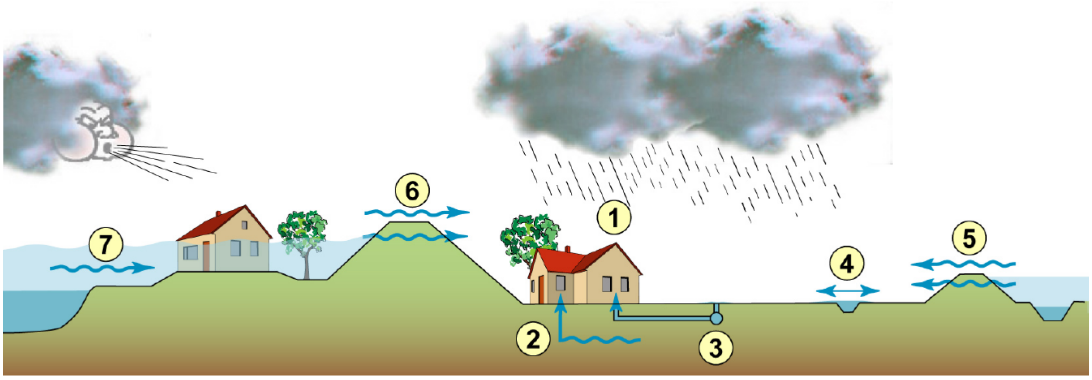


Figure 1.1: Types of floods in the Netherlands. 1: Precipitation directly on the object. 2: High groundwater level. 3: Overloaded sewage systems. 4: Overflowing of regional surface water. 5: Breach of regional flood defences. 6: Breach of primary flood defences. 7: Flooding of an outer dyke area (Klopstra & Kok, 2009).

Climate change leads to more extreme weather, which poses a risk to the water safety of the Netherlands (Ministry of Infrastructure and Water Management, 2023a). To reduce the risk of flooding, the multi-layer safety approach is used in the Netherlands (Figure 1.2). The original approach contained three layers: prevention, mitigating consequences and spatial planning. Recovery and water awareness were later added, bringing the total to five layers (Harbers, 2022):

1. Prevention. By building flood defences, floods can be prevented.
2. Consequence mitigation or spatial planning. When a flood occurs, spatial planning can mitigate the impact.
3. Crisis management. Through organisational preparation, further impact mitigation can be achieved.
4. Recovery. Damage cannot always be prevented, which is why recovery is an important aspect to consider.
5. Water awareness. Citizens should be aware of the flood risks that they are exposed to and should know what they can do themselves to prevent problems with excess water.

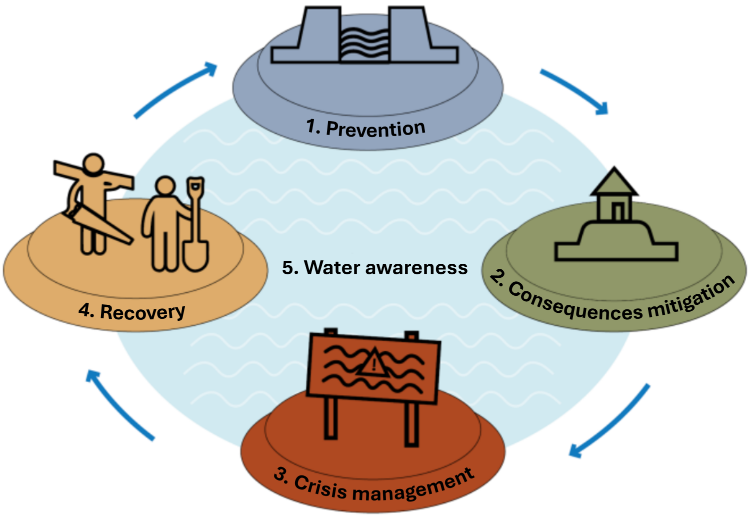


Figure 1.2: The five layers of multi-layer safety as proposed by the Pluvial and River Flooding Policy Platform (Harbers, 2022).

The Delta Programme for Spatial Adaptation (DPRA) is part of the multi-layer safety vision. This programme aims to make the Netherlands resilient to heat, water shortages, excess water and the effects of flooding by 2050 through spatial adaptation (Ministry of Infrastructure and Water Management, 2023a). Regional stress tests are conducted in the context of the DPRA to identify vital and vulnerable functions. After the stress tests, risk dialogues are held to arrive at an implementation agenda for that region.

In 2021, extreme precipitation in Belgium, Germany and the southern part of the Netherlands caused high water levels in the river Meuse. This event lead to floods throughout Limburg and to the evacuation of the VCMC in Venlo. This hospital is located adjacent to the Meuse and is protected by a dyke. Before the construction of the dyke, the VCMC had been flooded before in 1993 and 1995. In 2021 it was feared the dyke would overflow. Ultimately, no flooding occurred, but the hospital was out of use for five days. It took two days to reopen the hospital because all installations had to be restarted and their correct functioning had to be verified (VieCurie Medisch Centrum, 2021; Wijkhuis & Van Duin, 2023). In the aftermath, the Pluvial and River Flooding Policy Platform (in Dutch: Beleidstafel wateroverlast en hoogwater) was established. This platform recommended adding recovery and water awareness to the multi-layer flood risk approach. The platform also urged to start performing supra-regional stress tests (in Dutch: bovenregionale stresstesten) in addition to the existing regional stress tests to identify the consequences of an extreme precipitation event at the scale of the water system and possible cascade effects. Lastly, the platform proposed to have "Water and Soil as Leading Factors" (in Dutch: "water en bodem sturend"). This policy means that spatial planning is adjusted to (ground)water, instead of vice versa (Harbers, 2022).

1.2 Problem definition

The Dutch flood risk management approach (see Section 2.2) aims to achieve flood preparedness for vital and vulnerable functions, such as hospitals, through spatial adaptation. However, the risk dialogues used for this purpose are unstructured (Kennisportaal Klimaatadaptatie, 2021). There are no prescriptions for the involvement of certain stakeholders, such as hospitals (see Section 2.2). No method exists to systematically decide on which flood strategies (see Section 2.3) should be implemented to guarantee the flood preparedness of hospitals. The same applies to the decision of which stakeholders should be involved in the implementation of these flood strategies (see Section 2.4.3).

Hospitals are required by law to have disaster preparedness plans, but the required contents are not specified. The quality of hospitals' disaster preparedness is qualitatively assessed through self-evaluation and intercollegiate assessment (Landelijk Netwerk Acute Zorg, 2024). As a result, Dutch hospitals are not adequately prepared for disasters (Blanchette et al., 2023). Flood risk, for example, is often neglected by hospitals. Because hospitals do not have qualitative tools to compare flood strategies, they cannot make substantiated choices about flood coping strategies (Kolen, 2013; Van Eijk, 2022; World Health Organization, 2017). Hence, in practice, investments for flood risk management are rarely made (Kolen et al., 2017).

If a hospital is expected to be unable to maintain the continuity of healthcare, risking patient safety, the decision is made to evacuate (McGinty et al., 2017). In the Netherlands, this flood strategy has been proven to be possible for one threatened hospital. However, up to eleven hospitals can be simultaneously flooded in the Netherlands. In that scenario, hospitals, along with the local population, are unlikely to be able to leave the threatened area in time (Kolen, 2023). Other researches also indicate that evacuation is not always the preferred strategy, but deciding which strategy is "best" in specific situations is an ongoing matter (Kolen, 2013; McGinty et al., 2017; Zane et al., 2010).

In summary, hospitals in the Netherlands are not adequately prepared for floods. There are no guidelines on how to determine which flood strategies should be implemented at hospitals and how stakeholders should be involved in the implementation.

1.3 Research objectives and scope

The goal of this research is to overcome the problems stated in the previous section by developing a quantitative method to assess hospital flood preparedness, with the aim of enabling hospitals to decide on flood strategies. Furthermore, this research aims to obtain information on which stakeholders should be engaged for the implementation of each flood strategy considered and to make recommendations on how stakeholder engagement can be achieved.

This research is limited to the policy for improving the flood preparedness of hospitals in the Netherlands. More specifically, it makes recommendations on methods that could be used to decide between flood strategies and on methods to engage stakeholders. However, it does not prescribe the content of the results. In this line of thought, the execution phase is excluded.

It should be acknowledged that causes for floods may be different for certain regions of the Netherlands (e.g. caused by storm surges, extreme river discharges, etc.). For this research, floods caused by precipitation events and breaches in primary or regional dykes are considered. These different types of causes of floods may result in varying recommendations with regards to flood strategies for hospitals, depending on the region.

The methods of this research are intended to be applicable to Dutch hospitals. Other types of vital and vulnerable infrastructure are not considered in this research. Causes of disasters, different from floods, that can disturb healthcare continuity are beyond the scope of this study.

1.4 Research questions

The main research question is:

How can flood preparedness of hospitals in the Netherlands be assessed and improved?

To answer this question, several sub-questions (SQs) are formulated.

SQ1 Which flood preparedness indicators are relevant for contributing to the choice of flood strategies implemented by Dutch hospitals?

SQ2 What is the flood impact on Dutch hospitals given their level of flood preparedness?

SQ3 Which stakeholders should be involved per flood strategy in the process of implementing flood strategies for Dutch hospitals?

SQ4 How can relevant stakeholders be engaged for the implementation of flood strategies according to experts with lived experience?

To address the research gaps corresponding to the problems stated in Section 1.2, first, flood preparedness indicators will be identified that together indicate the level of flood preparedness of a hospital. Based on the level of flood preparedness, the flood impact can be assessed per flood strategy, allowing comparison of flood strategies. Then, it is researched which stakeholders should be engaged to implement flood strategies at hospitals. Finally, medical experts who have experience with hospital floods are asked about their view on how stakeholders could be engaged. These experts work on the interface between healthcare and flood risk management. Therefore, their interdisciplinary perspective is a valuable contribution to this research.

1.5 Report structure

Chapter 2 contains the literature review. Concepts fundamental to this research are introduced in this chapter. Chapter 3 describes the methodology for this research. The cases, flood scenarios and interviews are introduced. In Chapter 4 the flood preparedness indicators for hospitals are selected. In Chapter 5, the impact of floods on hospitals is quantified with the help of the flood preparedness indicators. In Chapter 6, stakeholders are selected per flood strategy for the implementation of these flood strategies. The applicability of the proposed methods is discussed in Chapter 7. In Chapter 8, the final conclusions are drawn and recommendations for further research are given.

2. Literature review

This chapter elaborates on the research problems and gaps introduced in Section 1.2. First, flood preparedness of hospitals is defined in Section 2.1. Section 2.2 discusses policies of the Dutch government that are aimed at flood protection of the Netherlands and hospitals in specific. In Section 2.3, the four *flood strategies* that are used throughout this thesis are introduced. Previous studies and their findings and limitations are discussed in Section 2.4. Research gaps are identified and the concept of *flood preparedness indicators* is introduced. Finally, Section 2.5 summarises the research gaps.

2.1 Defining flood preparedness of hospitals

Preparedness for disasters in the context of healthcare is the knowledge and capacity to ”anticipate effectively, respond to and recover from the impacts of likely, imminent or current hazard events or conditions” (World Health Organization, 2015, p. 132). This definition of preparedness is similar to the definition of *resilient healthcare systems* by Rentschler et al. (2021), who also state that such a system should be able to maintain its core functions and protect human life during a disaster. According to Van Beek et al. (2015), flood preparedness of hospitals is defined as being prepared for floods or extreme precipitation events that may threaten patient safety or the operations of the hospital. World Health Organization (2015, p. 7) elaborates on the safety aspect of hospitals during crises: the services of a hospital should ”remain accessible and functioning at maximum capacity” throughout disasters. The recurring aspects of these definitions are combined and yield a definition of flood preparedness of hospitals that will be used in this research. Flood preparedness of hospitals is defined as the anticipation and mitigation of flood disasters to reduce the impact on the core functions of hospitals during and directly after the flood event with the goal of protecting human life.

2.2 Flood risk management approach in the Netherlands

To ensure that the Netherlands remains safe for decades to come, new safety standards for flood defences were added to the Water Act in 2017. As of 1 January 2024, the Water Act has been merged with other acts into the Environment and Planning Act (Dutch: Omgevingswet). This act contains almost all laws regarding water. It specifies the responsibilities of government agencies with a water management function. These agencies are Rijksoverheid[1], provinces, water boards[2] and municipalities. The Environment and Planning Act also stipulates that the Delta Programme Commissioner, the head of the National Delta Programme,

[1]The Rijksoverheid, or central government, is the part of the government that works on national level. Ministries are part of the Rijksoverheid.

[2]The Netherlands has 21 water boards. They are responsible for water management in their region.

must publish a Delta Programme every year. The Delta Programme has three main themes: water safety, fresh water and spatial adaptation. Parts of the Delta Programme are highlighted to provide context of the Dutch flood risk management approach in the Netherlands and to address the policy gap related to determining and implementing flood mitigating measures at hospitals in the Netherlands.

2.2.1 Flood Protection Programme

The Flood Protection Programme (HWBP) is part of the Delta Programme for Water Safety. The water boards and Rijkswaterstaat (RWS) collaborate to execute the dyke reinforcements for the HWBP. The predecessor, named HWBP-2, is nearly finished. The current HWBP started in 2014. By 2050 all flood defences should meet the safety standards. Once the reinforcement is completed, for people living behind dykes, the chance of death caused by a flood is 1/100.000 per year or lower, depending on the consequences of a flood. It is the largest dyke reinforcement programme since the Delta Works, comprising 1500 km of dykes and more than 400 structures (Ministry of Infrastructure and Water Management, 2023b).

2.2.2 Delta Programme for Spatial Adaptation

Not only is there a focus on flood prevention in the Delta Programme, the DPRA focusses on spatial adaptation to minimise the impact of floods when they occur. Also heat stress and droughts are considered. The goal is to realise a climate-resilient and water-robust spatial planning. The yearly updated DPRA contains the progress and plans for the *Delta Decision for Spatial Adaptation*, *Preferential Strategies* and *Delta Plan for Spatial Adaptation*.

2.2.3 Delta Decision for Spatial Adaptation

The Delta Decision for Spatial Adaptation is a national framework that contains ambitions regarding spatial adaptation that apply to the whole of the Netherlands. Every six years, the framework is reassessed and updated accordingly. The ambitions are translated into regional specific Preferential Strategies. These give direction to the measures that are to be developed as part of the Delta Plan for Spatial Adaptation.

2.2.4 Delta Plan for Spatial Adaptation

The Delta Plan for Spatial Adaptation describes what measures will be implemented and the corresponding planning. The Netherlands has been divided into 45 working regions where the Rijksoverheid, provinces, water boards and municipalities cooperate to accelerate the implementation of spatial adaptation. The region have to conduct stress tests every six years to identify vulnerabilities of objects and functions regarding the themes water nuisance, heat stress, droughts and floods. Information is collected on the effects of climate change and predicted problems with regard to vulnerable objects and functions. Special attention is paid to the identification of vital and vulnerable functions. On a national level, 13 vital and vulnerable functions are distinguished. Access to healthcare is one of them. Then, risk dialogues are held among government agencies and other local stakeholders. The aim of these dialogues is to raise awareness, to determine which risks are acceptable and to develop measures. Subsequently, these measures are then put on the implementation agenda (Ministry of Infrastructure and Water Management, 2023a). It is not prescribed how the stress tests and risk dialogues should be conducted. The available time and work capacity determine how extensive and thorough this process will be (Kennisportaal Klimaatadaptatie, 2021). Therefore, consistency in the involvement of objects and stakeholders across different working regions cannot be guaranteed. Therefore, there is no consistent process for determining and implementing flood mitigating measures for hospitals.

2.3 Flood strategies used by hospitals

When there is a flood threat, the available information is based on weather forecasts and predicted water levels. Due to uncertainty in the prediction models, it is uncertain whether a flood will occur and where it would take place. As a result, the threatened area is likely to be larger than the flooded area. Consequently, only a part of the threatened hospitals will be flooded. The time available between the detection of the threat and the onset of the flood is used to initiate flood strategies to reduce the impact of a possible flood. Therefore, hospitals use flood strategies more often than they are flooded. These flood strategies may also have a negative impact. However, this impact is accepted because flood strategies reduce the impact of floods, which may possibly be greater than the impact of flood strategies (Kolen, 2023). Flood strategies that are typically used by hospitals are "preventive evacuation", "shelter in place with additional measures" and "shelter in place without additional measures" (Balsari et al., 2016; Kolen, 2023; McGinty et al., 2017). These flood strategies are described in detail in this section. As mentioned in Section 1.2, deciding which flood strategy is "best" can be different per hospital and is an ongoing matter. Section 2.4 addresses what is known in the literature about deciding between these flood strategies.

Preventive evacuation
This flood strategy is initiated when there is a flood threat, before the flood occurs. All patients and staff leave the threatened hospital and are relocated to other hospitals that are not threatened. Two factors determine the success of preventive evacuation: the size of the threatened area and the available time for evacuation. The size of the threatened area determines how many hospitals are simultaneously threatened. In the Netherlands, up to eleven hospitals may be simultaneously flooded, assuming that only one breach can occur simultaneously (Kolen, 2023). The number of simultaneously threatened hospitals may be much higher, because it is uncertain where the breach will occur. Due to this uncertainty, many of these threatened hospitals are expected to evacuate preventively, although not all of these hospitals are flooded. Hospital patients are vulnerable and often need special vehicles (such as ambulances) to be safely evacuated. If multiple hospitals are simultaneously evacuating, these resources have to be divided, resulting in a slower evacuation process. Besides hospitals, other people will also want to leave the threatened area at the same time, using the same infrastructure. This may lead to congestion and may further slow the evacuation. The accessibility of the non-threatened area also influences the evacuation progress. The amount of available time depends on when flood warnings are given. The evacuation fraction indicates what fraction of the evacuees is able to get to a safe area before the onset of the flood. Depending on these factors, preventive evacuation is not always viable. Especially for densely populated areas with a large number of hospitals the evacuation fraction is relatively low (Kolen, 2013). It should be noted that evacuation, even if successful, remains a

risky undertaking for patients and can cause death (McGinty et al., 2017).

Shelter in place with(out) additional measures
Another flood strategy is to shelter in place. The hospital is prepared for the flood by moving people and equipment to higher floors of the hospital where the flood cannot reach. However, this flood strategy can still lead to harsh conditions within the hospital, posing a threat to vulnerable patients. Therefore, it may be decided to take additional measures. Such flood mitigating measures may consist of (Kolen, 2023; Van Beek et al., 2015):

- Spatial adaptation of the hospital to reduce damage. This can consist of permanently relocating equipment to higher locations, waterproofing the hospital, constructing (temporary) flood barriers or adding redundant equipment. For example, after repeated flooding from the river Meuse, a dyke was constructed to protect the VCMC (Van Beek et al., 2015). At the hospital in Tampa (Florida), temporary flood barriers were installed outside the hospital to protect the hospital against Hurricane Milton (Toussaint, 2024). Alternatively, flood barriers can also be installed in doorways. The Slingeland Hospital in the Netherlands used sandbags and pumps to combat flooding caused by a heavy precipitation event (NOS, 2024). At the EMC, doorsteps are elevated to prevent water from easily flowing into or through the hospital (HKV lijn in water, 2017). Lastly, the Meander Medical Centre in the Netherlands has placed all critical equipment above the expected flood level (Van Beek et al., 2015). Each of these spatial adaptation measures has the goal to reduce the recovery time after the flood.
- Increasing stocks and staffing to be able to continue functioning independently for a longer period of time.
- Making emergency plans for the rescue or resupply of the hospital, reducing the time that patients are exposed to harsh conditions.
- Discharging patients who are healthy enough to be independent of acute medical care, reducing the number of patients in the hospital that is affected by the flood.

Accept
Another flood strategy may be to accept hospital flooding. No efforts are made to prepare the hospital or its patients for the flood. Although it is not realistic to expect hospitals to have no emergency plans at all, it can be argued that hospitals without emergency plans regarding floods have adopted this flood strategy. This flood strategy can be seen as a benchmark to compare other flood strategies.

Four flood strategies that are typically used by hospitals are considered for this research: ”preventive evacuation”, ”shelter in place without additional measures”, ”shelter in place with additional measures”, and ”accept”. These flood strategies are used to increase the flood preparedness of hospitals. In the next section, it is discussed how previous studies assess flood preparedness and decide on flood strategies.

2.4 Previous studies

2.4.1 Assessment of hospitals’ flood preparedness

To find literature on assessment of hospitals’ flood preparedness, the following search query was used in Scopus:

TITLE-ABS (flood AND hospital* AND ("flood impact" OR index OR preparedness))*

This query lead to the identification of 143 documents, of which 4 documents were selected based on title and abstract. Additional documents were provided by experts. The sources used by the researches that were found were used to identify additional documents.

In the area of flood risk management, several previous studies used indicators to assess flood risk and impact for an area or building. In these studies, a set of indicators is defined that together can model a flood-related concept, such as urban flood resilience (Batica & Gourbesville, 2014), flood susceptibility (Miranda et al., 2023), flood risk (Phongsapan et al., 2019) and hospital disaster preparedness (World Health Organization, 2015). These indicators are assessed separately and are subsequently aggregated, resulting in a single overall score. For instance, to quantify preparedness of hospitals for serval types of disasters, the Hospital Safety Index (HSI) was developed (World Health Organization, 2015). The HSI consists of 151 indicators that are assessed by experts. As a result, scores per indicator and an aggregated safety score are obtained. Therefore, the HSI yields a comprehensive overview of hospital disaster preparedness (including flood preparedness). In general, using indicators to assess flood risk and impact enables making specific recommendations on improvement and effective resource allocation (Phongsapan et al., 2019; World Health Organization, 2015). However, regarding the HSI, the assessment of the extensive set of indicators has to be carried out by a well-trained multidisciplinary team that requires full access to a hospital. This makes the application of the HSI impractical (Lamine et al., 2023). In addition, the tool considers a wide range of disasters making the tool less suitable for specifically assessing flood preparedness of Dutch hospitals.

Another study investigated the flood preparedness of hospitals in the Netherlands (Van Beek et al., 2015). A case study and questionnaires were conducted to identify critical hospital facilities and their location within the hospital building. By comparing the elevation of the hospital facilities and expected flood depths it was determined which facilities can get flooded. Recommendations were made for spatial adaptation of hospitals, but the recommendations do not take into account which measure best suits a particular flood strategy. Furthermore, it is not taken into account which stakeholders would be needed to implement these spatial adaptation measures. The research underlined that the availability of access roads and externally provided facilities (such as supplies, personnel and utilities) is a prerequisite for critical hospital functions to remain available. However, these externally provided facilities were not further considered.

That the flood impact as a direct consequence of flooding at the hospital is already quite well-researched is confirmed by another research (Kolen et al., 2017). The probability of occurrence of water depths at a certain location is, for example, summarised in flood risk profiles (see Section 3.3). It should be emphasised that hospitals function in a network (Kolen et al., 2017). So in addition to direct consequences, hospitals can experience indirect consequences from floods even though the hospital itself is not flooded. Certain supplies are delivered multiple times a day to a hospital. In addition, hospitals often buy medical supplies in bulk to save money. Many hospitals are simultaneously affected if such a supplier is flooded. The flooding of suppliers can disrupt the delivery of food or medicines, for instance, jeopardising the continuity of healthcare at hospitals. The cascade effects due to the failure of other parties in this network, such as suppliers, have not been mapped by previous studies.

Flood preparedness of hospitals has been analysed in previous studies. The applicability of indicator-based assessment in the area of flood risk management has been proven and has already been applied to hospitals. What is lacking is a set of indicators that is relevant for assessing flood preparedness of hospitals in the Netherlands. In this research, this set of indicators is referred to as *flood preparedness indicators*. Through considerate selection of these flood preparedness indicators, this research regards both direct and indirect flood impact.

2.4.2 Flood strategy decision-making

To find literature on flood strategy decision-making, the following search query was used in Scopus:

TITLE-ABS (flood AND hospital* AND (strategy OR measure*) AND (decide OR decision* OR compar*))*

In total, 71 documents were identified through this query. Based on title and abstract, 1 source was selected. Additional documents were suggested by experts to increase the number of useful sources. The bibliography of the identified documents led to the identification of more sources.

Besides assessing flood preparedness of Dutch hospitals with flood preparedness indicators, it is desirable to compare flood strategies (see Section 2.3) and decide which is preferable for a specific hospital. In the literature, there is a decision guide for hospital evacuation (Zane et al., 2010). This guide suggests self-assessment of hospitals to decide between evacuation and shelter in place. The self-assessment is supported with a list of questions pertaining to the vulnerability of critical hospital facilities. The decision process is summarised in a flow chart. However, this guide is not specific to flood disasters and only considers evacuation and sheltering in place. In addition, the guide does not allow for comparison of flood strategies. Research looking at the flood strategy decision process in hospitals during Hurricane Sandy suggested that data on morbidity and mortality associated with the stay or go decision would allow decision makers to better assess risks, aiding hospitals in the decision-making process (McGinty et al., 2017). Previous studies looked at quantitative comparison of flood strategies for hospitals in the Netherlands (Kolen, 2013, 2023). The number of expected fatalities was calculated per flood strategy with optimistic and pessimistic assumptions about the number of affected people and the mortality rate. Although the calculation allowed for comparison of flood strategies, it remains conceptual and is not applied to an existing hospital.

Deciding on flood strategies has previously been researched. Quantification of flood impact per flood strategy enables hospitals to compare flood strategies and decide on the most preferable option. Although calculations have been made in previous reports for illustrative purposes, quantitative comparison of flood strategies has not yet been applied to specific hospitals.

2.4.3 Stakeholder engagement and hospitals' flood preparedness

To find literature on stakeholder engagement to improve flood preparedness, the following search query was used in Scopus:

TITLE-ABS((flood AND (stakeholder* OR collaborative* OR engagement*) AND hospital*))*

This search query resulted in 36 sources from which, based on title and abstract, one source was selected. Various search queries with similar terms were used, which yielded no new useful results. Experts provided additional sources. Furthermore, the bibliography of relevant sources was used to further expand the number of papers.

In the collected literature, it was found that a knowledge gap exists at hospitals in terms of knowledge about the local impact of floods. Therefore, hospital employees cannot make informed decisions about flood preparation (Van Eijk, 2022; World Health Organization, 2017). In many hospitals, the knowledge of spatial and organisational factors, such as the vulnerability of hospital buildings and the redundancy of hospital resources, must be expanded. Many authors state that flood preparedness is necessary for hospitals to mitigate the effects of flood disasters and that flood preparedness must be achieved through the engagement of external experts, among others, from the field of flood risk management and spatial planning (Adelaine et al., 2016; Krause et al., 2023; Ministry of Infrastructure and Water Management, 2023a; Rattanakanlaya et al., 2021; Van Eijk, 2022; World Health Organization, 2017). However, other studies found that when the number of disciplines involved increases, social complexity arises (Bergman & Beehner, 2015; Den Heijer et al., 2023). People from different disciplines will have different roles, views and responsibilities in a framework. Furthermore, dependence on specific individuals (e.g. flood experts) during disasters makes disaster response unreliable (Adelaine et al., 2016). Nevertheless, despite its complexities, an integrated approach can overcome separated policy approaches, providing better solutions and facilitating their implementation (Cumiskey et al., 2019).

To combat the impact of floods on hospitals, the literature suggests that flood preparedness is necessary. To achieve flood preparedness, it is recommended that stakeholders from different disciplines are involved, in addition to hospitals. However, in the literature it is not discussed which stakeholders should be engaged to improve flood preparedness of hospitals, indicating a research gap. The small number of articles identified with the search query supports this finding. This research focusses on which stakeholders should be engaged to achieve flood preparedness of hospitals in the Netherlands. In addition, medical experts who have experience with hospital floods are asked for their view on how stakeholders could be engaged for the implementation of flood strategies, providing an interdisciplinary perspective.

2.5 Summary of research gaps

Several research gaps have been identified in this chapter. Firstly, the Dutch flood risk management approach does not contain clear guidelines on how to determine which flood strategies should be implemented at hospitals to improve their flood preparedness and which stakeholders should be engaged for implementation. The literature was used to identify to what extent these gaps have been addressed. Indicators have previously been applied to assess disaster preparedness of hospitals. However, there is no set of indicators to assess flood preparedness of hospitals. In addition, most studies have mainly considered the direct impact of floods when analysing flood preparedness, disregarding the indirect impact. The literature suggested that quantification of flood impact enables comparison of flood strategies. However, such calculations have not been applied to specific hospitals, considering four different flood strategies. Furthermore, many sources recommend engaging stakeholders from different disciplines to improve flood preparedness, but which stakeholders should be engaged per flood strategy has not been addressed. Moreover, how these stakeholders could be involved for the implementation of flood strategies at Dutch hospitals has not been explored. This research addresses these gaps by answering the research questions from Section 1.4.

3. Methodology

This chapter explains the methodology used for this research. First, the research setup is presented (Section 3.1). Then, cases for the case study are selected and introduced (Section 3.2). The corresponding flood scenarios and its source are discussed (Section 3.3). Next, the phase 1 and phase 2 interview methods are explained (Section 3.4). The methodology for the stakeholder analysis is explained (Section 3.5). Then, the selection process for flood preparedness indicators is explained (Section 3.6). Subsequently, it is described how the flood preparedness of hospitals can be quantitatively assessed (Section 3.7).

3.1 Research setup

In this section, the expected outcomes from the research questions are listed and the corresponding research setup is described. The type of research determines for a large part the research setup that is followed. This research's type is briefly analysed.

This section describes how each sub-question is answered. An overview of the expected results per study and for each sub-question is listed in Table 3.1. Figure 3.1 shows a schematic overview of the research setup. It indicates the order of the research, what processes are executed in parallel, which processes depend on each other and shows how the sub-questions are answered. This scheme will be described below.

Table 3.1: Expected research outcomes.

	Expected outcome
Main research question	A method for quantitatively assessing the flood preparedness of hospitals in the Netherlands along with recommendations on the engagement of stakeholders for the implementation of flood strategies.
SQ1	A selection of flood preparedness indicators that are critical to the continuity of healthcare at hospitals.
SQ2	A method for assessing the flood impact on hospitals in the Netherlands.
SQ3	A description of relevant stakeholders per flood strategy for the implementation process of flood strategies chosen by hospitals, structured by their power, interest and attitude.
SQ4	Experts' views on stakeholder engagement methods and their pros and cons.

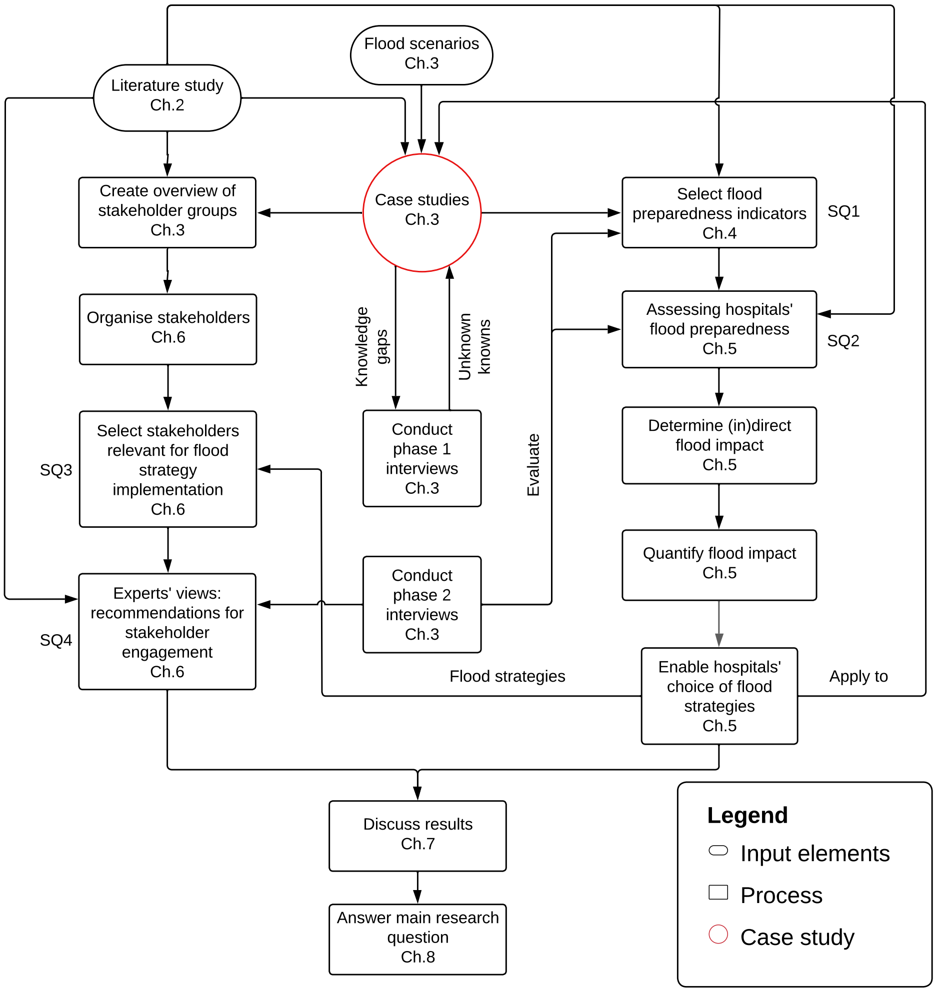


Figure 3.1: Scheme of the research setup. The steps in this figure are described in this section.

Cases: Two hospitals are selected as cases for the case study. As part of the case study, phase 1 interviews and tours of hospitals are held. The information obtained from this is used throughout the chapters. The case study serves as a tool for obtaining an overview of flood preparedness indicators (Chapter 4, *SQ1*). It is also used to develop an assessment method for flood preparedness of hospitals (Chapter 5, *SQ2*). Additionally, it yields an overview of stakeholder groups (Section 3.5, *SQ3*). The cases are introduced in Section 3.2 and the phase 1 interviews and tours are introduced in Section 3.4.1.

Select flood preparedness indicators: Several sources are used to identify flood preparedness indicators of hospitals. Flood scenarios are accessed via the LIWO (in Dutch: Landelijk

Informatiesysteem Water en Overstromingen) to obtain information about factors such as flood depth, the evacuation fraction and accessibility. The data from the LIWO can be accessed through the following url: https://basisinformatie-overstromingen.nl/#/maps. Literature on the continuity of healthcare in the context of floods, flood strategies, redundancy and critical services in hospitals are consulted. The phase 1 interviews are conducted with emergency management and logistics employees from hospitals and with a flood risk expert to complement the information found in the literature on flood preparedness indicators. The selected flood preparedness indicators were evaluated through the phase 2 interviews. This part of the research answers *SQ1* and is elaborated in Chapter 4.

Assessing hospitals' flood preparedness: The assessment of hospitals' flood preparedness is applied to the cases. The illustrative power of the cases make the assessment insightful. The flood preparedness indicators obtained from *SQ1* and the flood strategies are pivotal inputs to this process. The assessment is able to show how (in)direct impact of floods is influenced by the flood preparedness indicators, how flood impact can be quantified and which flood strategies are consequently at hand for hospitals to maintain continuity of healthcare. This answers *SQ2* and makes up Chapter 5. The assessment and underlying assumptions are evaluated. Historical case data could also be used for validation, but then it can only be validated whether the recorded flood impact, given the implemented flood strategies, corresponds with the predicted impact. The flood impact given other variations of flood strategies is unknown and therefore cannot be validated. Thus, limited validation can be achieved through this method. Therefore, expert interviews are used.

Stakeholder analysis and engagement: For *SQ3* stakeholder groups are identified through the cases, the literature and government websites and documents. These stakeholder groups are described and organised in a power-interest-attitude matrix (PIA matrix). The current and desired degree participation are analysed. The stakeholders are then selected if they have high power and interest and if they are relevant for the implementation of flood strategies. Selected stakeholders are organised per flood flood strategy. This part of the research answers *SQ3* and this content can be found in Chapter 6. It can be executed in parallel with the parts belonging to *SQ1* and *SQ2*. Subsequently, the phase 2 interviews are used to identify the view of experts with lived experience regarding stakeholder engagement methods. This answers *SQ4* and is described in Chapter 6.

3.2 Selecting cases

3.2.1 Selection criteria

Cases are used to understand the current response to flood risk at hospitals and to explore hospitals' vulnerabilities, methods for selecting flood strategies and the network of stakeholders. For this research, two cases are selected, which allows for variation in a number of hospital characteristics. The variation enables comparison and should be regarded as a first step towards providing solutions that can benefit all Dutch hospitals. Given the time frame available for this research, it was decided to look into only two hospitals more in depth, rather than analysing many hospitals, but superficially. The hospitals to be analysed are therefore of great influence to this research. The selection criteria for this "purposeful sampling" are discussed below.

- **Country:** Only Dutch hospitals are considered.

- **The type and severity of the flood threat:** Both of these factors may vary, based on a hospital's location within the Netherlands. For instance, there may be different causes of floods. As stated in the scope (Section 1.3), floods caused by precipitation events and breaches in primary or regional dykes are considered. The origin of the flood has implications for the predictability of a flood. In the Netherlands, riverine floods are more predictable than coastal floods. River discharges can be predicted by forecasting rainfall in the catchment area of a river and later on by measuring upstream discharges (Strijker et al., 2023). Coastal floods have a higher probability of being unforeseen (Kolen, 2013). The predictability determines the amount of time available for evacuation, which has a significant influence on the evacuation fraction of an area (Kolen, 2013). To enable comparison, it was decided to select hospitals that have a similar cause of flooding.
- **The number of simultaneously threatened hospitals:** This aspect is determined by area in which a hospital is situated. If many hospitals are threatened simultaneously, it is more difficult for an individual evacuating hospital to find hospitals in the vicinity that are able to take up patients. In addition, resources for evacuation, such as ambulances, have to be divided over multiple hospitals. This slows down the evacuation process and may affect the viability of the flood strategy "preventive evacuation". Therefore, one of the selected hospitals must be flooded on its own, while the other must have at least one other simultaneously flooded hospital.
- **The location within a flooded area:** This aspect affects the accessibility of a hospital. A hospital that is located in the middle of a large flooded area is less accessible than a hospital that is situated near the edge of a flooded area. This characteristic must be similar for both cases.
- **The size of the hospital (in terms of patient capacity, number of employees and floor area) and whether it is a university hospital:** Characteristics of university hospitals are that they conduct research and have a larger number of specialised departments compared to a regular hospital. In addition, they obtain grants for their research, meaning they have increased funds compared to other hospitals. For these reasons, university hospitals are also expected to have a more complex internal organisational structure and a more extensive network of stakeholders when compared to non-university hospitals. To be able to compare how these characteristics influence the implementation of flood strategies, one university and one non-university hospital is selected.
- **Previous flood experience:** Previous experience with floods may result in investments in flood preparedness, because of lessons learnt during the flood. Only few hospitals in the Netherlands have flood experience. Therefore, it is not a prerequisite for selection.
- **Practical considerations:** Data availability from previous studies and reports, experience with floods and accessibility through the personal network are pros when selecting cases.

3.2.2 Case introduction: Reinier de Graaf Gasthuis

The fist hospital that was selected is the RdGG. The RdGG is a non-university hospital that located in Delft, in the province of South Holland. This is part of the central coastal area of the Netherlands (see Figure 3.2). What makes this hospital special is that it was built entirely new in 2015 and that flood scenarios were taken into account during the design. It has a total capacity of 481 beds, of which 12 are intensive care (IC) beds. The hospital has approximately 2600 employees and a floor area of 56.500m^2 (MultiBel, 2022; Nationale

Intensive Care Evaluatie, 2023; Stevens Van Dijck, n.d.). The RdGG can be flooded due to a breach in the regional dyke system or by precipitation events. For both types of floods result in a confined flooded area with flood depths of less than 1 metre at the hospital location. The flood scenarios are discussed more extensively in Section 3.3. The hospital cannot be flooded as a result of a breach in a primary dyke. No other hospitals are simultaneously threatened by floods and no densely populated area is flooded. The hospital is located close to the edge of the flooded area. The hospital has no significant flood experience.

3.2.3 Case introduction: Erasmus Medical Centre

The second hospital that was selected it the EMC. The EMC is a large university hospital in Rotterdam, also located in the province of South Holland. After the completion of the most recent expansion in 2017, the hospital has approximately 1200 beds (of which 56 are IC beds), 14.000 workers and 400.000m^2 of floor space (HKV lijn in water, 2017). The hospital is located close to the river Meuse. Floods originate from storms at sea and extreme river discharges. A flood is caused by a breach at the Parksluizen, a lock in the (primary) dyke. Assuming one flood scenario will occur at the same time, up to 3 other hospitals will be simultaneously flooded: the Erasmus Medical Centre Cancer Institute, Erasmus Medical Centre Sophia Hospital and Franciscus Gasthuis Internal Medicine Outpatient Clinic. However, multiple breaches along the coastal area are expected to occur before a breach occurs at Parksluizen. The primary flood defence protecting the EMC was built before the Maeslant barrier was constructed and is therefore designed for higher water levels than it is currently exposed to (HKV lijn in water, 2017). Because an extreme storm at sea could also cause breaches in different places along the coast, 33 hospitals are simultaneously threatened (Kolen, 2023). Flood scenarios are discussed in more detail in Section 3.3. The EMC has not experienced significant floods. However, its flood risk has previously been analysed. And through contacts from the Pandemic & Disaster Preparedness Center (PDPC) additional information can be acquired from the Frontrunner Project *"Pandemic lessons for flood disaster preparedness"*.

Figure 3.2: Location of the RdGG and EMC.

Table 3.2: Characteristics of the RdGG and EMC.

Characteristic	RdGG	EMC
City	Delft	Rotterdam
Flood origin	Regional dyke breach & precipitation	Primary dyke breach
# simultaneously threatened hospitals	0	33
University hospital	No	Yes
Beds (IC)	481 (12)	1200 (56)
Employees	2600	14.000
Floor area [m^2]	56.500	400.000
Previous flood experience	None	None

The RdGG case will be elaborated in this research. The EMC case is analysed to a lesser extent. The cases are used to see to what extent recommendations regarding flood strategies may vary based on certain hospital characteristics. Neither hospital has experience with floods. However, as described, it is reasonable to think that there is enough information available to be valuable cases to this research. In addition, the hospitals are located in the vicinity of Delft, allowing visits to the hospitals and conversations with hospital staff in person. To add a broader view, phase 2 interviews (Section 3.4.2) will be held with (former) staff from the VCMC, a hospital with repeated and recent flood experience.

3.3 Flood scenarios and risk profiles

3.3.1 Data from the LIWO

The data used comes from the LIWO, from 2023. It is presented in maps of flood scenarios and flood risk profiles. The flood scenarios describe the water levels that result from extreme precipitation, high water levels and breaches of primary or regional dykes. The flood risk profiles show the frequency of occurrence of the flood depth at the chosen location in the Netherlands. It is a collection of all flood scenarios that can occur at that location. The flood probabilities are given as the yearly chance of experiencing a flood.

A conservative calculation method is used for the flood risk profiles. The safety standards for flood defences use the probability of exceeding a certain governing water level as the failure probability. However, it is recognised that the actual failure probability is smaller because of factors that are unaccounted for. Additionally, system behaviour and emergency measures are disregarded. An example of system behaviour is that the flood caused by failure of one dyke leads to the failure of a second dyke. Governing water levels and flood processes are not adjusted for breaches elsewhere. However, for flood scenarios of regional dykes, full interdependency has been assumed. If a breach occurs, the boezem[1] will drain, resulting in lower water levels, thus reducing the chance that another breach occurs. To account for this, the LIWO uses a failure probability that is five times smaller than the norm (HKV lijn in water, 2020).

3.3.2 Reinier de Graaf Gasthuis flood scenarios

There are four flood scenarios that threaten the RdGG. Table 3.3 and Figure 3.3 show the flood risk profile at the location of the RdGG. The scenario names, predicted water levels and their probability of occurrence are stated. The flood impact is discussed in Chapter 5.

Table 3.3: Flood scenarios for the current situation at the RdGG.

Scenario name	Flood depth [m]	Water level probability
Precipitation 10	0,15	1/9,8
Precipitation 100	0,30	1/83
Precipitation 1000	0,50	1/330
Regional 100	0,76	1/500

[1] A boezem stores water from a polder before it is discharged.

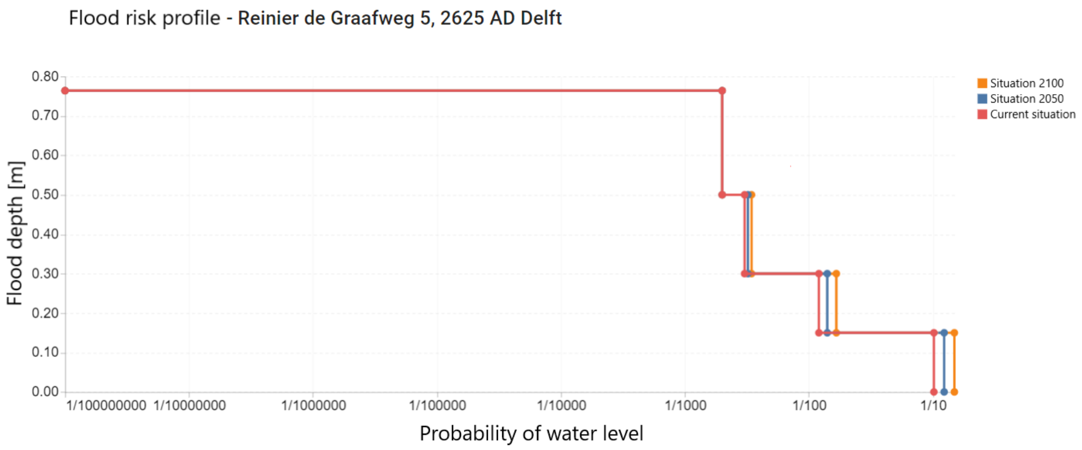
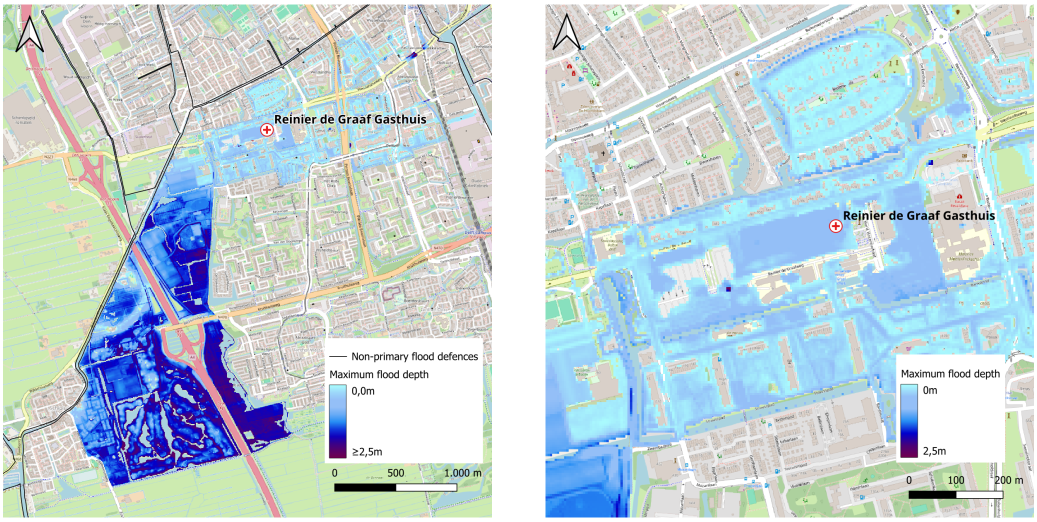


Figure 3.3: Flood risk profile of the RdGG.

Breach in regional dyke
The "Regional 100" flood scenario results from a breach in a regional dyke. Figure 3.4 shows how the region around the hospital is affected. Because a regional dyke system is breached, the extent of the flood and the flood depth are limited. Therefore, the hospital remains relatively easily accessible once flooded. The RdGG is the only hospital threatened and flooded by this scenario. Therefore, rescue efforts can all be focused on the RdGG. Usually, such breaches occur suddenly. In such cases, there is no time available for preventive evacuation. If the flood can be predicted, based on the stated flood conditions, it is expected that the entire hospital can be evacuated. The exact breach location cannot be identified from the LIWO data. However, this is not strictly necessary, since the impact is relevant for this research. According to the LIWO, the probability of exceedance of the dyke's water level norm is 1/100. As previously discussed, this results in a failure probability that is five times smaller: 1/500.



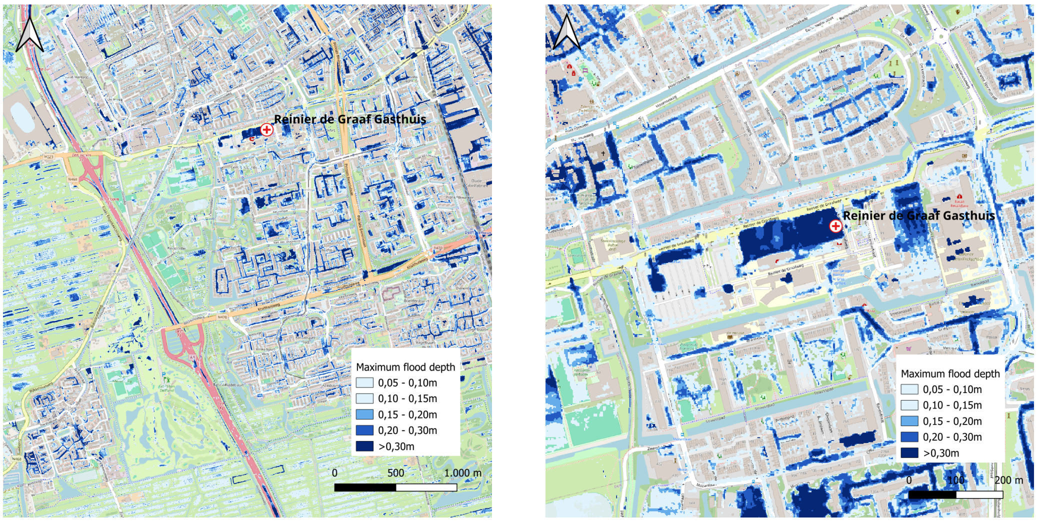
(a) Overview

(b) Zoomed in

Figure 3.4: Flood depth map resulting from a breach in the regional dyke system with classified chance of failure of 1/100, retrieved from LIWO (scenario 20931). The probability of the shown water level is assumed to be 1/500. The location of the RdGG has been indicated.

Precipitation scenario with a 1000 year return period

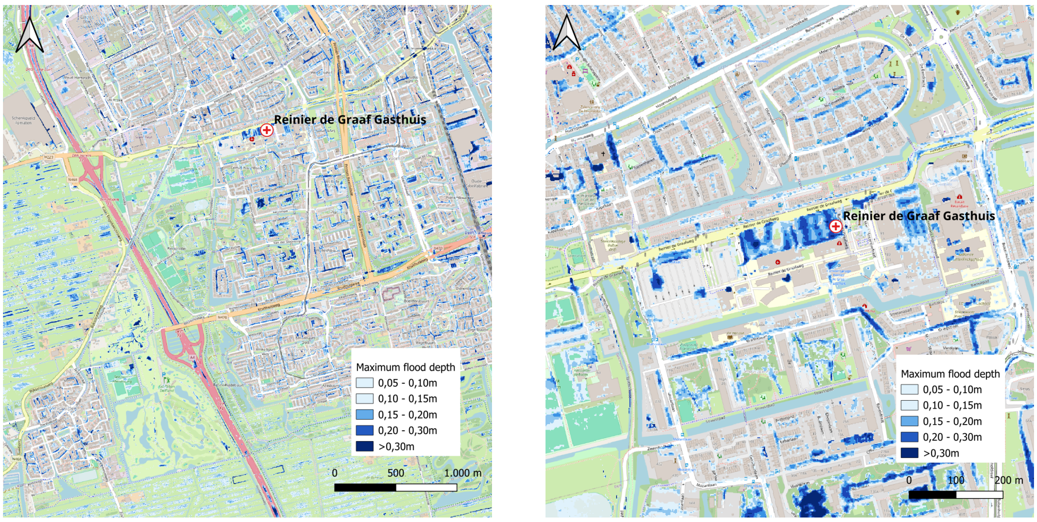
The "Precipitation 1000" scenario results from a short and intense precipitation event with a probability of occurrence of 1/1000 (see Figure 3.5). The precipitation event was modelled as a rain event of 140mm in 2 hours' time. Heavy precipitation events occur locally and can be predicted. However, uncertainty remains regarding their exact location, duration and intensity.



(a) Overview (b) Zoomed in

Figure 3.5: Flood depth map resulting from a heavy precipitation event. The probability of the shown water level is 1/1000. The location of the RdGG has been indicated.

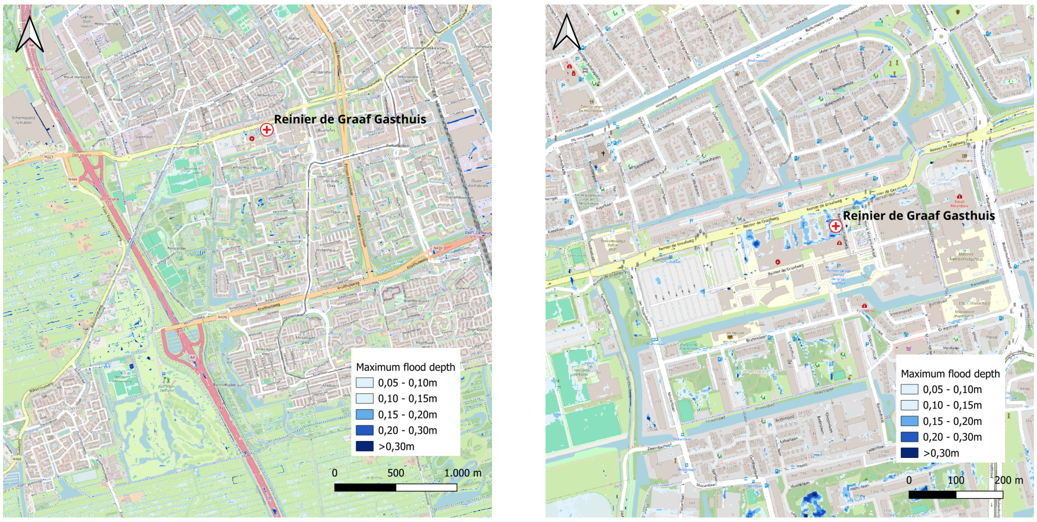
Precipitation scenario with a 100 year return period
The "Precipitation 100" scenario results from a short and intense precipitation event with a probability of occurrence of 1/100 (see Figure 3.6). The precipitation event was modelled as a rain event of 70mm in 2 hours' time.



(a) Overview (b) Zoomed in

Figure 3.6: Flood depth map resulting from a heavy precipitation event. The probability of the shown water level is 1/100. The location of the RdGG has been indicated.

Precipitation scenario with a 10 year return period
The "Precipitation 10" scenario results from a short and intense precipitation event with a probability of occurrence of 1/10 (see Figure 3.7). The precipitation event was modelled as a rain event of 35mm in 2 hours' time.



(a) Overview (b) Zoomed in

Figure 3.7: Flood depth map resulting from a heavy precipitation event. The probability of the shown water level is 1/10. The location of the RdGG has been indicated.

3.3.3 Erasmus Medical Centre flood scenarios

There are two flood scenarios that threaten the EMC. Table 3.4 and Figure 3.8 show the flood risk profile at the location of the EMC. The scenario names, predicted water levels and their probability of occurrence are stated. The flood impact is discussed in Chapter 5.

Table 3.4: Flood scenarios for the current situation at the EMC.

Scenario name	Flood depth [m]	Water level probability
Parksluizen 1	1,60	1/600.000
Parksluizen 2	1,84	1/690.000

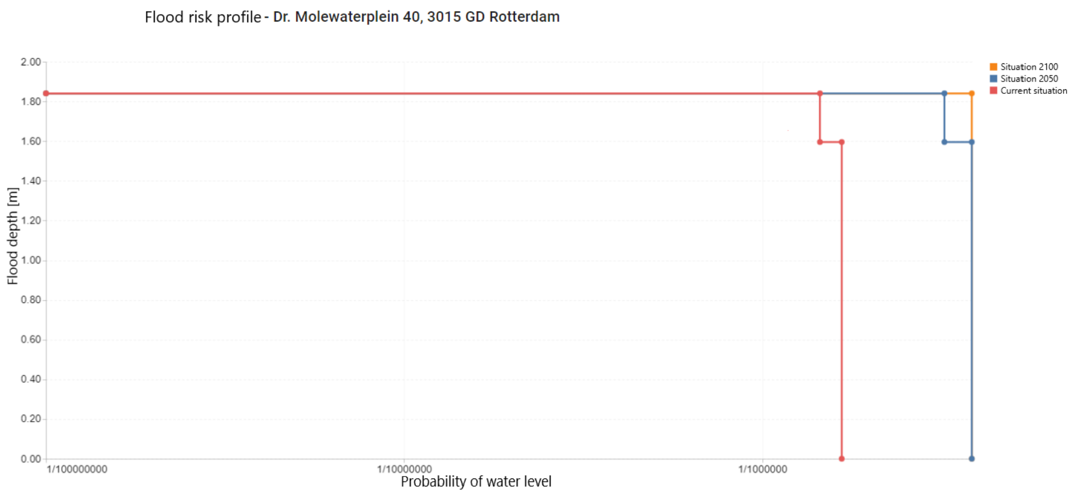
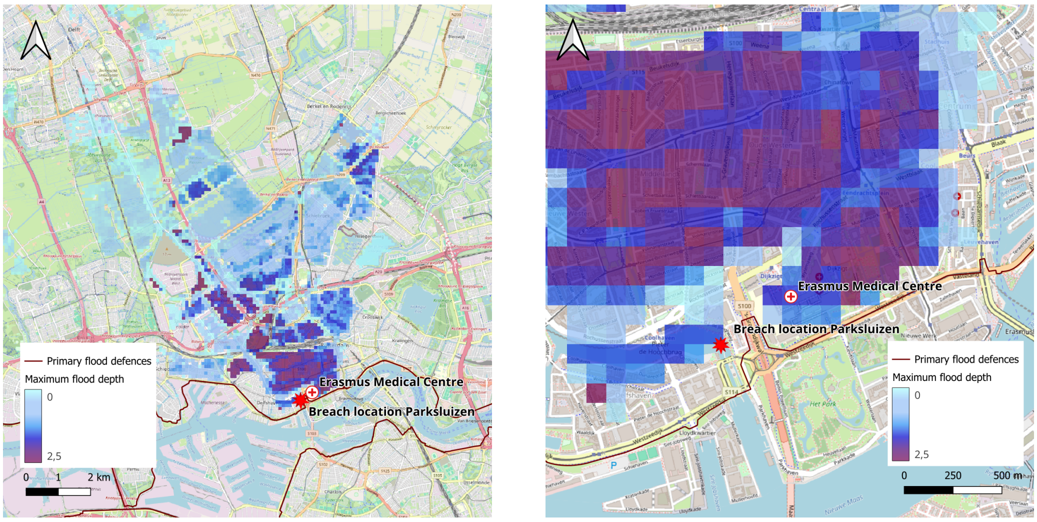


Figure 3.8: Flood risk profile of the EMC.

Breach in primary flood defence 1

The "Parksluizen 1" scenario results from a breach in a primary flood defence, at a lock in the dyke (see Figure 3.9). Given the location, such a breach can be the result of a storm surge, extreme river discharges or a combination of both. Storms and river discharges can be predicted, which results in a warning time of multiple days. However, a large part of the Netherlands is simultaneously threatened under such circumstances. This flood scenario simultaneously floods three other hospitals. In addition, this part of the Netherlands is very densely populated. These factors pose an obstacle for the evacuation process. It should be noted that Rotterdam is protected by storm surge barriers. Should these barriers fail to close, the water levels will rapidly rise. In such cases, little time is available for the execution of flood strategies because failure only becomes apparent during the storm (Kolen, 2023).

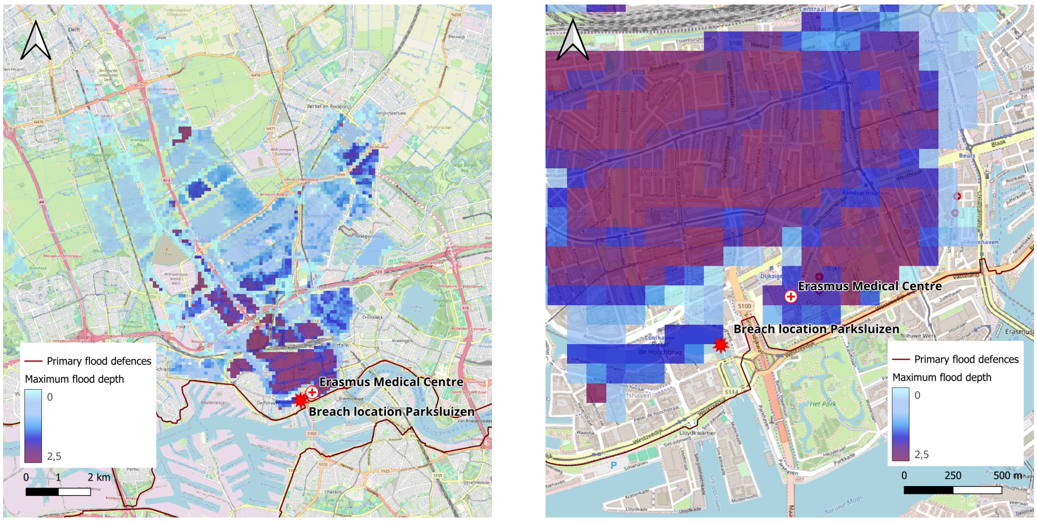


(a) Overview (b) Zoomed in

Figure 3.9: Flood depth map resulting from a breach at Parksluizen. The probability of the shown water level is 1/600.000. The locations of the EMC and breach location have been indicated.

Breach in primary flood defence 2

For the flood scenario ”Parksluizen 2”, the causes are similar to the ”Parksluizen 1” scenario. However, the event has a smaller probability of occurrence and causes higher flood levels (see Figure 3.10).



(a) Overview (b) Zoomed in

Figure 3.10: Flood depth map resulting from a breach at Parksluizen. The probability of the shown water level is 1/690.000. The locations of the EMC and breach location have been indicated.

3.3.4 Considerations regarding the flood depth

Figures 3.11 and 3.12 show the "Regional 100" flood scenario at the hospital in the years 2004 and 2021 respectively. In Figure 3.12, it stands out that the most water accumulation (0,76m flood depth) seems to occur at the exact location of the hospital building, whereas the parking lots seems to remain dry. Figure 3.11 reveals the reason behind this. The "Regional 100" flood scenario is based on AHN2 data, which is an elevation map of the Netherlands. This part of the Netherlands was measured in 2008. The current RdGG was built in 2017. Hence, the flood scenario is representative for the old situation (Figure 3.11), where there used to be a parking lot at the location of the current hospital building. The old hospital buildings were located East and West of this location, explaining why these places seem to remain dry. Naturally, this is not fully representative of the current situation (Figure 3.12). Unfortunately, this flood scenario is the most recent available.

From interviews with employees of the RdGG, it became clear that the surface below the new hospital has been elevated compared to the old situation. When the hospital was designed, a governing value for the flood depth of 0,30m was used. Additionally, it was observed that the hospital is slightly elevated relative to its surroundings. Therefore, it may be questioned whether a flood depth of 0,76m is realistic. The elevations of AHN2 have been compared to the most recent elevation map from 2023: AHN5. Also the corresponding predicted flood depths of the "Regional 100" scenario have been regarded. It can be deduced that the predicted water level reaches approximately −0,30m NAP. The elevation of the direct surroundings of the hospital ranges between −0,45m NAP and −0,10m NAP. This suggests that the design value of 0,30m as maximum flood depth at the hospital could be more realistic than the 0,76m suggested by the LIWO.

Nevertheless, one should still be aware of measurement errors in the elevation maps. The maximum systematic error is 5cm. The standard deviation is also 5cm. 99,7% of the data has a maximum error of 20cm (Actueel Hoogtebestand Nederland, n.d.). The flood models may also contain errors. In addition, it is observed that the flood depth can vary significantly across a large hospital terrain because of spatial variation. Using a strict flood depth of 0,30m for the design may result in unanticipated failures and a false sense of safety. So, on the one hand, it may be argued that the flood depths from the flood scenarios are too large at this location, hence too pessimistic. On the other hand, for the purpose of analysing the vulnerability of the RdGG to floods, it makes sense to consider a range of water levels. All reported water levels from Table 3.3 lie within a reasonable margin of what may be expected. Additionally, the data from the LIWO contains the most recent scenarios. And within the given time frame of this research, it is impracticable to update each flood scenario before use. An elevation map is a snapshot in time, which inherently means that the data is "outdated" right after data collection. However, this does not mean that the data immediately becomes useless. This knowledge should be taken into account and the results critically reviewed. In conclusion, the flood depths from the most recent flood scenarios are used, without prior correction.

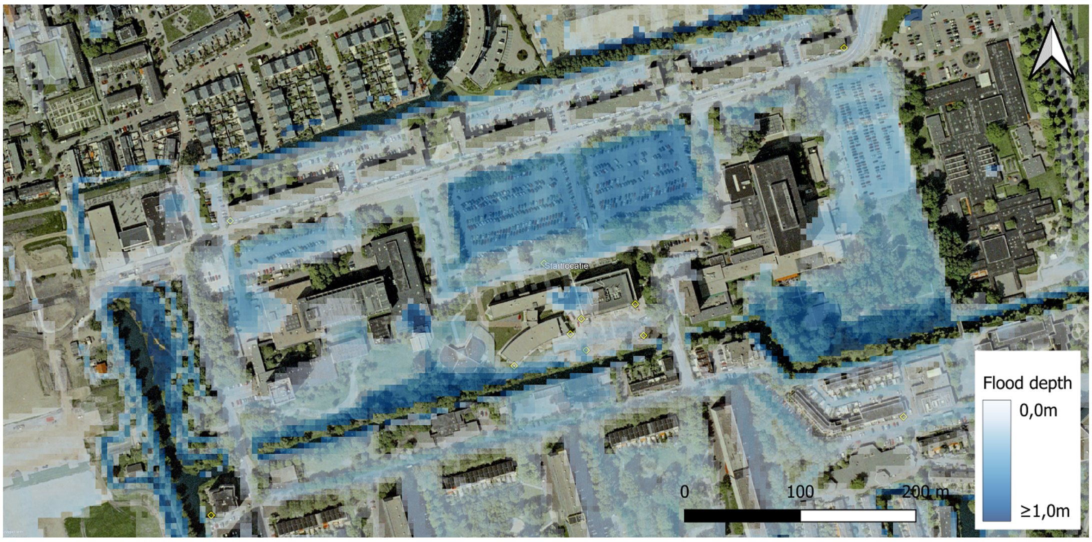


Figure 3.11: Flood depth map resulting from a breach in the regional dyke system with classified chance of failure of 1/100, projected over the RdGG in 2004, retrieved from the LIWO (scenario 20931). The probability of the shown water level is 1/500.

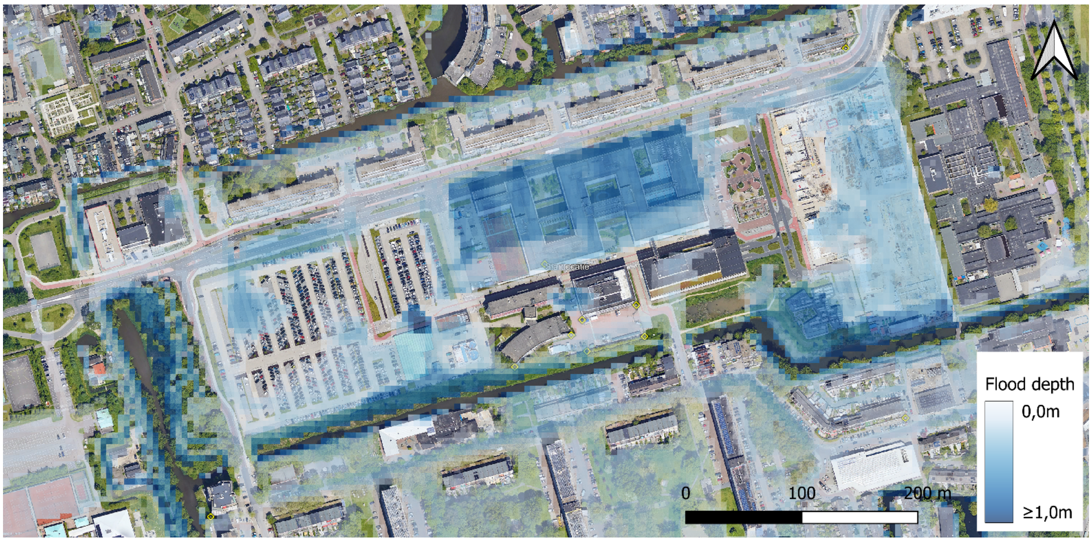


Figure 3.12: Flood depth map resulting from a breach in the regional dyke system with classified chance of failure of 1/100, projected over the RdGG in 2021, retrieved from the LIWO (scenario 20931). The probability of the shown water level is 1/500.

3.4 Interviews

3.4.1 Phase 1 interviews

As discussed in Section 3.1, this research is mainly qualitative in nature. Key informant interviews were used to collect information on hospitals' flood preparedness. This type of interview is especially useful for obtaining in-depth information from a person with specific and expert knowledge. Questions about experience with floods, logistics, spatial adaptation and emergency plans at the hospital were formulated to guide the interview. The questions are listed in Appendix B. Key informant interviews are also flexible. They allow interviewees to raise topics that are important in their view, adding to the exploratory part of the interviews. The prepared questions are focused on obtaining factual information (in contrast to opinions). Nevertheless, with key informant interviews, one cannot omit personal perspectives or experiences, which may yield biased information (Jones Taylor & Blake, 2015).

Contact persons at the RdGG and the EMC were approached through the personal network. They recommended contacting employees of the emergency management and logistics department to obtain answers to all questions. Specific employees were recommended and have thus been invited to participate in the interview. At both hospitals, interviews were conducted with employees from the departments of emergency management and logistics. Additionally, a flood risk expert from RWS was interviewed. This expert was also approached through the personal network. The interview was scheduled to obtain an additional perspective on the flood preparedness of hospitals. The flood expert can provide an outside view on the hospitals, with knowledge from the water sector and the context of the water safety policies in the Netherlands. This knowledge was deemed valuable to add to the research.

The phase 1 interviews were conducted in May 2024. The interviews were held by the researcher and lasted between 44 and 55 minutes. In total, four phase 1 interviews took place with five participants. Two employees per hospital participated: one from the logistics department and one from the emergency management department. One participant was a flood risk expert from RWS. Most interviews were held individually, but the interviews with the employees from the RdGG were held together because this was more convenient in terms of planning. All interviews were held in person, except for the one with the emergency management employee from the EMC. This interview was held online, via Microsoft Teams, for convenience. The interviews were held in Dutch, because all participants are from the Netherlands. After receiving consent, the recording was started. For the interviews that were held in person, only the audio was recorded. One interview was held online. Audio and video were recorded for this meeting. The recording and automatic transcription were done using Microsoft Teams. For each interview, the recordings and transcript were used to create a summary, which was shared afterwards with the participant for approval. An overview of characteristics of the interview participants is shown in Table 3.5. The results of the phase 1 interviews and tours are used throughout the next chapters to elaborate the cases.

Table 3.5: Overview of characteristics of phase 1 interview participants.

Participant	Country	Professional background	Employer	Interview type
1	The Netherlands	Logistics	RdGG	In person
2	The Netherlands	Emergency management	RdGG	In person
3	The Netherlands	Logistics	EMC	In person
4	The Netherlands	Emergency management	EMC	Online
5	The Netherlands	Flood expert	RWS	In person

In addition to the interviews, a tour of the RdGG and EMC hospital was arranged. The tour of the RdGG took place with the two employees after the interview. The tour of the EMC was guided by the logistics employee, also after the interview. The tours lasted for approximately one hour. These tours have great added value to the research. The purpose of these tours was to see the installations pertaining to the hospitals' flood preparedness, rather than just discussing them. After receiving consent, photos and height measurements were taken of installations that fulfill a critical role in the continuity of healthcare at hospitals. This enabled analysis of the vulnerability of these installations to floods (Chapter 5).

3.4.2 Phase 2 interviews

The phase 2 interviews were conducted to evaluate the selected flood preparedness indicators, the results and the underlying assumptions of the assessment of hospitals' flood preparedness, and to identify methods to engage stakeholders for implementation of flood strategies. An interview setup similar to the phase 1 interviews was used: questions were prepared and during the interview there was flexibility for the interviewee to add information that was deemed important. The interview questions can be found in Appendix C.

Since the hospitals from the case study, the RdGG and EMC, do not have any flood experience, it was decided to contact (former) employees of the VCMC. This hospital has experienced floods in 1993, 1995 and a close call in 2021. The interviewees worked for the hospital during these events and have valuable experience with floods at hospitals. The employees were approached through the personal network.

The phase 2 interviews were conducted by the researcher in September and October 2024. The interviews lasted 60 and 104 minutes. Two persons were interviewed during two separate interviews. One interviewee is a former employee at the VCMC. They were interviewed via Microsoft Teams. The other interviewee currently works at the VCMC and was interviewed at the hospital. The interviews were held in Dutch. The audio was recorded from both interviews and an automatic transcription was created with Microsoft Teams. A summary was created and shared with the participants for approval. Participant characteristics are summarised in Table 3.6.

Table 3.6: Overview of characteristics of phase 2 interview participants.

Participant	Country	Professional background	Employer	Interview type
6	The Netherlands	Doctor with flood experience	VCMC	Online
7	The Netherlands	Doctor with flood experience	VCMC	In person

3.4.3 Ethical considerations

The phase 1 and phase 2 interviews were prepared and conducted in accordance with guidelines of the Delft University of Technology and were approved by the Human Research Ethics Committee of the faculty of Technology, Policy and Management. In preparation for the interviews, a risk assessment was carried out to identify potential ethical concerns. Preemptive mitigation measures were applied where needed. A Data Management Plan was created and approved by the Data Stewards from the faculty of Civil Engineering and Geosciences. An Informed Consent Form was drafted to inform participants about the research, how the personally identifiable information is treated and to what potential risks participants may be exposed. All personally identifiable information was anonymised. The data could only be accessed by the researcher and the thesis supervisors.

3.5 Stakeholder analysis

First, stakeholders are identified that are relevant for the preparation or execution of flood strategies. A principal stakeholder is appointed and the surrounding stakeholders are identified. These stakeholders are listed below and are discussed in more detail in Sections 6.1 and 6.2.

- Hospital Executive Board
- Hospital personnel
- Hospitals receiving patients
- Patients
- Ambulance services
- Suppliers
- Utility companies
- Water boards
- Municipalities
- Safety regions
- Insurance companies

From the identified stakeholders, a selection is made per flood strategy on who *could* be involved in the implementation (see Section 6.3). This decision is based on the characteristics discussed in the stakeholder assessment (see Section 6.2). Then, the stakeholders will be categorised per flood strategy with the help of the PIA matrix by Murray-Webster and Simon (2006) (Section 6.4). Categorisation results in recommended actions regarding the involvement of stakeholders per flood strategy. Next, the current and desired stakeholder engagement for flood strategy implementation is presented in the form of bullseye diagrams (Section 6.5). Based on these bullseye diagrams and the phase 2 interviews, a selection is made of stakeholders that *should* be engaged per flood strategy (Section 6.6). Finally, the phase 2 interviews are used to obtain views from experts with lived experience on how these stakeholders can be engaged.

3.6 Selecting flood preparedness indicators

3.6.1 Selection process

The literature, phase 1 interviews and hospital tours were used to obtain an overview of factors that are important for the regular operation of hospitals. The factors are categorised and briefly described.

Scientific articles, reports and grey literature on flood preparedness and hospital floods were analysed to find factors that contribute to the flood preparedness of hospitals. Search words that were used in various combinations are: ”Flood”, ”Disaster”, ”Preparedness”, ”Hospital”, ”Healthcare”, ”Index” and ”Indicator”. The sources were found through Web of Science. In addition, some sources were recommended by supervisors. In total, 14 sources were selected based on their title and abstract. Some sources directly relate to the flood preparedness of hospitals. Other sources relate to flood indexes or the preparation of hospitals for disasters in general. These sources are listed in Appendix F.

A list of factors that are claimed to contribute to the flood preparedness of hospitals was kept. Every time that a new factor was discussed, it was added to the list. The factors were grouped to find common denominators. These groups are regarded as *flood preparedness indicators*. If multiple factors belonging to one indicator are mentioned by the same source, it was only counted once toward the indicator count. For example, water, electricity and sewerage were grouped as ”utilities”. If an article mentioned both water and electricity, this increased the count of the indicator ”utilities” by one. The phase 1 interviews and hospital tours were used to complement the literature. The interview questions can be found in Appendix B. The results are described in Chapter 4.

3.6.2 Evaluation

This section’s methodology and the corresponding results (see Chapter 4) are discussed with experts for evaluation. The methodology for these phase 2 interviews is described in Section 3.4.2, the interview questions are presented in Appendix C under ”Flood preparedness indicators” and the interview results are presented in Section 4.2.

3.7 Assessing hospitals’ flood preparedness

In this section, the method for assessing hospitals’ flood preparedness is presented. First, it is explained how the flood preparedness indicators are used to determine the flood impact on hospitals. Then it is discussed how this flood impact can be used to quantify flood preparedness of hospitals.

3.7.1 Flood impact

Flood impact can be classified into direct and indirect impact. Direct impact refers to physical damage caused by a flood (Kolen, 2013, 2023). In case of indirect impact, one is affected by a flood event, but not by the flood itself. This includes being affected by a process that fails due to a flood and is unavailable for a certain duration (Kolen, 2013).

With regard to the direct impact, the failure of hospital facilities due to flooding is considered. An overview of the elevation of hospital facilities is obtained through phase 1 interviews and tours. The elevation (in m NAP) is used as the critical flood level for each hospital facility. If this critical flood level is exceeded, the facility is assumed to have failed. The expected maximum flood depths were obtained by accessing the hospital's flood scenarios through the LIWO. It is assumed that once the flood reaches the hospital, the maximum flood depth is immediately reached.

For the indirect impact, the availability of suppliers, their routes to the hospital are considered. In addition, it is considered how long hospital functions can remain available during a flood without deliveries and if they fail, for how long they will remain unavailable. During the phase 1 interviews, it is asked which facilities have to be provided externally to the hospital and which parties are involved (see Appendix B). Examples of externally provided facilities are medical supplies, food and utilities. For each supplier location, the level of the lowest entrance to the building is used as the critical flood level. Regarding the suppliers' routes, transport takes place by road or by utility grid, depending on the type of supplier. Transport by road can occur up to a maximum flood depth of 0,20m. Given this flood depth, even small vehicles (comparable in dimensions and weight to a Seat Ibiza) can travel by road with a velocity of up to 1m/s (Bocanegra & Francés, 2021; Evans et al., 2024). Hence, the elevation level of the road plus 0,20m is used as the critical flood level for delivery by road. The routes that are considered are determined by a navigation system and take the least time given free-flowing traffic, avoiding flood depths greater than 0,20 metres. If no route is available, given that criterion, the supply of the corresponding function is considered unavailable. The delivery of utilities (electricity, water and sewerage) occurs by utility grid (electrical cables, water pipes and sewer pipes respectively). The utility grid is assumed to be unaffected by a flood, because they are usually located underground or suspended in the air in the Netherlands. Utility stations (e.g. electrical substations or sewage pumping stations) are treated as supplier location, hence the lowest entrance level is used as critical flood level. The phase 1 interviews are used to determine how long hospital functions can last during a flood if no deliveries can take place (see Appendix B). Regarding the duration of the unavailability of hospital functions once they have failed, it is assumed that recovery can only occur after the flood has receded or once new supplies are delivered. For example, a helicopter could provide emergency supplies. The duration may vary per flood strategy. The result of the flood impact analysis of a hospital is an overview of which facilities fail per flood scenario that poses a threat to the hospital.

The hospital's facilities are grouped according to the flood preparedness indicators from Chapter 4. Subsequently, it is determined if and when the flood preparedness indicators fail. If any of the facilities that fall under a certain flood preparedness indicator fail, that particular indicator is considered to have failed. Failure of one flood preparedness indicator is assumed to cause failure of the hospital's continuity of healthcare. Hence, a series system is assumed for the continuity of healthcare (see Figure 3.13).

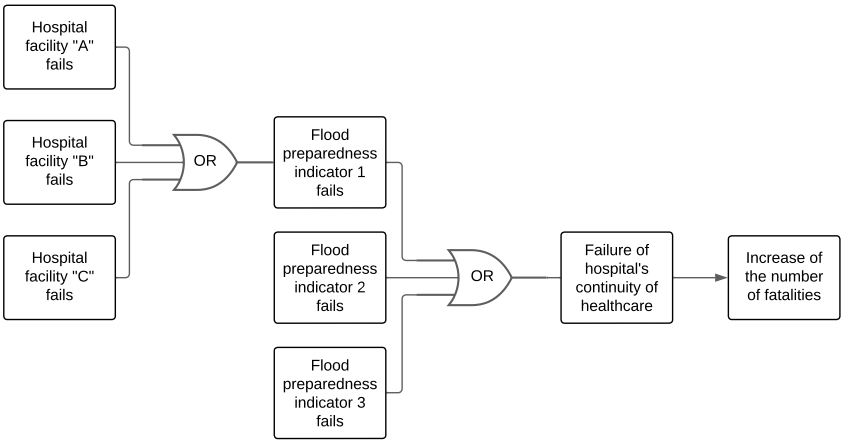


Figure 3.13: Scheme of the proposed model for continuity of healthcare at hospitals. The system is in series: if any hospital facility fails, the associated flood preparedness indicator fails. If any flood preparedness indicator fails, the hospital's continuity of healthcare fails, resulting in an increased number of fatalities.

3.7.2 Quantification

The method described thus far uses flood preparedness indicators to analyse the impact of floods per flood strategy. This section describes how the consequences of the flood impact can be quantitatively represented, with the aim of enabling comparison of flood strategies. First, factors are selected for quantification. Subsequently, the method for quantifying these factors is explained.

Common factors that are used to quantify flood impact are the number of fatalities and costs (Kok et al., 2004; McGinty et al., 2017; Ministry of Infrastructure and Water Management, 2018). As discussed in Section 2.1, the goal of preparing hospitals for floods is to reduce the number of fatalities. In this research, the fatalities among patients as a result of discontinuity of healthcare, caused by flooding, are considered. Flood strategies can be implemented to reduce the number of fatalities, thus increasing the flood preparedness of hospitals. Various types of costs are associated with flood strategies. In this research, the costs considered consist of direct damages to the hospital to due a flood and costs regarding preparation and execution of a flood strategy. The method for determining fatalities and costs for "preventive evacuation", "shelter in place with additional measures", "shelter in place without additional measures" and "accept" are explained.

Fatalities

The number of fatalities determined by three factors: the number of people affected, the mortality rate and the duration of exposure of the affected people to this mortality rate. Equation 3.1 is the basic formula to calculate the number of fatalities. Each component of the formula will be elaborated.

$$F = N * M * t \tag{3.1}$$

Where:

F	[dths]	Fatalities
N	[#ppl]	Number of affected people
M	[dths/#ppl/d]	Mortality rate per day
t	[d]	Duration of exposure of the affected people to the mortality rate during a flood emergency situation

Number of affected people
It is assumed that only patients are affected by floods. Therefore, N represents the number of affected patients. The number of affected patients is divided into three patient groups to account for the variability in vulnerability between patients (Kolen, 2013). Patients' vulnerability is reflected by their special needs:

- High vulnerability ($i = 1$): These patients depend on instruments and personal care.
- Medium vulnerability ($i = 2$): These patients depend on personal care.
- Low vulnerability ($i = 3$): These patients have special needs, but they are independent. They are mainly at the hospital for observation.

The number of affected patients varies per flood strategy. For the flood strategy "shelter in place with additional measures" ($j = 1$), it is considered that the patient group with low vulnerability is discharged from the hospital in anticipation of the flood. This measure allows personnel to focus on the care of the most vulnerable patients. For "shelter in place without additional measures" ($j = 2$) and "accept" ($j = 3$), it is assumed that all three patients groups are present in the hospital. The number of affected patients per patient group (i) and per flood strategy (j) is defined as $N_{i,j}$. For the flood strategies "shelter in place with additional measures" ($j = 1$), "shelter in place without additional measures" ($j = 2$) and "accept" ($j = 3$), summation over the patient groups yields the number of affected patients per flood strategy: N_j (see Equation 3.2).

$$N_j = \sum_{i=1}^{3} N_{i,j} \quad \text{for } j \in [1, 3] \tag{3.2}$$

For the flood strategy "preventive evacuation" ($j = 4$), a different equation is used to calculate the number of affected patients. All three patient groups are assumed to be present in the hospital and they are evacuated to other hospitals. In addition, preventive evacuations occur more often than floods, because a flood may not occur after a preventive evacuation was performed. When an evacuation is based on wrong information or incorrectly followed procedures and no flood occurs, it is called a "false alarm" (Kolen, 2013). However, even if the procedures are followed correctly, the decision can be made to evacuate. Often, thresholds for water levels are defined for flood risk management. These thresholds are defined below the safety levels of flood defences to allow timely implementation of flood strategies.

For example, the VCMC evacuates if the river Meuse reaches a water level of +19,60m NAP, but the hospital is not yet flooded at this water level (Van Beek et al., 2015). Because the impact of a flood is greater than the impact of an evacuation, the frequency of evacuations is higher than the frequency of floods. This policy is called the ”better safe than sorry philosophy” (Kolen, 2013). It should be noted that evacuating vulnerable patients can result in fatalities, even if no flood occurs (McGinty et al., 2017). To compare flood strategies, the number of fatalities per flood is considered. Therefore, the number of evacuations relative to one flood is taken into account (defined as r). This number includes the preventive evacuation with subsequent flood (1 out of r times) and the preventive evacuations where no flood occurs ($r-1$ times). Therefore, the number of affected patients for the flood strategy ”preventive evacuation” is equal to the number of patients in the hospital multiplied by the number of evacuations relative to one flood (see Equation 3.3).

$$N_4 = \sum_{i=1}^{3} N_{i,4} * r \tag{3.3}$$

Mortality rate

The mortality rate depends on the flood strategy and the vulnerability of patients. Regarding the mortality rate per flood strategy, an average daily mortality rate at Dutch hospitals (M_{avg}) is used as a baseline mortality rate. This mortality rate occurs at hospitals in the Netherlands under normal circumstances. During a flood, certain flood preparedness indicators may fail. As a result, some special needs of patients can no longer be met, which leads to increased patient mortality (Kolen, 2013). Which flood preparedness indicators fail depends on the implemented flood strategy. The more flood preparedness indicators fail, the worse the conditions in the hospital become, resulting in a higher mortality rate. This principle is accounted for by multiplying M_{avg} with a flood strategy factor (f_j). The mortality rate for the flood strategies ”shelter in place with additional measures” ($j=1$), ”shelter in place without additional measures” ($j=2$) and ”accept” ($j=3$) is given by Equation 3.4.

$$M_j = M_{avg} * f_j \quad \text{for } j \in [1,3] \tag{3.4}$$

However, it is expected that the mortality rate among highly vulnerable patients will be higher than patients with low vulnerability. The vulnerability of patients is accounted for by a vulnerability factor that is applied to each patient group (v_i). Combining the number of affected people (Equation 3.2) with the mortality rate (Equation 3.4) and vulnerability factor per patient group (v_i) results in the number of fatalities per day for the flood strategies ”shelter in place with additional measures” ($j=1$), ”shelter in place without additional measures” ($j=2$) and ”accept” ($j=3$) (see Equation 3.5).

$$F_{daily,j} = \sum_{i=1}^{3} (N_{i,j} * v_i) * M_{avg} * f_j \quad \text{for } j \in [1,3] \tag{3.5}$$

For ”preventive evacuation”, the mortality rate depends on whether evacuation is successful (patients arrive at their intended location before the onset of the flood) or unsuccessful (patients are hit by a flood before the intended location is reached). Unsuccessful preventive evacuation will result in a higher mortality rate than successful preventive evacuation. For successful ”preventive evacuation”, flood strategy factor $f_{4,suc}$ is multiplied with M_{avg}. If ”preventive evacuation” is unsuccessful, $f_{4,fail}$ is multiplied with M_{avg}. The expected number of people that is able to reach their planned destination is described by the evacuation fraction (e) (Kolen, 2013). The evacuation fraction ranges between 0 and 1, where 0 implies that 0% of the patients reaches their intended location because of the flood. If e equals 1, all patients are able to evacuate successfully.

Figure 3.14 explains how the number of fatalities per day for ”preventive evacuation” is built up from three components. For every preventive evacuation, all patients present in the hospital (all three patient groups, equal to $\sum_{i=1}^{3} N_{i,4}$) are evacuated. As previously mentioned, preventive evacuations occur more often than floods. The number of preventive evacuations relative to a flood is defined as r. Out of r preventive evacuations, a flood occurs once and $(r-1)$ evacuations are executed without the occurrence of a flood. Hence, $\sum_{i=1}^{3} N_{i,4} * 1$ and $\sum_{i=1}^{3} N_{i,4} * (r-1)$ patients are evacuated respectively. For the one preventive evacuation where a flood occurs, the evacuation fraction describes which part of the patients can be evacuated successfully, indicated with e. The other patients are unable to evacuate successfully, indicated with $(1-e)$. For the $(r-1)$ preventive evacuations where no flood occurs, everyone can be successfully evacuated, hence $e = 1$. To obtain the number of fatalities per day, the mortality rates for successful ($M_{avg} * f_{4,suc}$) and unsuccessful preventive evacuation ($M_{avg} * f_{4,fail}$) and the vulnerability factor per patient group (v_i) are applied to the number of affected patients. As a result, three components are distinguished that contribute to the number of fatalities per day. Adding up these components results in Equation 3.6. This equation can be simplified, resulting in Equation 3.7.

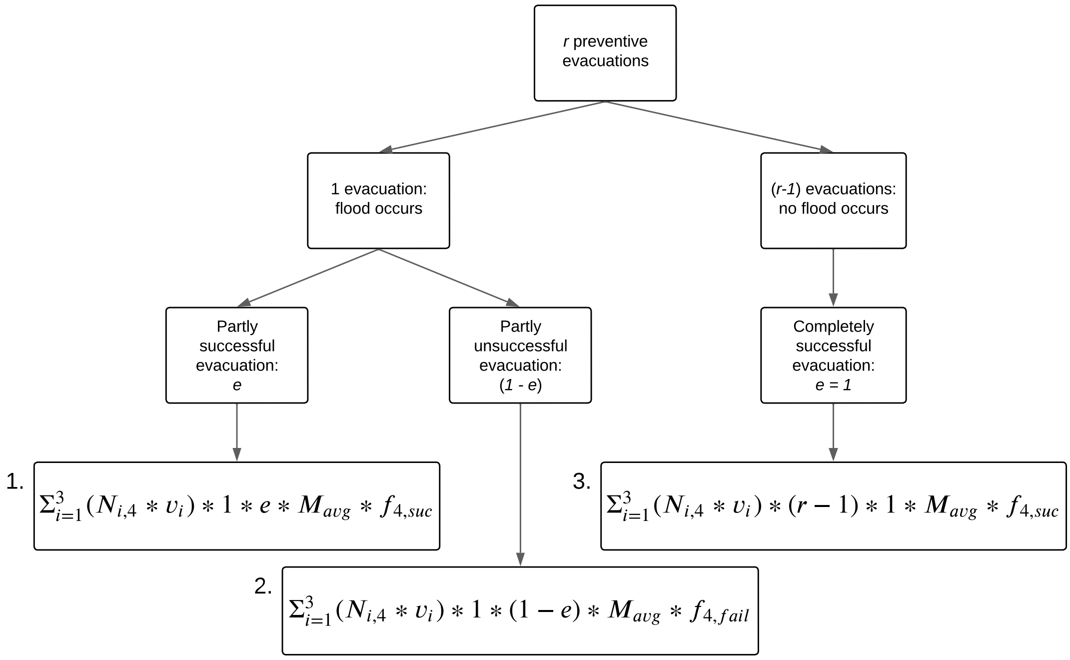


Figure 3.14: The number of fatalities per day for ”preventive evacuation” (Equation 3.6) is built up from three components.

$$F_{daily,4} = \sum_{i=1}^{3}(N_{i,4} * v_i) * 1 * e * M_{avg} * f_{4,suc} + \sum_{i=1}^{3}(N_{i,4} * v_i) * 1 * (1-e) * M_{avg} * f_{4,fail} + \sum_{i=1}^{3}(N_{i,4} * v_i) * (r-1) * 1 * M_{avg} * f_{4,suc} \quad (3.6)$$

$$F_{daily,4} = \sum_{i=1}^{3}(N_{i,4} * v_i) * M_{avg} * (e * f_{4,suc} + (1-e) * f_{4,fail} + (r-1) * f_{4,suc}) \quad (3.7)$$

Duration
To make the transition from the number of fatalities *per day* to the number of fatalities *per flood event*, the duration and time-dependency of the mortality rates must be considered. These two aspects are first elaborated for the flood strategies "shelter in place with additional measures" ($j = 1$), "shelter in place without additional measures" ($j = 2$) and "accept" ($j = 3$). It should be determined **1)** at what moment the mortality rates can be said to be applicable, **2)** what the duration of exposure to the mortality rate is, and **3)** how the the mortality rate develops over time.

1) As discussed in Section 3.7.1, the continuity of healthcare at hospitals is disrupted when any of the flood preparedness indicators fail. Regarding the moment of the onset of the mortality rates, it is assumed that if disruption of the continuity of healthcare occurs, the mortality rates are applicable. This moment is defined as $t = 0$.

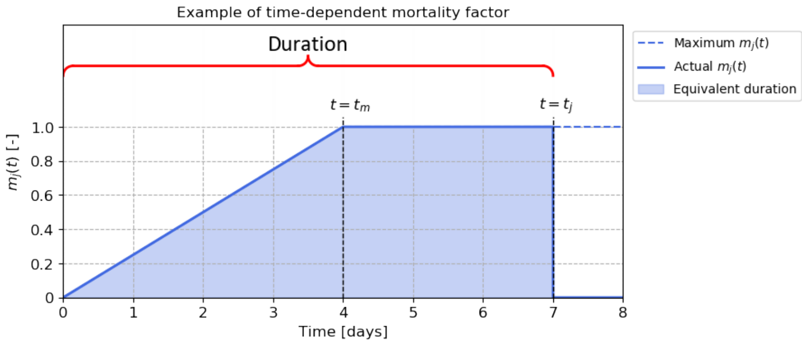
2) Furthermore, the end of the exposure of patients to the mortality rate is determined by the duration of failure of the flood preparedness indicators. Recovery of all flood preparedness indicators ends the exposure of patients to the mortality rate. Recovery can occur after the flood has ended or when the hospital is rescued. This moment is marked as $t = t_j$. The difference between $t = 0$ and $t = t_j$ is the duration of the exposure of patients to the mortality rate.

3) Regarding the development of the mortality rate over time, one interviewee from the phase 2 interviews stated:

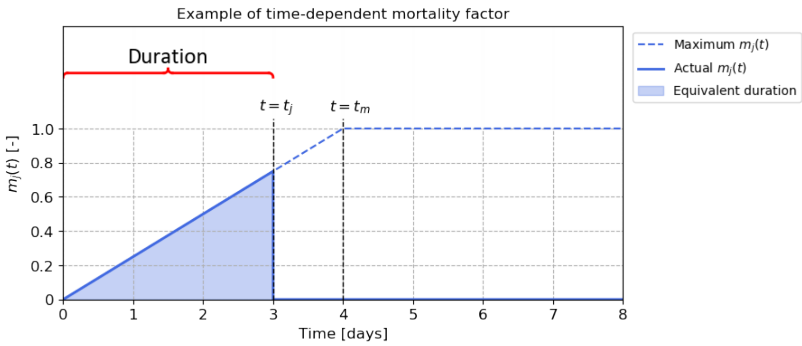
"Suppose you have not arranged that [preparing a hospital for floods], then that [loss of functions] will have a kind of cumulative effect. (...) The longer it lasts, the larger the problem becomes." [participant 6]

Both phase 2 interviewees agreed that the increase in mortality over time is dynamic, rather than abrupt. However, they were unable to indicate how the mortality rate increases over time, eventually reaching the maximum mortality rate, which is equal to M_j. To account for this dynamic increase of the mortality rate, the time-dependent mortality factor $m_j(t)$ is introduced (see Figure 3.15). The maximum mortality rate is multiplied by $m_j(t)$. It is assumed that $m_j(t)$ linearly increases from zero at $t = 0$ to its maximum value of 1 at $t = t_m$. After $m_j(t)$ has reached its maximum value, it remains constant until the exposure of patients to the mortality rate ends at $t = t_j$ (Figure 3.15a). Note that t_j could also be lower than t_m, in which case the maximum value of $m_j(t)$ is not reached (Figure 3.15b). Because $m_j(t)$ varies over time, using the difference between $t = 0$ and $t = t_j$ as the duration overestimates the actual duration of exposure of patients to the mortality rate. Therefore, an equivalent duration is used, which is equal to the area below $m_j(t)$. This equivalent duration is calculated taking the integral of $m_j(t)$ from $t = 0$ to $t = t_j$. Combining the number of deaths per day (Equation 3.5) with the equivalent duration of the mortality rate yields the formula for the number of fatalities for the flood strategies ”shelter in place with additional measures” ($j = 1$), ”shelter in place without additional measures” ($j = 2$) and ”accept” ($j = 3$): Equation 3.8.

It should be noted that for the number of fatalities per patient group for any flood strategy ($F_{i,j}$) can never exceed the number of affected patients per patient group and flood strategy ($N_{i,j}$). After all, it is impossible to have more fatalities than patients.



(a)



(b)

Figure 3.15: Two examples of the time-dependent mortality factor ($m_j(t)$). This factor ranges from 0 to 1, where 0 represents a mortality rate of 0 and 1 represents the maximum mortality rate for a flood strategy. At $t = 0$, the flood reaches the hospital. At $t = t_m$ the maximum mortality rate is reached. At t_j, the exposure of patients to the mortality rate ends. The area below $m_j(t)$ between $t = 0$ and $t = t_j$ is the equivalent duration. (a) shows an example of the development of $m_j(t)$ when $t_j > t_m$. (b) shows an example where $t_j < t_m$.

$$F_j = \sum_{i=1}^{3}(N_{i,j} * v_i) * M_{avg} * f_j * \int_{t=0}^{t_j} m_j(t)dt \quad \text{if } j \in [1,3] \tag{3.8}$$

To obtain the number of fatalities per flood event for the flood strategy ”preventive evacuation”, the number of fatalities per day (Equation 3.7) is multiplied by the duration of an evacuation (t_4). The number of fatalities for the flood strategy ”preventive evacuation” can be calculated with Equation 3.9.

$$F_4 = \sum_{i=1}^{3} (N_{i,4} * v_i) * M_{avg} * (e * f_{4,suc} + (1 - e) * f_{4,fail} + (r - 1) * f_{4,suc}) * t_4 \tag{3.9}$$

Where:

i	[-]	Patient groups with high (i = 1), medium (i = 2) and low vulnerability (i = 3)
j	[-]	Flood strategies “shelter in place with additional measures” (j = 1), “shelter in place without additional measures” (j = 2), “accept” (j = 3) and ”preventive evacuation” (j = 4)
F_j	[dths]	Fatalities per flood strategy $(F_{i,j} \leq N_{i,j})$
$N_{i,j}$	[#ppl]	Number of affected patients per patient group and flood strategy
v_i	[-]	Vulnerability factor per patient group
M_{avg}	[dths/#ppl/d]	Average daily mortality rate at Dutch hospitals
f_j	[-]	Flood strategy factor for $j \in [1..3]$
f_{suc}	[-]	Flood strategy factor for successful evacuation
f_{fail}	[-]	Flood strategy factor for unsuccessful evacuation
e	[-]	Evacuation fraction $(e \in [0, 1])$
r	[-]	Number of evacuations relative to one flood
t_j	[d]	•For $j \in [1..3]$: time when the flood is over, when the hospital is rescued or when processes can be resumed •For $j = 4$: duration of preventive evacuation
$m_j(t)$	[-]	Time-dependent mortality factor $(m_j(t) \in [0, 1])$

Inputs
The maximum number of patients present in a hospital is assumed to be equal to the number of hospital beds. The number of patients per patient group and flood strategy ($N_{i,j}$) and the vulnerability factor per patient group (v_i) are defined below (Kolen, 2013):

- High vulnerability ($i = 1$): This group is considered for every flood strategy and occupies 5% of all hospital beds. These patients are 8 times more vulnerable than average ($v_i = 8$).
- Medium vulnerability ($i = 2$): This group is considered for every flood strategy and occupies 25% of all hospital beds. These patients are 2 times more vulnerable than average ($v_i = 2$).

- Low vulnerability ($i = 3$): This group is considered for every flood strategy except for ”shelter in place with additional measures” and occupies 70% of all hospital beds. These patients have special needs, but they are independent. These patients are 0,14 times more vulnerable than average ($v_i = 0,14$).

The average daily mortality rate at Dutch hospitals (M_{avg}) is deduced from data collected by the Central Agency for Statistics (CBS) from the years 2015 to 2021. The result is a mortality rate of 0,0023, which is approximately 1 fatality per 430 beds per day (see Table 3.7).

Table 3.7: Fatality statistics at Dutch hospitals between 2015 and 2021, from the CBS (2024a, 2024b).

Year	Fatalities per 10.000 persons in hospitals	Dutch population in millions	Fatalities per year in hospitals	Hospital beds	Fatalities per day per hospital bed
2015	19,7	16,901	33.295	42.600	0,0021
2016	19,2	16,979	32.600	41.500	0,0022
2017	18,8	17,082	32.144	40.300	0,0022
2018	19,1	17,181	32.816	39.900	0,0023
2019	18,4	17,282	31.799	38.300	0,0023
2020	19,8	17,408	34.468	36.800	0,0026
2021	21,2	17,475	37.047	37.800	0,0027
				Mean	0,0023

To allow for comparison between flood strategies, a flood strategy factor is proposed per flood strategy.

- Shelter in place without additional measures ($j = 2$): based on reports about hurricane Katrina, it is estimated that 10% of the patients die during a four-day event (Kolen, 2013). The daily mortality rate for ”shelter in place without additional measures” is therefore estimated to be 2,5%, which corresponds to a flood strategy factor (f_2) of 10 for ”shelter in place without additional measures”.

- Shelter in place with additional measures ($j = 1$): the mortality rate of this flood strategy is assumed to be a factor of 1,5 less than ”shelter in place without additional measures” (Kolen, 2013). The daily mortality multiplication factor for the flood strategy ”shelter in place with additional measures” (f_1) is 6,67.

- Accept ($j = 3$): in the literature, no mortality rates are reported for hospitals that were flooded without any anticipation. However, it is reasoned that no degree of flood preparation results in a higher mortality rate than sheltering in place without additional measures. It is assumed that this results in a mortality rate that is 50% higher than ”shelter in place without additional measures”. The daily mortality multiplication factor for the flood strategy ”accept” (f_3) is 15.

- Preventive evacuation ($j = 4$): during evacuation, patients are exposed to less ideal circumstances compared to a hospital. Shortage of equipment and personnel leads to an increase in mortality of 50% compared to the average regular mortality if the evacuation is successful. A flood strategy factor of 1,5 is used for successful preventive evacuation (f_{suc}). If there is not enough time for complete and successful evacuation, it is assumed that the flood strategy factor is much higher. A value of 40 is assumed for f_{fail}, which produces a mortality rate per day for patients with high, medium and low vulnerability (in mathematical form: $M_{avg} * v_i * f_{fail}$) of approximately 0,75, 0,20 and 0,01, respectively. In consultation with a flood expert from HKV, it was decided that these values are plausible. The influence of f_{fail} on the estimated number of fatalities is analysed in the sensitivity analysis.

Regarding the evacuation fractions (e), no hospital-specific evacuation fractions are available for the Netherlands. Therefore, evacuation fractions from the LIWO are used. These values vary depending on the location and amount of time available for evacuation, ranging from zero (unexpected) up to four days. The evacuation fractions from the LIWO are only applicable to flood scenarios resulting from breaches in primary flood defences. For hospitals threatened by breaches in regional flood defences, an estimation has to be made per case.

The number of evacuations relative to one flood (r) depends on the location of the hospital in the Netherlands. For coastal areas in the Netherlands, the frequency of evacuations due to a storm surge or high water levels at rivers is 25 to 50 higher than the frequency of a flood. For a river area, the evacuation frequency is 5 to 10 times higher than the flood frequency (Kolen, 2013). These numbers only apply to breaches in primary flood defences. For breaches in regional flood defences, a specific estimation of r has to be made per case.

As previously discussed, exposure of patients to the mortality rate is caused by failure of flood preparedness indicators. If any of the flood preparedness indicators fail exposure ensues. This moment in time is defined as $t = 0$. When all flood preparedness indicators are recovered, the exposure ends. This moment in time is defined as t_j. Recovery can occur after the flood is over, but may occur earlier if the hospital is rescued and evacuated or resupplied. For the duration of the flood, the LIWO distinguishes between days, weeks, months and up to half a year. For most of the flood-prone area in the Netherlands, the flood duration will be several weeks or longer. How long it takes for a rescue mission or emergency supplies to arrive at a flooded hospital depends on the case considered. However, it is assumed that for "shelter in place with additional measures" a rescue mission is able to reach the hospital earlier compared to the flood strategies "shelter in place without additional measures" and "accept" because of advance agreements.

For the development of the time-dependent mortality factor ($m_j(t)$) a bilinear function was assumed to account for the increase of the mortality rate over time. The time t_m indicates when $m_j(t)$ reaches its maximum value of 1. All interview participants from phase 1 and phase 2 interviews that work at hospitals mentioned that failure of hospital facilities is "dynamic" and that a hospital goes into "survival mode". One participant from the RdGG stated:

"During emergencies, people are first of all: super resourceful, [and secondly:] become super united, because everyone is very willing to work together and there is a solution for everything." [participant 1]

Because the moment of failure of flood preparedness indicators is ambiguous, estimating t_m is difficult. For t_m a value of four days assumed. The influence of this value on the estimated number of fatalities is analysed in the sensitivity analysis.

Lastly, the duration of an evacuation (t_4) is determined. Previous experience with evacuations of Dutch hospitals shows that evacuation of a single hospital is possible if the direct surroundings remain unaffected (Kolen, 2023). Examples are the evacuations of the VCMC, VU Medical Centre in Amsterdam and the Meander Medical Centre in Amersfoort. These evacuations were executed within one day. Therefore, the duration of one evacuation is assumed to be one day.

Sensitivity analysis

A sensitivity analysis is performed to gain insight into which parameters of Equations 3.8 and 3.9 have the largest impact on the calculated number of fatalities. For Equation 3.8, the parameters t_j, t_m and f_j are varied individually. For Equation 3.9, the parameters f_{suc}, f_{fail}, e, and r are varied individually. First, the parameters are considered individually and are compared with each other once each parameter has been reviewed.

Costs

The fatalities and costs associated with each flood strategy can be weighed against each other. Phase 2 interviews confirmed that estimating the amount of costs related to floods is very difficult. Therefore, the types of costs associated with physical flood damage to the hospital and the implementation of flood strategies are collected per flood strategy through expert opinions from the phase 2 interviews. Other costs are disregarded. The types of costs per flood strategy are used to qualitatively estimate how expensive the flood strategies are relative to each other. The costs per flood strategy are categorised in terms of "high", "medium" and "low". "Low" is awarded to the least expensive flood strategy and the most expensive flood strategy is labelled "high".

3.7.3 Evaluation

This section's methodology and the corresponding results (see Chapter 5) are discussed with experts for evaluation. Specifically, the mortality rates and the classification of patients are discussed. The methodology for these phase 2 interviews is described in Section 3.4.2, the interview questions are presented in Appendix C under "Hospitals' flood preparedness evaluation" and the interview results are presented in Section 5.8.

4. Flood preparedness indicators

In this chapter, the selected flood preparedness indicators are presented. The selection is based on the literature and phase 1 interviews. The phase 2 interviews are used to evaluate the selection of indicators through expert judgement. The evaluation leads to a final selection of flood preparedness indicators.

4.1 Selection

The list of selected flood preparedness indicators and factors can be found in Table 4.1. Figure 4.1 shows how often indicators were considered relevant by the interviewees and authors. Critical equipment, stocks, utilities, transport of patients, accessibility, emergency management capacity and personnel were mentioned by 10 sources or more. When comparing the literature with the interviews, the same seven indicators stand out, except for "personnel". This indicator was not mentioned during the interviews, which may be explained by the fact that the interviews focused more on the physical aspects of the hospital, rather than human resources. An overview of sources from the literature and the interviews per flood preparedness indicator can be found in Table F.1.

Table 4.1: Flood preparedness indicators and identified factors that contribute to the flood preparedness of hospitals.

Indicator	Factor	Additional information
Critical equipment	Air treatment Cardio Care Unit Central Sterilisation Department Communication "Critical medical equipment" Dialysis centre Elevators Emergency room Intensive Care IT systems Laboratory Logistics Medium Care Neonatology Operation Room Radiology	This group contains hospital departments and technical installations that are considered critical for the maintenance of high-quality healthcare. Therefore, the equipment that belongs to these departments should remain operational. Some sources were nonspecific when mentioning equipment. Such cases have been placed under "Critical medical equipment".
Stocks	Food Fuel Medical gasses Medical supplies Medication "Supplies" Water	This group contains supplies that should be in stock in order for a hospital to be able to operate under regular circumstances or independently if supplies are cut off. Some sources were nonspecific when mentioning supplies. Such cases have been placed under "Supplies".
Utilities	Electricity Sewerage Water	This group contains utilities, which are deemed a basic need for any hospital.
Personnel	Personnel	Providing healthcare remains mainly human work. Without hospital personnel, healthcare cannot be provided. This indicator pertains to sufficient and qualified personnel, as well as resting schedules.
Transport of patients	Ambulances Helicopters "Patient transport"	This group contains modes of transport for patients. The only specific modes that were named in the sources studied were ambulances and helicopters. If sources were nonspecific, "Patient transport" was used.

Continued on the next page.

Indicator	Factor	Additional information
Accessibility	Accessibility	This factor describes to what extent a hospital can be reached and entered, for instance by patients, personnel and suppliers, through various means of transport.
Emergency management capacity	Emergency management capacity	This factor pertains to having emergency plans prepared to ensure an adequate response. Advance agreements between hospitals regarding the distribution of patients from the flooded hospital among the operational hospitals are also included.
Structural integrity	Structural integrity	Structural integrity pertains to the capability of the hospital building to resist the loads of flood.
Financing	Financing	A hospital should have sufficient financial resources to overcome the financial setback caused by the flood. This may be in terms of physical damage, as well as missed revenues.
Patient capacity	Patient capacity	This group represents the hospital's capacity to take up patients, expressed in the number of beds.
Safeguarding personnel's family	Safeguarding personnel's family	The hospital personnel's safety is a prerequisite for personnel to show up during disasters.

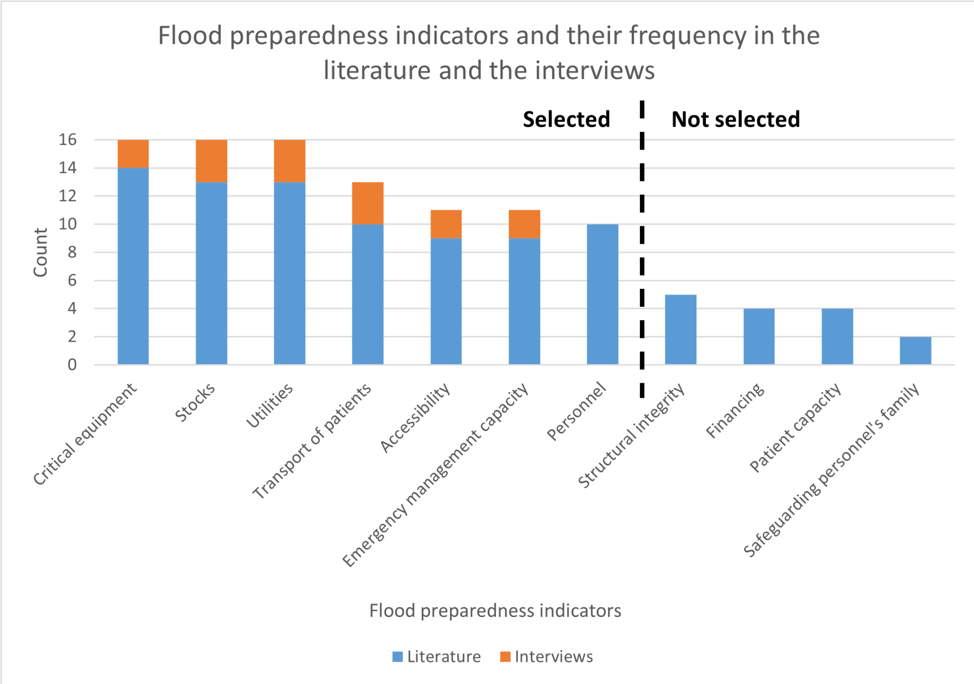


Figure 4.1: Indicators for hospitals' flood preparedness and how often these indicators are considered relevant in the literature and the interviews. In total, 14 sources from the literature were used. The indicator count for the interviews has been aggregated for the RdGG, the EMC and RWS. Therefore, the maximum count for the interviews is 3.

4.2 Evaluation

During the phase 2 interviews, the experts were asked to what extent the considered flood preparedness indicators cover the aspects that a hospital should consider when preparing for a flood (see Appendix C). In this context, the experts agreed with the proposed flood preparedness indicators. The proposed adjustments and reasons (not) to adopt them are discussed.

First, it was mentioned that varying flood preparedness indicators are relevant depending on the flood strategy selected. If ”preventive evacuation” is selected, the hospital is abandoned. Therefore, indicators such as ”critical equipment”, ”stocks” and ”utilities” are not so relevant. For the other flood strategies, which involve staying at the hospital, the indicator ”transport of patients” is irrelevant.

The indicator ”critical equipment” could be divided into infrastructure and patient-related equipment. It is reasoned that all equipment, as currently specified, is essential to guarantee the well-being of patients. In addition, some equipment finds itself in a grey area between infrastructure and patient-related equipment. To keep the number of indicators limited, it is decided not to divide the indicator ”critical equipment”.

The indicator ”accessibility” can be placed under the indicators ”stocks” and ”transport of patients”, rather than being defined as a separate indicator. Although accessibility is often mentioned as a separate aspect of hospital preparedness, it can often be related to the two indicators mentioned. Furthermore, for some indicators, a distinction is made between the direct and indirect impact. The failure of hospital accessibility can be considered to be part of the direct impact on a hospital. Hence, the proposed adjustment is adopted.

The experts agreed on not selecting the excluded indicators (see Figure 4.1). The indicator ”safeguarding personnel's family” was said to play a role during an evacuation, which confirms the findings from the literature. However, it was not acknowledged to be of such importance that it should be included as flood preparedness indicator.

The experts recommended to also consider the size of the hospital's catchment area as an indicator. This size is important to determine whether the remaining hospitals in the healthcare network are able to compensate for the failure of the flooded hospital in order to maintain regional continuity of healthcare. The flood preparedness indicators represent a hospital function and can be categorised as ”available” or ”failed”. The underlying function of the size of the catchment area is that hospitals are able to take up patients from flooded hospitals and people from the catchment that would have visited the flooded hospital. This is represented by the indicator ”patient capacity”, but this indicator was purposefully excluded by the experts. Therefore, this proposal is not adopted.

4.3 Final selection

In summary, based on the literature and (phase 1 and 2) interviews, a final selection of flood preparedness indicators is made. The characteristics of the flood strategy ”preventive evacuation” significantly differ from the other flood strategies, as the hospital is left behind. Hence, indicators related to supplies and the hospital building are not as relevant for this flood strategy. However, indicators related to moving patients are only relevant for ”preventive evacuation”. Therefore, a different set of flood preparedness indicators is selected for this and the other flood strategies.

For preventive evacuation, the following flood preparedness indicators are selected:

- Transport of patients
- Emergency management capacity
- Personnel

For the other flood strategies (”shelter in place with additional measures”, ”shelter in place without additional measures” and ”accept”) the flood preparedness indicators below are selected:

- Critical equipment
- Stocks
- Utilities
- Emergency management capacity
- Personnel

5. Assessing hospitals' flood preparedness in the Netherlands: the Reinier de Graaf Gasthuis and Erasmus MC cases

In this chapter, the method for evaluating flood preparedness of a hospital is applied to the Reinier de Graaf Gasthuis (RdGG) and EMC. These hospitals and relevant flood scenarios were introduced in Sections 3.2 and 3.3 respectively. First, the flood impact per flood scenario is determined. Subsequently, the expected number of fatalities and costs per flood strategy are derived. A sensitivity analysis is also conducted.

5.1 Reinier de Graaf Gasthuis - Flood impact

5.1.1 Direct impact

The phase 1 interviews were used to obtain an overview of the hospital facilities from the RdGG, their suppliers (if relevant) and elevation. The hospital has six levels above ground and is approximately 24 metres high. Therefore, each level is estimated to be four metres high. The ground floor is located at $-0{,}10$m NAP, the first floor is located at $+3{,}90$m NAP, the second flood is situated at $+7{,}90$m NAP, etc. The hospital does not have a basement, but some facilities are situated underground. The elevation of the underground facilities could not be verified. Therefore, it was estimated to be four metres below the ground floor, at $-4{,}10$m NAP.

The elevations are used as critical flood levels. Some facilities are elevated relative to the ground level. If measurements could be carried out, the precise elevation is reported. Else, the facilities are said to be "raised". The hospital employees stated that these facilities are elevated by at least 0,30m relative to their surroundings. For the underground facilities, it is unrealistic to assume that a water level of $-4{,}10$m NAP causes failure. The groundwater table in Delft is at approximately $-0{,}40$m NAP, which does not cause failure of underground facilities. For these facilities, the elevation of the ground floor ($-0{,}10$m NAP) is used as critical water depth. The availability of each hospital facility per flood scenario is summarised in table Table 5.4.

5.1.2 Indirect impact

To determine the the indirect impact, suppliers and their routes to the hospital are considered. The phase 1 interviews led to the identification of seven suppliers. The group "personnel" was added to this list based on the identified flood preparedness indicators. The indirect impact on these entities is elaborated per flood scenario. The identified suppliers are:

- Electricity supplier: Stedin
- Drinking water supplier: Evides
- Wastewater treatment plant: Delfluent
- Medical products supplier: ZorgserviceXL
- Sterilised equipment supplier: Combi-Ster
- Medical gases supplier: Linde Gas
- Fuel companies
- Personnel

In this chapter, the elaboration of the indirect impact of the "Regional 100" flood scenario is included. The elaboration of the indirect flood impact of the other flood scenarios ("Precipitation 1000", "Precipitation 100" and "Precipitation 10") can be found in Appendix D. The availability of the suppliers per flood scenario that threatens the RdGG is summarised in Table 5.4. The other scenarios that form a threat to suppliers are not included.

Electricity supplier (Stedin) - Utilities
The RdGG is connected to two separate medium voltage (MV) (10kV) power grids of energy company Stedin. The cables are connected to an on-site MV substation, which is located in the so-called "E-building" (Figure 5.1). On the other side of the power cables is a high voltage (HV) substation, South of Delft's city centre (Figure 5.2). This building is elevated approximately 0,30m above ground level, resulting in a critical flood level of +0,60m NAP. There are no intermediate substations between the RdGG and the HV substation. The HV substation is not threatened by floods and the underground power grid is assumed to remain unaffected by floods. Therefore, it may be assumed that this flood scenario does not result in failure of the power grid because of failure on the side of the supplier.

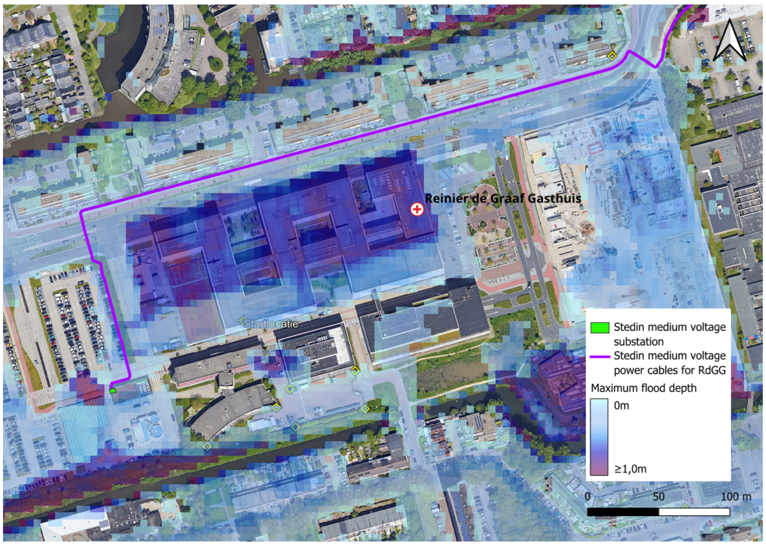


Figure 5.1: The two power cables connect to a MV substation in E-building, at the site of the RdGG. Flood scenario: Regional 100.

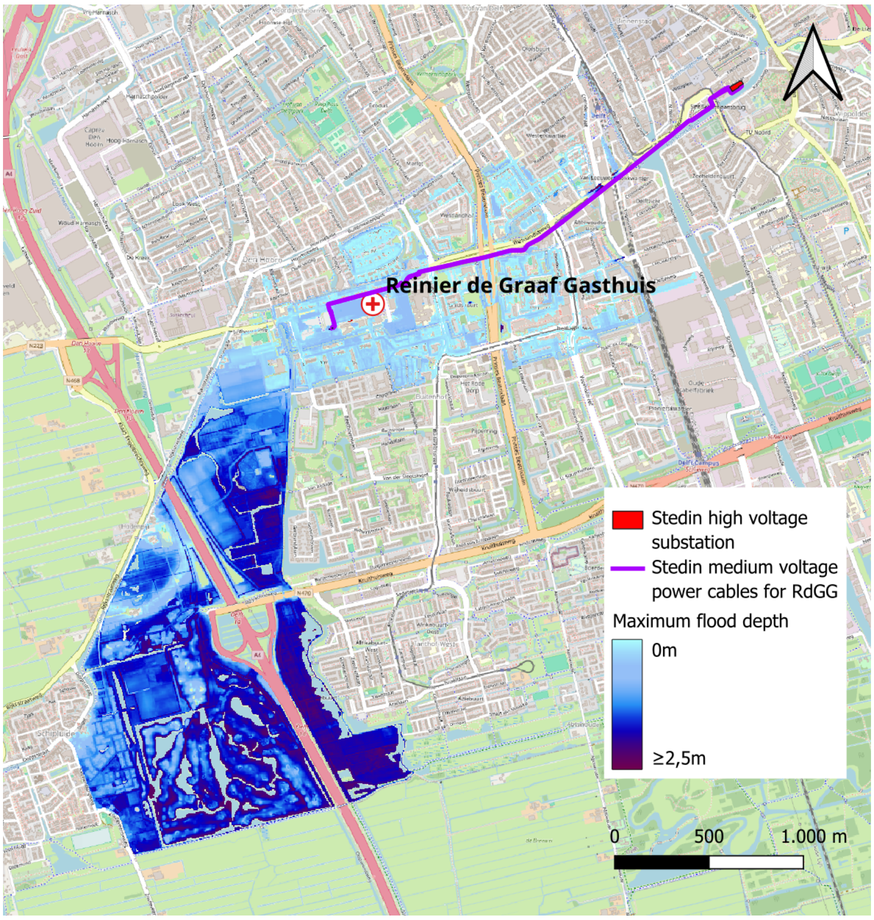


Figure 5.2: The two MV power cables run from the HV substation, South of the city centre of Delft, to the RdGG. Flood scenario: Regional 100.

Drinking water supplier (Evides) - Utilities
Drinking water is supplied by Evides. The water is most likely produced at Evides' location in Kralingen, Rotterdam (see Figure 5.3). This location is not threatened by the "Regional 100" scenario. The only flood that can occur at Evides is caused by the "Precipitation 1000" scenario (see Appendix D). The water grid is assumed to be unaffected by floods. Considering the flood scenario "Regional 100", the supply of water is not disrupted. Evides supplies drinking water to a part of the Southwest of the Netherlands (see Figure 5.3). This includes approximately 40 hospitals. It is unknown if failure of one production location can be compensated by another location.

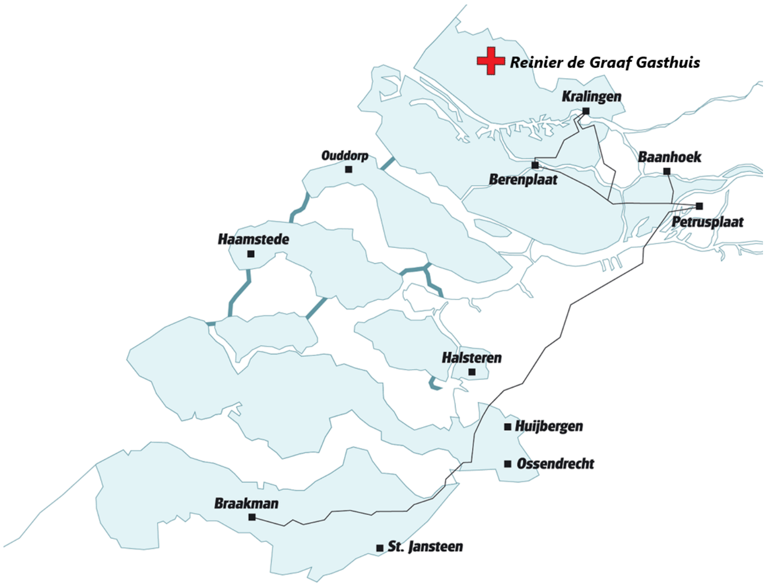


Figure 5.3: Drinking water supply area of Evides, including the production locations. The location of the RdGG has been indicated.

Wastewater treatment plant (Delfluent) - Utilities
The hospital's sewage systems are connected to the Harnaschpolder wastewater treatment plant, which is owned by Delfluent and is located in Den Hoorn. This location is not threatened by the "Regional 100" scenario, but can be flooded by three other scenarios: "Ter Heijde 1.000.000", "Scheveningen Uitwateringssluit 1.000.000" and "Kijkduin 1.000.000" (see Table 5.1). The latter two are expected to cause disturbance of operations when they occur. However, the probabilities are much lower than that of the "Regional 100" scenario. The underground sewage system is assumed to remain unaffected by floods.

Table 5.1: Flood scenarios for Delfuent. Address: Peuldreef 4, 2635 BX Den Hoorn. Adapted from *Mijn Waterrisicoprofiel*, by HKV lijn in water, 2020 (https://mijnwaterrisicoprofiel.nl/).

Scenario name	Flood depth [m]	Water level probability
Ter Heijde 1.000.000	0,02	1/1.100.000
Scheveningen Uitwateringssluis 1.000.000	0,11	1/1.200.000
Kijkduin 1.000.000	0,51	1/25.000.000

Medical products supplier (ZorgserviceXL) - Stocks
ZorgserviceXL is located in Delfgauw (see Figure 5.4) and delivers medical supplies to the RdGG. The company is only 7,0km from the hospital. Its location is not threatened by flooding. However, a small part of the route to the hospital is flooded by the "Regional 100" scenario. The maximum expected flood depth on the road to the hospital is approximately 0,20m. This amount of water is not expected to disrupt deliveries. Figure 5.4 shows the

supply route, avoiding all areas that can get flooded. ZorgserviceXL is also supplies four other hospitals in the region: the HagaZiekenhuis, Franciscus Gasthuis, Franciscus Vlietland and IJsselland Ziekenhuis. So locally, it has an important role in the delivery of medical supplies.

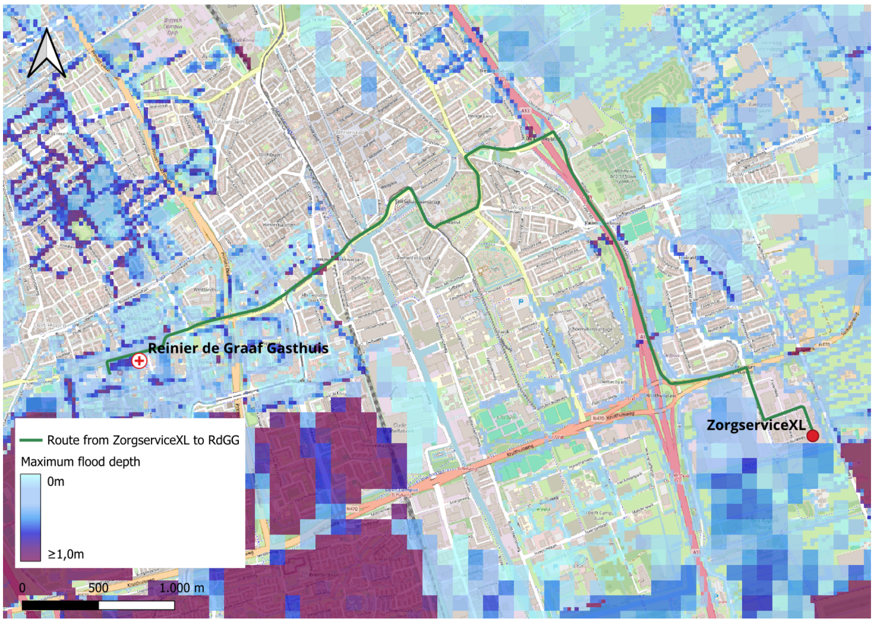


Figure 5.4: Route from ZorgserviceXL to the RdGG. The projected flood depth is a combined scenario for the case where all dykes are breached. In practice this cannot occur, but it shows how the route is accessible given the maximum flood depth for each location and as such, for each possible scenario.

Sterilised equipment supplier (Combi-Ster) - Stocks

The company Combi-Ster is located in Delft and sterilises the medical supplies that are used during surgical procedures. Its location is not flooded by the "Regional 100" scenario. However, it is flooded during the "Parksluizen 100.000" and "Parksluizen 1.000.000" scenarios (see Table 5.2). The location Parksluizen lies in Rotterdam at the Meuse river. The probabilities of occurrence for the Parksluizen scenarios are much lower than that of the "Regional 100" scenario. These probabilities are also well below the maximum allowable value of 1/30.000, which is the norm for 2050 for this dyke. The corresponding flood depths would make delivery of goods impossible. If the Parksluizen scenarios are not taken into account, delivery can continue as the building remains dry and the flood depth along the route is approximately 0,20m (see Figure 5.5). Combi-Ster also works for the HagaZiekenhuis and Reinier Haga Orthopedisch Centrum. This increases the impact if the company is flooded.

Table 5.2: Flood scenarios for Combi-Ster. Address: Marconiweg 18, 2627 BA Delft. Adapted from *Mijn Waterrisicoprofiel*, by HKV lijn in water, 2020 (https://mijnwaterrisicoprofiel.nl/).

Scenario name	Flood depth [m]	Water level probability
Parksluizen 1	0,52	1/600.000
Parksluizen 2	0,53	1/690.000

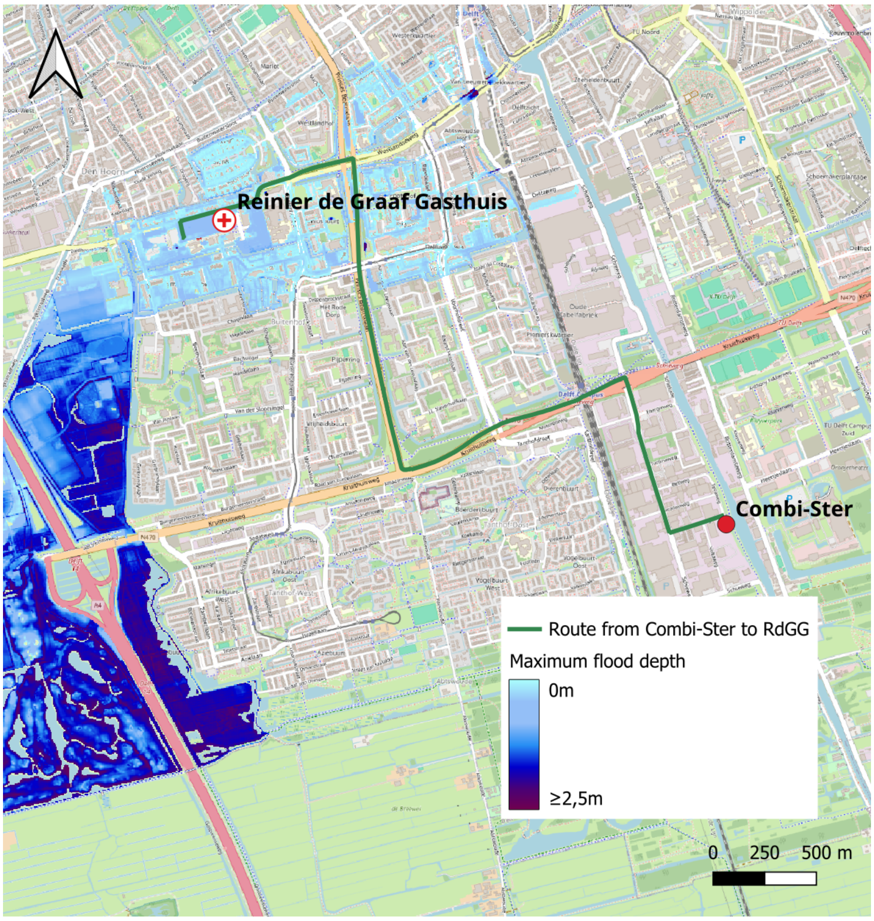


Figure 5.5: Route from Combi-Ster to the RdGG. The depicted flood scenario is "Regional 100". The route remains accessible.

Medical gases supplier (Linde Gas) - Stocks

The company Linde Gas supplies the medical gasses. Delft is supplied from the distribution centre in Schiedam, close to the Meuse river. This location is unaffected by the "Regional 100" scenario. The route to the RdGG is flooded by this scenario by approximately 0,20m and is therefore available. The company is impacted by the "Rivieren en Meren Rijn-Maasmonding" scenarios (see Table 5.3). These scenarios cause flooding at the company location. Assuming that only one flood scenario occurs simultaneously, there is always a route available to the RdGG (see Figure 5.6). Linde Gas supplies medical gasses to numerous other hospitals, among others: the EMC, VCMC, Franciscus Gasthuis and IJsselland ziekenhuis. Unfortunately, there is no overview of hospitals that receive their medical gases from Linde Gas.

Table 5.3: Flood scenarios for Linde Gas. Address: Havenstraat 23, 3115 HC Schiedam. Adapted from *Mijn Waterrisicoprofiel*, by HKV lijn in water, 2020 (https://mijnwaterrisicoprofiel.nl/).

Scenario name	Flood depth [m]	Water level probability
Rivieren en Meren Rijn-Maasmonding 100	0,06	1/100
Rivieren en Meren Rijn-Maasmonding 1000	0,24	1/1000
Rivieren en Meren Rijn-Maasmonding 10.000	0,50	1/10.000

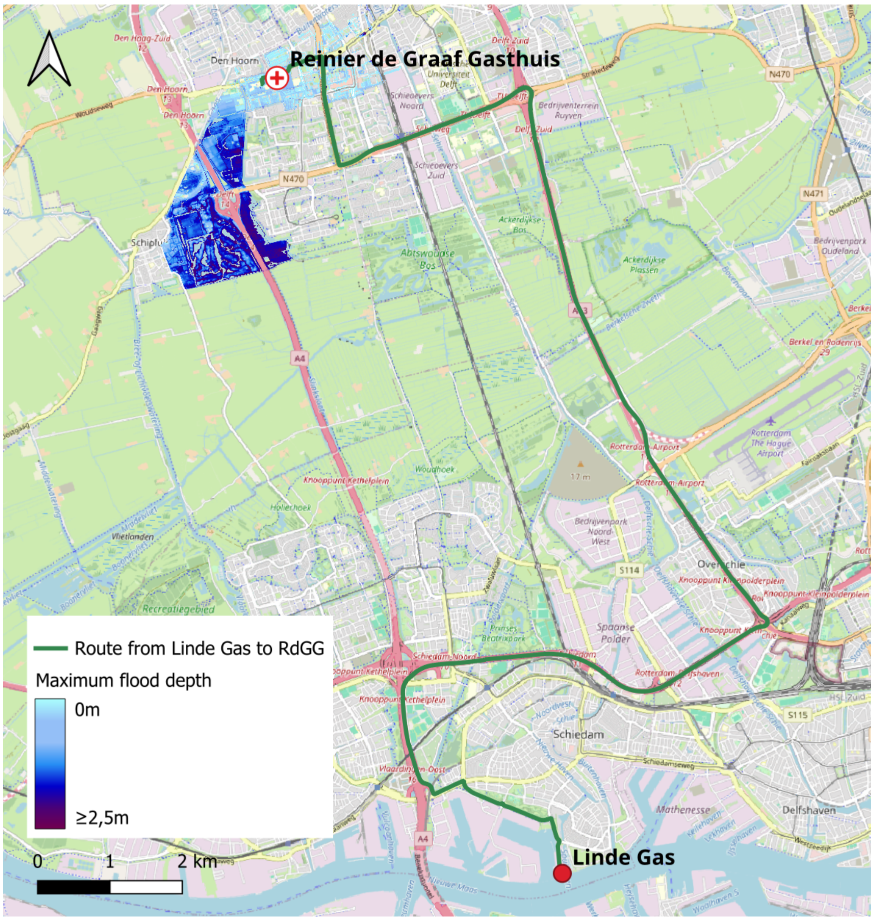


Figure 5.6: Route from Linde Gas to the RdGG. The depicted flood scenario is "Regional 100". The route remains accessible.

Fuel companies - Stocks
There are no scenarios that isolate the RdGG. Assuming that only one flood scenario occurs simultaneously, there will always be a fuel station that is able to supply the hospital with fuel for the backup generators. During the interview, the employees indicated that hospitals are very versatile and flexible in finding alternative products in times of scarcity. Because there is no flood scenario that results in flooded roads of more than 0,20m in the direct vicinity of the hospital, it is plausible that the hospital will be able to source fuel before running out of stock.

Personnel - Personnel
For the "Regional 100" scenario, it is expected that sufficient and and qualified personnel is available and able to reach the RdGG. The extent of the flooded area is limited and does not cover a large and densely populated area. In addition, access roads are flooded up to 0,20m, which means that they remain available by car. However, to guarantee accessibility of the hospital to personnel, additional measures must be taken to transport personnel to the hospital.

5.1.3 Total impact

The flood impact is presented in Table 5.4. Hospital facilities and suppliers have been grouped according to the flood preparedness indicators. The suppliers are printed in italics. Availability of each facility and supplier is indicated per flood scenario, using "○" for "available" and "●" for "unavailable". The flood level (in "m NAP") at the RdGG per flood scenario is indicated at the top between brackets. Because the suppliers are located at a different location than the hospital, the flood level at the supplier location may be different from the flood level at the hospital. The flood level at each supplier location is indicated in parentheses per flood scenario. The flood level is compared with the critical flood level to determine the availability of hospital facilities and suppliers. If the supplier location is not threatened by a flood scenario, "(-)" is added. Supplier failure due to flooded roads has been indicated with "(roads)". The flood preparedness indicator "emergency management capacity" is assumed not to be affected by floods, since agreements and emergency plans are not tangible. At the bottom of each flood preparedness indicator, the overall availability of that indicator is assessed per flood scenario. If any of the hospital facilities or suppliers is unavailable for a given flood scenario, it is also assumed that the corresponding indicator is unavailable (i.e., has failed).

Table 5.4: Flood impact per flood scenario that threatens the RdGG.

Indicator	Facility or supplier	Critical flood level [m NAP]	Regional 100 [+0,66m NAP]	Precipitation 1000 [+0,40m NAP]	Precipitation 100 [+0,20m NAP]	Precipitation 10 [+0,05m NAP]
Critical equipment	Compressed air	19,90	○	○	○	○
	ER	-0,10	●	●	●	●
	Hydrophore	0,20	●	●	●	○
	IC	11,90	○	○	○	○
	ICT	11,90	○	○	○	○

Continued on the next page.

Indicator	Facility	Critical flood level [m NAP]	Regional 100 [+0,66m NAP]	Precipitation 1000 [+0,40m NAP]	Precipitation 100 [+0,20m NAP]	Precipitation 10 [+0,05m NAP]
	Mortuary	0,20	•	•	•	○
	Nursing departments	7,90	○	○	○	○
	Operating rooms	15,90	○	○	○	○
	Outpatient clinics	3,90	○	○	○	○
	Pharmacy	3,90	○	○	○	○
	Ventilation	13,90	○	○	○	○
	Indicator		•	•	•	•
Stocks	Central storage room	-0,10	•	•	•	•
	Food	-0,10	•	•	•	•
	Fuel basin	-0,10	•	•	•	•
	Fuel take-in point	0,60	•	○	○	○
	Linen	7,90	○	○	○	○
	Logistics	-0,10	•	•	•	•
	Materials for operation rooms	19,90	○	○	○	○
	Medical gases	0,20	•	•	•	○
	Medication	7,90	○	○	○	○
	(Non)sterile material	7,90	○	○	○	○
	Water basin	-0,10	•	•	•	•
	Water take-in point	0,60	•	○	○	○
	Fuel companies	-0,20 (roads)	○ (-0,20)	○ (-)	○ (-)	○ (-)
	Medical gas supplier (Linde Gas)	3,60	○ (-)	○ (-)	○ (-)	○ (-)
	Medical products supplier (ZorgserviceXL)	-1,90	○ (-)	• (roads)	○ (-)	○ (-)
	Sterilised equipment supplier (Combi-Ster)	-0,20	○ (-)	• (roads)	• (roads)	○ (-)
	Indicator		•	•	•	•
Utilities	Backup generators	0,20	•	•	•	○
	Water take-in point	0,60	•	○	○	○

Continued on the next page.

Indicator	Facility	Critical flood level [m NAP]	Regional 100 [+0,66m NAP]	Precipitation 1000 [+0,40m NAP]	Precipitation 100 [+0,20m NAP]	Precipitation 10 [+0,05m NAP]
	10kV grid connections	0,20	●	●	●	○
	Electrical transformers	0,20	●	●	●	○
	Electrical distribution boards	0,20	●	●	●	○
	Sewage	-0,10	●	●	●	●
	Drinking water supplier (Evides)	4,70	○ (-)	● (4,80)	○ (-)	○ (-)
	Electricity supplier (Stedin)	0,60	○ (-)	○ (0,50)	○ (0,45)	○ (-)
	Wastewater treatment plant (Delfuent)	0,00	○ (-)	○ (-)	○ (-)	○ (-)
	Indicator		●	●	●	●
Personnel	Availability of sufficient and qualified personnel	-	○	○	○	○
	Hospital accessibility	-0,10	●	●	●	●
	Indicator		●	●	●	●
Transport of patients	Ambulance department	-0,10	●	●	●	●
	Hospital accessibility	-0,10	●	●	●	●
	Indicator		●	●	●	●
Emergency management capacity	Unaffected by floods	-	○	○	○	○
	Indicator		○	○	○	○

Available: ○
Unavailable: ●

Regarding the continuity of healthcare at the RdGG, if any of the facilities that fall under a certain flood preparedness indicator fail, that particular indicator is considered to have failed. The overall availability of each flood preparedness indicator per flood scenario is shown in Table 5.4. Failure of one flood preparedness indicator is assumed to cause failure of the hospital's continuity of healthcare. From Table 5.4 it becomes apparent that for every flood scenario, all flood preparedness indicators can be considered to have failed due to hospital facility failure, except for "emergency management capacity". Therefore, in all of the four flood scenarios, continuity of healthcare is disrupted. This disruption leads to an increased number of fatalities compared to the "normal" situation. The expected number of fatalities for the flood scenarios depends on the implemented flood strategy, which is calculated in the next section.

5.2 Reinier de Graaf Gasthuis - Fatalities

In this section, the number of fatalities for the RdGG is calculated per flood strategy, using the method from Section 3.7. As discussed in the previous section, the continuity of healthcare at the RdGG is disrupted during the "Precipitation 1000", "Precipitation 100", "Precipitation 10" and "Regional 100" flood scenarios. Therefore, the number of fatalities that is calculated per flood strategy is applicable to each scenario.

The RdGG has 481 beds. Therefore, the number of patients per patient group and their vulnerability factor are shown in Table 5.5. The average daily mortality rate at Dutch hospitals (M) is 0,0023 deaths per hospital bed per day. The number of fatalities per flood strategy is calculated below and strategies are compared.

Table 5.5: Parameters for the patient group with high, medium and low vulnerability.

Patient group (i)	$N_{i,j}$ [#ppl]	v_i [-]
High ($i = 1$)	24	8
Medium ($i = 2$)	120	2
Low ($i = 3$)	337	0,14

Shelter in place with additional measures
Table 5.6 shows the parameters that are specific to the flood strategy "shelter in place with additional measures". The flood strategy factor f_1 is 6,67 (as discussed in Section 3.7). Considering each of the four flood scenarios that threaten the RdGG, there are no other hospitals that are simultaneously flooded. Furthermore, the extent of the area covered by the flood scenarios is limited and does not cover densely populated areas. The flood depths are limited too. Therefore, it is assumed that all rescue efforts are aimed at saving the RdGG and that the hospital can relatively easily be reached. In addition, it is assumed that, as part of the additional measures of this flood strategy, rescue plans and advance agreements have been made to ensure a swift emergency response. Hence, it is considered that exposure of patients to flooding is limited to 0,5 days ($t_1 = 0,5$).

Table 5.6: Parameters for the flood strategy "shelter in place with additional measures" ($j = 1$).

Parameter	Value
Flood strategy factor f_1 [-]	6,67
Time when the flood is over t_1 [d]	0,5

Table 5.7 shows the number of fatalities for the flood strategy "shelter in place with additional measures". These values are calculted with Equation 3.8 from Section 3.7. As one of the additional measures, the patient group with low vulnerability is assumed to be discharged in anticipation of the flood. Hence, this group is set to 0. The expected number of fatalities is 0,2.

Table 5.7: Fatalities for the flood strategy "shelter in place with additional measures".

Patient group (i)	$N_{i,1}$ [#ppl]	$F_{i,1}$ [dths]
High ($i = 1$)	24	0,1
Medium ($i = 2$)	120	0,1
Low ($i = 3$)	0	0,0
	$F_1 =$	0,2

Shelter in place without additional measures
Table 5.8 contains parameters specific to the flood strategy "shelter in place without additional measures". The flood strategy factor f_2 is 10. As discussed at the previous flood strategy, due to the characteristics of to the four flood scenarios considered, it is expected that the RdGG will be rescued rather quickly. However, since no additional measures have been taken, the hospital is assumed to be rescued after one day ($t_2 = 1$).

Table 5.8: Parameters for the flood strategy "shelter in place without additional measures" ($j = 2$).

Parameter	Value
Flood strategy factor f_2 [-]	10
Time when the flood is over t_2 [d]	1

The number of fatalities for "shelter in place without additional measures" is calculated with Equation 3.8 and is shown in Table 5.9. For this flood strategy, it is assumed that all patients are present at the hospital when the flood arrives. Because no additional measures have been taken, the flood strategy factor (f_2) is higher and help arrives later (t_2), compared to "shelter in place with additional measures". As a consequence, the number of expected fatalities is approximately seven times higher: 1,4 fatalities. Especially the patient groups with high and medium vulnerability are affected the most.

Table 5.9: Fatalities for the flood strategy "shelter in place without additional measures".

Patient group (i)	$N_{i,2}$ [#ppl]	$F_{i,2}$ [dths]
High ($i = 1$)	24	0,6
Medium ($i = 2$)	120	0,7
Low ($i = 3$)	337	0,1
	$F_2 =$	1,4

Accept
The flood strategy factor (f_3) and the time when the RdGG is rescued (t_3) for "accept" are shown in Table 5.10. The flood strategy factor was defined in Section 3.7 and is higher than the previous two flood strategies, reflecting that the conditions at the hospital are worse during this flood strategy. It is assumed that a rescue mission is able to rescue the hospital after one day.

Table 5.10: Parameters for the flood strategy "accept" ($j = 3$).

Parameter	Value
Flood strategy factor f_3 [-]	15
Time when the flood is over t_3 [d]	1

Table 5.11 shows the number of fatalities for the flood strategy "accept". Equation 3.8 is used to calculate this value. All patient groups are in the hospital when the flood reaches the hospital. The flood strategy "accept" results in 2,1 fatalities, which is 50% more than "shelter in place without additional measures".

Table 5.11: Fatalities for the flood strategy "accept".

Patient group (i)	$N_{i,3}$ [#ppl]	$F_{i,3}$ [dths]
High ($i = 1$)	24	0,8
Medium ($i = 2$)	120	1,0
Low ($i = 3$)	337	0,2
	$F_3 =$	2,1

Preventive evacuation
Table 5.12 shows the parameters that are input to Equation 3.9, which is used to calculate the number of fatalities for "preventive evacuation". The flood strategy factors for successful and unsuccessful preventive evacuation (1,5 and 40, respectively) are determined in Section 3.7. For flood scenarios involving regional breaches (such as the "Regional 100" scenario), preventive evacuation is only possible if the flood can be predicted. If a breach in a regional flood defence occurs unexpectedly, there is no time to preventively evacuate the RdGG. However, if the flood can be anticipated, it is expected that the entire RdGG can be

evacuated successfully. This assumption is based on the expected flood conditions: firstly, the RdGG is the only hospital that can be flooded by the "Regional 100" scenario. Hence, all regional emergency management resources can focus on the RdGG. In addition, the extent of the flooded area is limited. Therefore, patients can be moved outside the flood-prone area relatively quickly. The evacuation fraction for the "Regional 100" flood scenario is assumed to be 1. The number of evacuations relative to one flood is assumed to be 1, based on the judgement of a flood expert at HKV. With regard to floods resulting from precipitation events, the flood depths are usually limited. Although such flood depths can cause water nuisance, in practice hospitals in the Netherlands do not preventively evacuate for such events. The value of t_4 is always equal to one day, as discussed in Section 3.7. The number of fatalities for "preventive evacuation" of the RdGG is presented in Table 5.13. The total number of fatalities is 1,7, which is less than for "accept", but worse than "shelter in place with additional measures" and "shelter in place without additional measures".

Table 5.12: Parameters for the flood strategy "preventive evacuation" ($j = 4$).

Parameter	Value
Flood strategy factor f_{suc} [-]	1,5
Flood strategy factor f_{fail} [-]	40
Evacuation fraction e [-]	1,0
Number of evacuations relative to one flood r [-]	1
Duration t_4 [d]	1

Table 5.13: Fatalities for the flood strategy "preventive evacuation".

Patient group (i)	$N_{i,4}$ [#ppl]	$F_{i,4}$ [dths]
High ($i = 1$)	24	0,7
Medium ($i = 2$)	120	0,8
Low ($i = 3$)	337	0,2
	$F_4 =$	1,7

5.3 Erasmus MC - Flood impact

5.3.1 Direct impact

The phase 1 interviews and a previous study analysing flood risk for the EMC (HKV lijn in water, 2017) were used to obtain an overview of the hospital facilities from the EMC, their suppliers (if relevant) and elevation. The hospital consists of various buildings that are linked to each other (see Figure 5.7). Elevation maps of the Netherlands (Actueel Hoogtebestand Nederland (AHN)) were used to determine the elevation of hospital facilities (Algemeen Hoogtebestand Nederland, n.d.). The main entrance at the front of the hospital (address: Dr. Molewaterplein 40) is situated at −0,20m NAP. This level is assumed to be the ground floor level. In 2017, a new part of the hospital was completed. The highest part of the building is approximately 120 metres high. There is also a basement, but it does not contain critical installations (HKV lijn in water, 2017).

The elevation of facilities are used as critical flood levels. Some facilities on the ground floor of the building (−0,20m NAP) are elevated by several decimetres (HKV lijn in water, 2017). The exact elevation could not be determined. Therefore, these facilities are said to be "raised". The main entrance is used to determine hospital accessibility. Its critical flood level is −0,20m NAP. The logistics centre (see Figure 5.7) is located on the east side of the hospital (address: Westzeedijk 353) and is situated lower than ground level, at −1,20m NAP. The ambulance department is situated at −1,00m NAP (see Figure 5.7). The availability of each hospital facility per flood scenario is summarised in table Table 5.16.

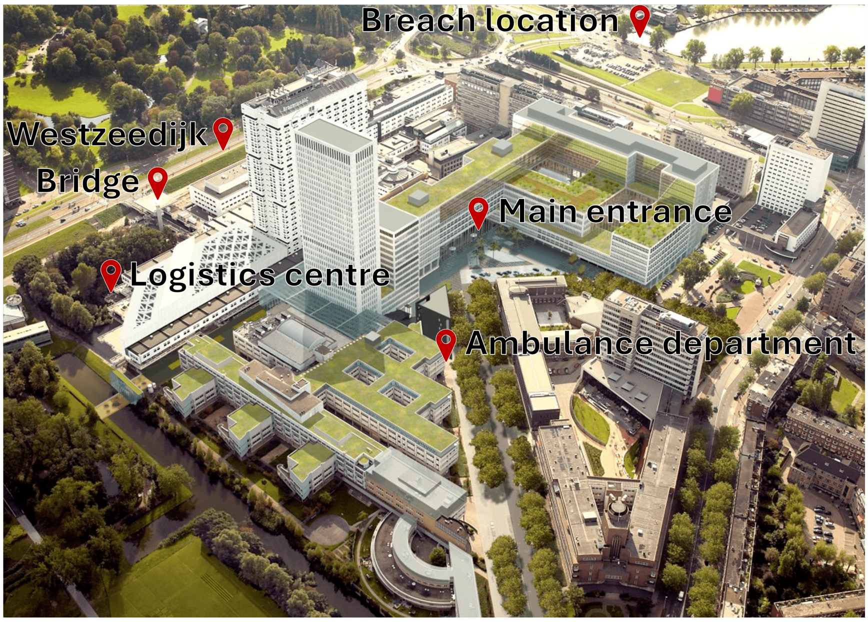


Figure 5.7: Overview of the EMC. Important locations are indicated. Adapted from *Erasmus MC Daktuinen*, by Erasmus MC Foundation, n.d. (https://erasmusmcfoundation.nl/erasmus-mc-daktuinen/).

5.3.2 Indirect impact

To determine the the indirect impact, suppliers and their routes to the hospital are considered. The phase 1 interviews led to the identification of eight suppliers. The group "personnel" was added to this list based on the identified flood preparedness indicators. The indirect impact on these entities is elaborated per flood scenario. The identified suppliers are:

- Fuel companies
- Linen supplier: Nedlin Healthcare
- Medical gas supplier: Linde Gas

- Distribution centre
- Medicine supplier: Alliance Healthcare
- Drinking water supplier: Evides (Berenplaat)
- Drinking water supplier: Evides (Kralingen)
- Electricity supplier: Stedin
- Personnel

In this chapter, the elaboration of the indirect impact of the "Parksluizen 2" flood scenario is included. The elaboration of the indirect flood impact of the "Parksluizen 1" flood scenario can be found in Appendix E. The availability of the suppliers per flood scenario that threatens the EMC is summarised in Table 5.4. The other scenarios that form a threat to suppliers are not included.

It should be noted that during the storm that causes a breach at Parksluizen, delivery is impossible due to the rough weather conditions. In addition, the storm is expected to cause extensive damage to the infrastructure, possibly cutting off the EMC from suppliers.

Fuel companies - Stocks
As depicted in Figure 5.8, the EMC becomes isolated due to the "Parksluizen 2" flood scenario. The primary flood defence on the north side of the Meuse is breached at "Parksluizen". It is assumed that the storm that causes this breach causes a high water level outside the dyke. As a result, the area outside the dyke (south of the EMC) will also flood, even though this is not indicated on the flood map. The dyke forms an alternative access route to the hospital, because delivery could take place via the bridge connecting the dyke (Westzeedijk) and EMC (see Figures 5.7 and 5.9). However, the breach in this primary flood defence is located close to the hospital and the rest of the dyke may also be damaged by the storm. Therefore, the availability of the road on top of the dyke cannot be guaranteed. Due to the isolation of the hospital, it is expected that no fuel company can reach the EMC to deliver fuel. All access roads to the EMC are flooded by more than 0,20 metres.

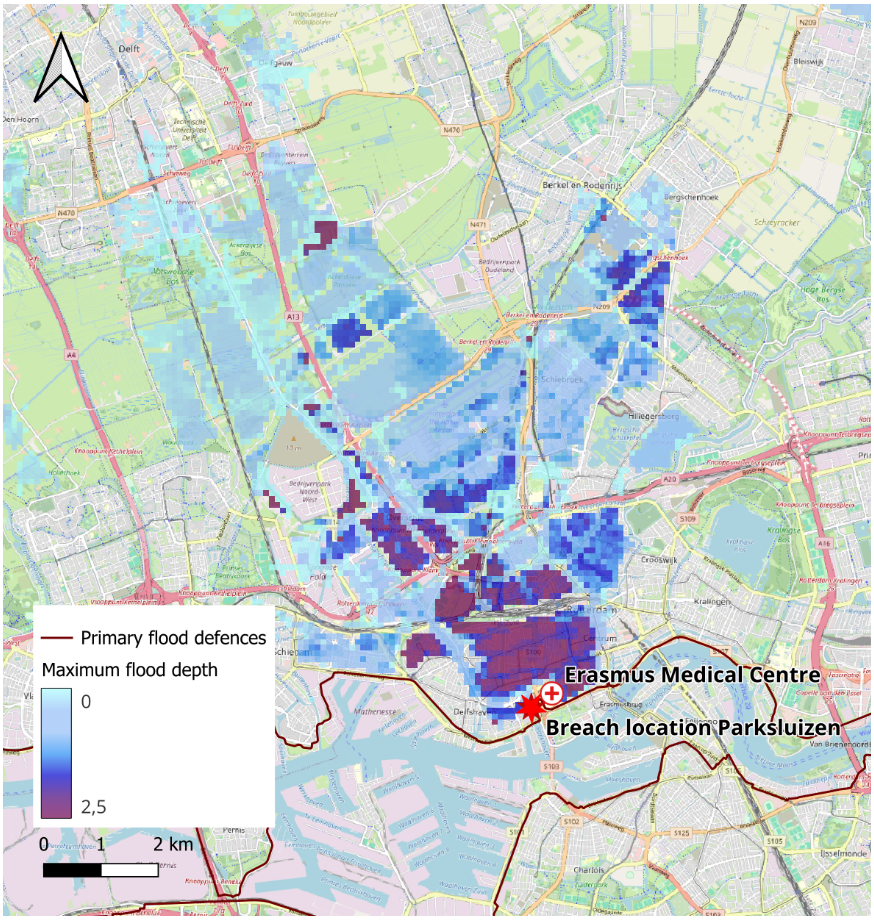


Figure 5.8: Flood depth map resulting from a breach at Parksluizen. The depicted flood scenario is "Parksluizen 2". The EMC is expected to become isolated during this flood scenario.

Figure 5.9: Brigde connecting the EMC (on the right) with the Westzeedijk (on the left).

Linen supplier (Nedlin Healthcare) - Stocks
Nedlin Healthcare supplies linen to the EMC. The company is located in Elsloo, in the province of Limburg. Its critical flood level is determined to be +69,70m NAP. This location can only be flooded by a precipitation event with a probability of 1/1000 per year, resulting in a flood depth of 0,20 metres (see Table 5.14). Assuming that only one flood scenario occurs simultaneously, during the "Parksluizen 2" scenario the route from Nedlin Healthcare to the EMC is available for the most part. However, in the vicinity of the hospital, the route is not available due to flooding (see Figure 5.10) and no alternative routes are available due to isolation of the hospital.

Table 5.14: Flood scenarios for Nedlin Healthcare. Address: Business Park Stein 133, 6181 MA Elsloo. Adapted from *Mijn Waterrisicoprofiel*, by HKV lijn in water, 2020 (https://mijnwaterrisicoprofiel.nl/).

Scenario name	Flood depth [m]	Water level probability
Precipitation 1000	0,20	1/1000

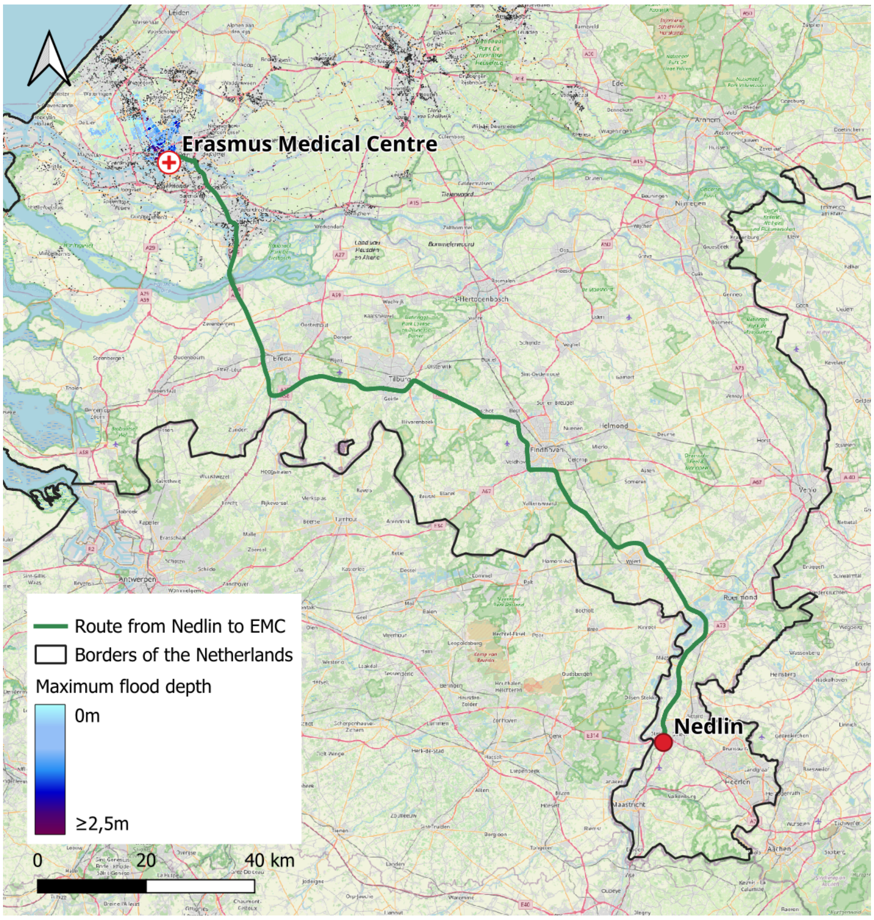


Figure 5.10: Route from Nedlin Healthcare to the EMC. The depicted flood scenario is "Parksluizen 2". The route is inaccessible near the EMC.

Medical gas supplier (Linde Gas) - Stocks
The company Linde Gas supplies multiple hospitals with medical gases, including the EMC. The hospital is supplied by the same location as the RdGG, which is located in Schiedam. The company is situated at +3,60m NAP and is not threatened by the "Parksluizen 2" flood scenario. The flood scenarios that can threaten Linde Gas are shown in Table 5.3. The route from Linde Gas to the EMC is depicted in Figure 5.11. The route near the hospital is inaccessible due to flooding, as the route crosses the breach location.

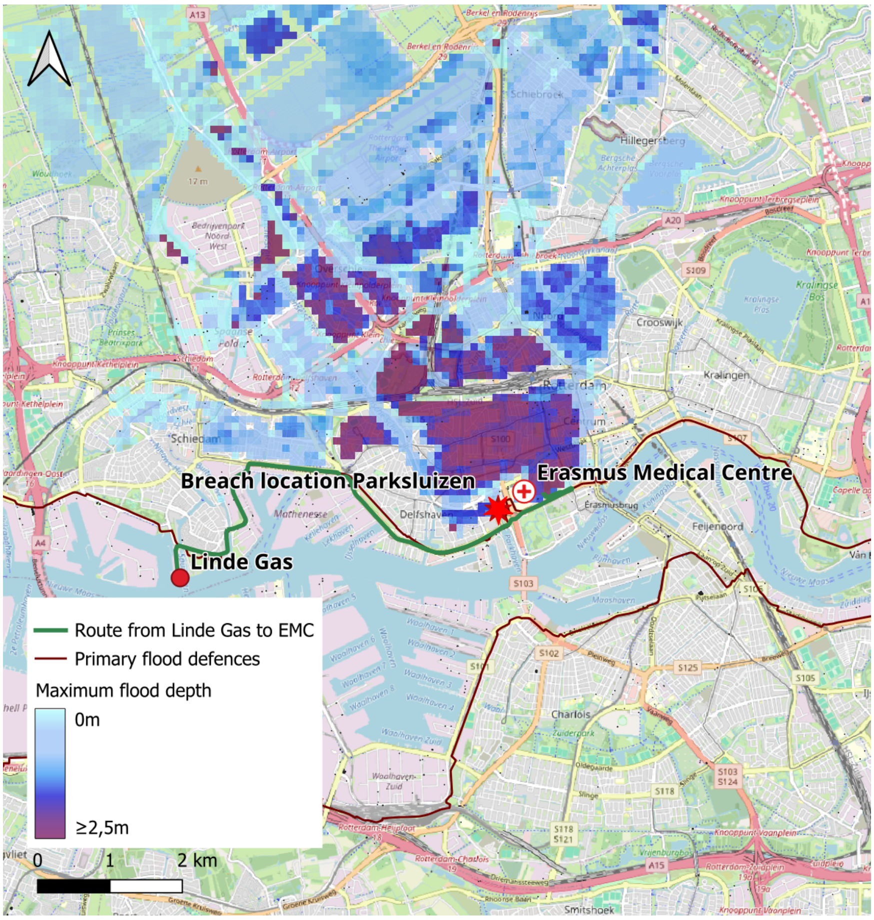


Figure 5.11: Route from Linde Gas to the EMC. The depicted flood scenario is "Parksluizen 2". The route is inaccessible near the EMC.

Medical supplies (distribution centre) - Stocks

The EMC has its own distribution centre that stores and delivers medical supplies. The distribution centre is located on the other side of the river Meuse, is situated at −0,90m NAP and cannot be flooded by the "Parksluizen 2" flood scenario. However, during this scenario, the route near the EMC is flooded and therefore inaccessible (see Figure 5.12). The distribution centre can be flooded by other flood scenarios, as shown in Table 5.15.

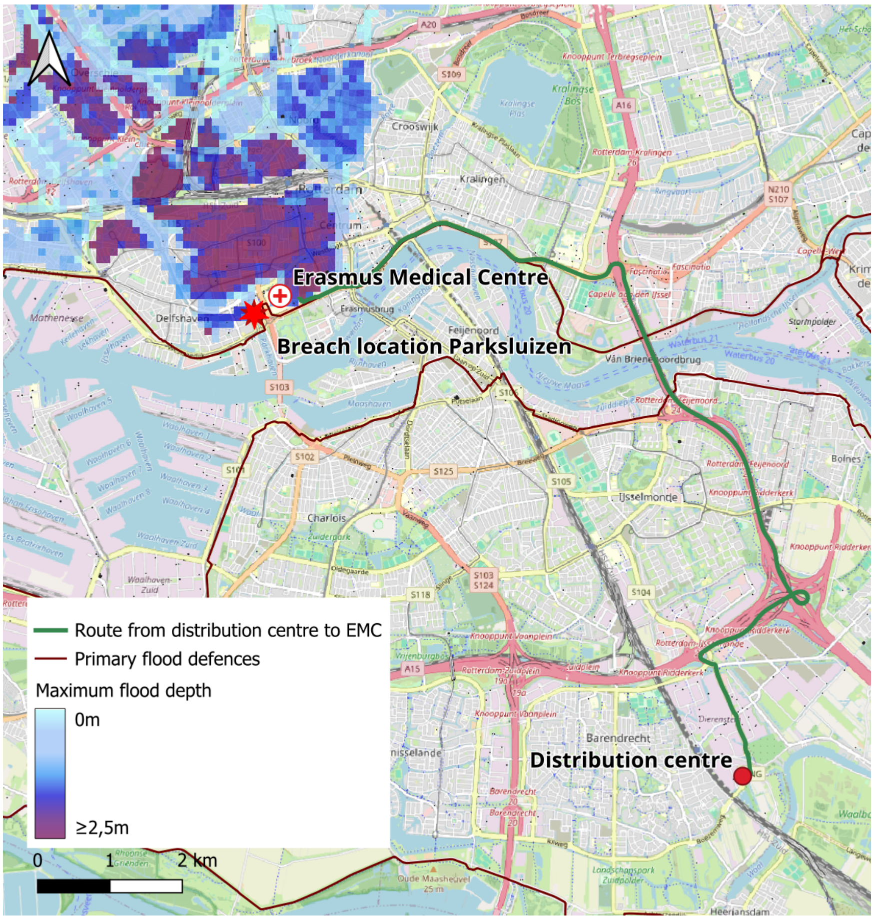


Figure 5.12: Route from the distribution centre to the EMC. The depicted flood scenario is "Parksluizen 2". The route is inaccessible near the EMC.

Table 5.15: Flood scenarios for the distribution centre of the EMC. Address: Ebweg 7, 2991 LS Barendrecht. Adapted from *Mijn Waterrisicoprofiel*, by HKV lijn in water, 2020 (https://mijnwaterrisicoprofiel.nl/).

Scenario name	Flood depth [m]	Water level probability
Oude Maas 1	0,74	1/5300
Nieuwe Maas	1,31	1/5900
Oude Maas 2	1,41	1/7500
Oude Maas 3	2,14	1/12.000

Medicine supplier (Alliance Healthcare) - Stocks
Medicines are supplied by the company Alliance Healthcare, which is located in Veghel. This company is situated at +10,50m NAP and is not threatened by any floods. Delivery of

supplies cannot take place during the "Parksluizen 2" flood scenario, because the road near the hospital is flooded (see Figure 5.13).

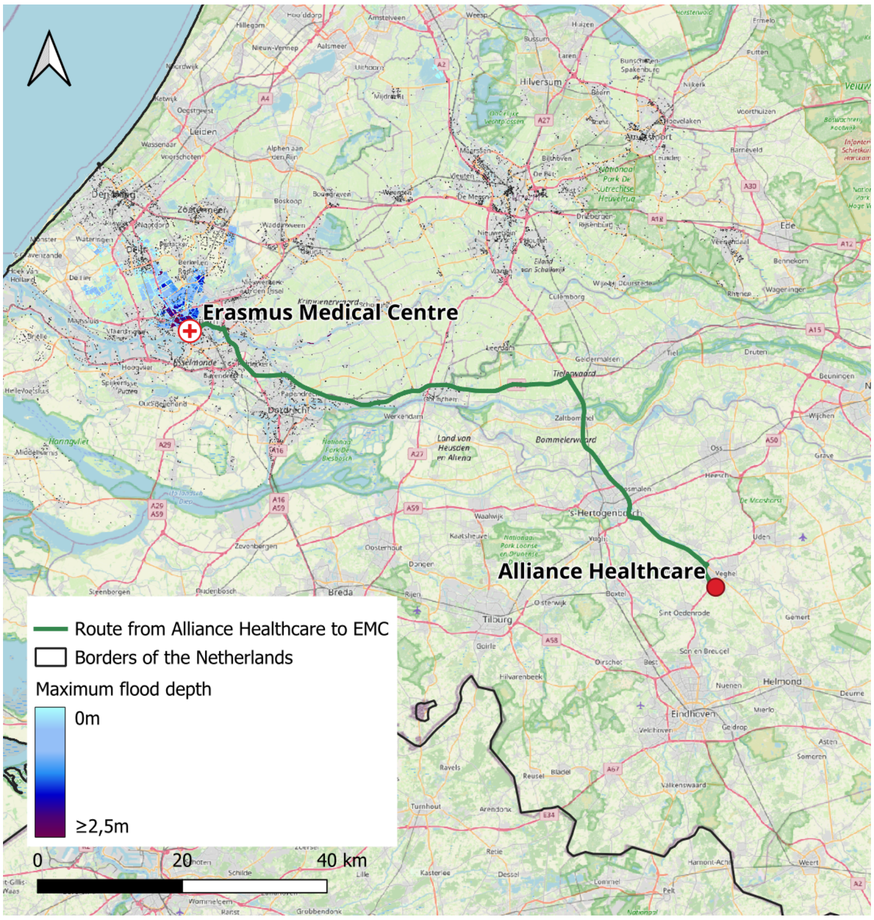


Figure 5.13: Route from Alliance Healthcare to the EMC. The depicted flood scenario is "Parksluizen 2". The route is inaccessible near the EMC.

Drinking water supplier (Evides, Berenplaat) - Utilities
Drinking water is supplied by Evides, which has multiple production locations. The production sites Berenplaat and Kralingen (Figure 5.14) provide drinking water to the EMC (Kolen et al., 2017). The production site Berenplaat is situated at +4,10m NAP and cannot be flooded by the "Parksluizen 2" flood scenario. In addition, it is not threatened by other flood scenarios. The water grid is assumed to remain unaffected by floods. Therefore, the supply of drinking water remains available.

Drinking water supplier (Evides, Kralingen) - Utilities
The production site Kralingen was previously analysed for the RdGG. The critical flood level for production site Kralingen is +4,70m NAP and this location is only threatened by a precipitation event with a probability of 1/1000 per year. This flood scenario is addressed in Appendix D. The "Parksluizen 2" flood scenario does not affect production site Kralingen.

The water grid is assumed to remain unaffected by floods. Therefore, the supply of drinking water remains uninterrupted.

Figure 5.14: Drinking water supply area of Evides, including the production locations. The location of the EMC has been indicated. The locations Berenplaat and Kralingen provide drinking water to the EMC.

Electricity supplier (Stedin) - Utilities
The EMC has several connections to the power grid spread across the hospital terrain. The hospital has two 23KV connections, each connecting to a different power grid. In addition, there are three 10KV connections (Kolen et al., 2017). Although underground cables are assumed to remain unaffected by floods, the MV substations in the direct vicinity of the hospital are flooded. No single critical flood level can be determined, but it can be assumed that a flood depth of more than one metre in the vicinity of the EMC causes failure of the electricity supply.

Personnel - Personnel
For the "Parksluizen 2" flood scenario, it is expected that there will not be sufficient and qualified personnel available without implementation of specific measures. The flooded area is extensive, covering large densely populated parts of the city Rotterdam. The flood depth in these areas is also significant, reaching a flood depth of more than 1 metre. In addition, the hospital becomes isolated. These factors contribute to the assessment that personnel cannot reach the EMC.

5.3.3 Total impact

The direct and indirect flood impact are summarised in Table 5.16. The availability of hospital facilities and suppliers is indicated per flood scenario. These facilities and suppliers are grouped according to the flood preparedness indicators. The overall availability of these indicators is also assessed. Every indicator fails during both flood scenarios, except for "emergency management capacity". This indicator is assumed to remain unaffected by floods. As a result, the continuity of healthcare is disrupted in both flood scenarios. The expected number of fatalities resulting from this disruption depends on the flood strategy implemented and is calculated in the next section.

Table 5.16: Flood impact per flood scenario that threatens the EMC.

Indicator	Facility or supplier	Critical flood level [m NAP]	Parksluizen 1 [+1,20m NAP]	Parksluizen 2 [+1,44m NAP]
Critical equipment	ER	-0,20	•	•
	Data centre (raised)	-0,20	•	•
	Nursing departments	-0,20	•	•
	Waste disposal	-0,20	•	•
	Indicator		•	•
Stocks	Central storage room	-0,20	•	•
	Drinking water	-0,20	•	•
	Logistics centre	-0,20	•	•
	Logistics hallway	-0,20	•	•
	Medical gases	-1,20	•	•
	Fuel companies	-0,20 (roads)	• (roads)	• (roads)
	Linen supplier (Nedlin Healthcare)	69,70	• (roads)	• (roads)
	Medical gas supplier (Linde Gas)	3,60	• (roads)	• (roads)
	Medical products supplier (distribution centre)	-0,90	• (roads)	• (roads)
	Medicine supplier (Alliance Healthcare)	10,50	• (roads)	• (roads)
	Indicator		•	•
Utilities	Backup generators	-0,20	•	•
	Control cabinet (raised)	-0,20	•	•
	Drinking water supplier (Evides, Berenplaat)	4,10	◦ (-)	◦ (-)
	Drinking water supplier (Evides, Kralingen)	4,70	◦ (-)	◦ (-)
	Electricity supplier (Stedin)	-	•	•
	Indicator		•	•

Continued on the next page.

Indicator	Facility or supplier	Critical flood level [m NAP]	Parksluizen 1 [+1,20m NAP]	Parksluizen 2 [+1,44m NAP]
Personnel	Availability of sufficient and qualified personnel	-	•	•
	Hospital accessibility	-0,20	•	•
	Indicator		•	•
Transport of patients	Ambulance department	-1,00	•	•
	Hospital accessibility	-0,20	•	•
	Indicator		•	•
Emergency management capacity	Unaffected by floods	-	○	○
	Indicator		○	○
			Available:	○
			Unavailable:	•

5.4 Erasmus MC - Fatalities

In this section, the number of fatalities for the EMC is calculated for the flood scenarios "Parksluizen 1" (flood depth: 1,60m) and "Parksluizen 2" (flood depth: 1,84m), using the method from Section 3.7. The continuity of healthcare is disrupted during the two flood scenarios. Therefore, the number of fatalities calculated per flood strategy is applicable to both scenarios. First, the number of fatalities for just the EMC is considered (Section 5.4.1). In Section 5.4.2, the number of fatalities for all simultaneously threatened hospitals are regarded per flood strategy.

5.4.1 Considering only the Erasmus MC

The EMC has 1200 beds. Therefore, the patient groups with high, medium and low vulnerability consist of 60, 300 and 840 patients respectively. The average daily mortality rate at Dutch hospitals (M) is 0,0023 deaths per hospital beds per day. The number of fatalities per flood strategy is calculated below.

Table 5.17: Parameters for the patient group with high, medium and low vulnerability.

Patient group (i)	$N_{i,j}$ [#ppl]	v_i [-]
High ($i = 1$)	60	8
Medium ($i = 2$)	300	2
Low ($i = 3$)	840	0,14

Shelter in place with additional measures
Table 5.18 shows the parameters specific to "shelter in place with additional measures" that are input to Equation 3.8. The flood strategy factor f_1 was defined in Section 3.7. Based on the judgement of a flood expert from HKV, the time when the flood is over was estimated to be three days for this flood strategy ($t_1 = 3$). Considerations for this value are that a large area is flooded in both flood scenarios. The flood depth in the vicinity of the hospital is more than one metre. Furthermore, three other hospitals are simultaneously flooded, which means that the attention and resources of rescue workers have to be divided. However, it is assumed that as part of the additional measures of this flood strategy, emergency plans are made. Therefore, help will arrive sooner compared to the other flood strategies.

Table 5.18: Parameters for the flood strategy "shelter in place with additional measures" ($j = 1$).

Parameter	Value
Flood strategy factor f_1 [-]	6,67
Time when the flood is over t_1 [d]	3

Table 5.19 contains the number of fatalities for "shelter in place with additional measures" at the EMC. As part of the additional measures, the patient group with low vulnerability is discharged from the hospital before the flood arrives. Therefore, these patients are not considered in the calculations. The total number of fatalities for this flood strategy is 18,8.

Table 5.19: Fatalities for the flood strategy "shelter in place with additional measures".

Patient group (i)	$N_{i,1}$ [#ppl]	$F_{i,1}$ [dths]
High ($i = 1$)	60	8,4
Medium ($i = 2$)	300	10,5
Low ($i = 3$)	0	0,00
	$F_1 =$	18,8

Shelter in place without additional measures
In Table 5.20 the flood strategy factor f_2 and time when the flood is over t_2 are stated. The flood strategy factor was previously defined in Section 3.7. The value for t_2 is estimated to be five days. Like the estimation for t_1, t_2 was estimated by a flood expert from HKV, and

considers the flood conditions corresponding to the flood scenarios. Because no additional measures have been taken, the flood strategy factor (f_2) is higher and help arrives later (t_2), compared to "shelter in place with additional measures".

Table 5.20: Parameters for the flood strategy "shelter in place without additional measures" ($j = 2$).

Parameter	Value
Flood strategy factor f_2 [-]	10
Time when the flood is over t_2 [d]	5

The number of fatalities for "shelter in place without additional measures" is 83,4 (see Table 5.21, which is approximately four times higher than "shelter in place with additional measures". The patient groups with high and medium vulnerability contribute most to the total number of fatalities, despite the fact that these patient groups contain less patients than the patient group with low vulnerability.

Table 5.21: Fatalities for the flood strategy "shelter in place without additional measures".

Patient group (i)	$N_{i,2}$ [#ppl]	$F_{i,2}$ [dths]
High ($i = 1$)	60	33,4
Medium ($i = 2$)	300	41,8
Low ($i = 3$)	840	8,2
	$F_2 =$	83,4

Accept
The flood strategy factor f_3 for "accept" is 15, as defined in Section 3.7. It is assumed that the conditions in the hospital during this flood strategy are worse than for the previous two flood strategies that were discussed. The time when the flood is over is estimated to be five days ($t_3 = 5$), because of the flood conditions and lack of additional rescue plans.

Table 5.22: Parameters for the flood strategy "accept" ($j = 3$).

Parameter	Value
Flood strategy factor f_3 [-]	15
Time when the flood is over t_3 [d]	5

In terms of fatalities, the flood strategy "accept" performs worse than the other two flood strategies, resulting in 125,2 fatalities (see Table 5.23). The number of fatalities is 50% higher than was calculated for "shelter in place without additional measures" and is more than six times higher than the fatalities for "shelter in place with additional measures".

Table 5.23: Fatalities for the flood strategy "accept".

Patient group (i)	$N_{i,3}$ [#ppl]	$F_{i,3}$ [dths]
High ($i = 1$)	60	50,2
Medium ($i = 2$)	300	62,7
Low ($i = 3$)	840	12,3
	$F_3 =$	125,2

Preventive evacuation
To calculate the number of fatalities for "preventive evacuation", Equation 3.9 is used. The input parameters are given in Table 5.24. The flood strategy factors were determined in Section 3.7 and represent the difference in mortality rate if preventive evacuation is successful (f_{suc}) or unsuccessful (f_{fail}). For the lower Meuse region, the average evacuation fraction (e) is 0,15 (Kolen, 2023). The number of evacuations relative to one flood (r) for this part of the Netherlands is 25 (Kolen, 2013). A fixed value of one day was chosen for the duration of preventive evacuation (t_4).

Table 5.24: Parameters for the flood strategy "preventive evacuation" ($j = 4$).

Parameter	Value
Flood strategy factor f_{suc} [-]	1,5
Flood strategy factor f_{fail} [-]	40
Evacuation fraction e [-]	0,15
Number of evacuations relative to one flood r [-]	25
Duration t_4 [d]	1

The EMC is evacuated 25 times relative to one flood. Hence, all patients in the EMC are evacuated 25 times. The total number of patients that is evacuated is equal to $N_{i,4} * r$ (see Table 5.25). Out of the 25 evacuations, 24 times there was no flood, so the preventive evacuation was successful. One out of 25 times, a flood occurs. Of all patients that are evacuated, 15% (e) can evacuate successfully. The other patients, 85% ($1 - e$), is unable to evacuate successfully. The flood strategy factor f_{suc} is applied to the successfully evacuated patients, whereas the much higher flood strategy factor f_{fail} is applied to the unsuccessfully evacuated patients. All 25 evacuations considered together, the flood strategy "preventive evacuation" results in a total of 195,3 fatalities (see Table 5.25), which is the highest number of fatalities out of the four flood strategies considered.

Table 5.25: Fatalities for the flood strategy "preventive evacuation".

Patient group (i)	$N_{i,4} * r$ [#ppl]	$F_{i,4}$ [dths]
High ($i = 1$)	1500	78,3
Medium ($i = 2$)	7500	97,8
Low ($i = 3$)	21.000	19,2
	$F_4 =$	195,3

5.4.2 Considering simultaneously threatened hospitals

Until now, only the EMC has been analysed. However, the EMC should not only be regarded on its own, because the storms that flood the EMC also threaten (or even flood) other hospitals in the coastal region of the Netherlands. An estimation of the number of fatalities is made per flood strategy, considering all hospitals affected by the "Parksluizen 1" and "Parksluizen 2" flood scenarios. During either of these two flood scenarios, 33 hospitals are simultaneously threatened (Kolen, 2023). For this research, it is assumed that only one breach can occur simultaneously in the primary flood defences. If the breach occurs at "Parksluizen", 4 out of the 33 threatened hospitals are simultaneously flooded, including the EMC.

If a hospital decides to implement "shelter in place with additional measures", "shelter in place without additional measures" or "accept", the mortality rate only increases when the hospital is flooded. Without a flood, the conditions inside the hospital remain at the "regular" level. Only the average daily mortality rate at Dutch hospitals (M_{avg}) applies, causing no additional fatalities. Only if a flood occurs, are flood strategy factors (f_j) applicable, increasing the mortality rate and resulting in additional fatalities. Hence, if all 33 threatened hospitals decide to implement any of these three flood strategies, additional fatalities only occur at the four hospitals that are flooded, assuming that only a breach at "Parksluizen" occurs. However, if a hospital decides to implement "preventive evacuation", fatalities occur for every instance of preventive evacuation. Therefore, if all 33 threatened hospitals decide to implement "preventive evacuation", fatalities occur at all 33 hospitals every time they are preventively evacuated.

It is assumed that the threatened hospitals, besides the EMC, are average-sized for the Netherlands, which corresponds to a capacity of 450 hospital beds (Van Hulst & Blank, 2017). Furthermore, because these hospitals are located in the same region as the EMC, the same parameters for patients groups (Table 5.17, except size of patient groups) and flood strategies (Tables 5.18, 5.20, 5.22 and 5.24) as for the EMC are assumed to apply to these hospitals. Table 5.26 contains the number of fatalities per flood strategy for the EMC and average-size Dutch hospital. If a breach occurs at "Parksluizen", 33 hospitals are threatened and 4 (including the EMC) are flooded. For "shelter in place with additional measures", "shelter in place without additional measures" or "accept", the EMC and three other hospitals are simultaneously flooded, resulting in fatalities. The other 29 hospitals remain unaffected. Hence, no fatalities occur at these hospitals. Adding up the number of fatalities for the EMC and the three other (average-sized) hospitals results in the total number of fatalities: 40, 177 and 266 for "shelter in place with additional measures", "shelter in place without additional measures" or "accept". For "preventive evacuation", all 33 threatened hospitals are evacuated 25 times. All 33 hospitals are evacuated 24 times without the occurrence of a flood. Therefore, evacuation is successful and the mortality rate is low. The one time that a flood occurs at "Parksluizen", 4 out of 33 hospitals are flooded (including the EMC and three other hospitals). Hence, a part of these four hospitals cannot evacuate successfully, resulting in a high mortality rate. The other 29 hospitals can evacuate successfully, resulting in a relatively low mortality rate. However, it should be noted that evacuating 29 hospitals successfully 25 times can still result in a large number of fatalities. The number of fatalities for the four hospitals that are evacuated successfully 24 times and are flooded once is 415. The number of fatalities for the 29 hospitals that evacuate successfully 25 times is 1134 fatalities. In total, the number of fatalities for "preventive evacuation" is 1549. The number of fatalities for "preventive evacuation" is much higher than for the other flood strategies.

Table 5.26: Fatalities at the EMC and other hospitals threatened by the "Parksluizen 1" and "Parksluizen 2" scenario.

Flood strategy	Fatalities EMC	Fatalities average-sized Dutch hospital	# affected average-sized Dutch hospitals	Total fatalities
Shelter in place with additional measures	18,8	7,1	3	40
Shelter in place without additional measures	83,4	31,3	3	177
Accept	125,2	46,9	3	266
Preventive evacuation				
25 evacuations, incl. 1 flood	195,3	73,2	3	415
25 evacuations, no flood	n/a	39,1	29	1134
Total				1549

In Table 5.26, the main contribution to the number of fatalities for "preventive evacuation" comes from the non-flooded hospitals, because this concerns the majority of hospitals. The number of average-sized Dutch hospitals simultaneously flooded by the Parksluizen scenarios is increased from 3 to 20, to see how the total number of fatalities of each flood strategy changes and compares to the other flood strategies. Table 5.27) shows that the number of fatalities per flood strategy increases, which is expected. "Preventive evacuation" still results in significantly more fatalities than the other flood strategies. This result is also expected, because on an individual scale, "preventive evacuation" also results in the most fatalities. This example shows that, given the flood conditions of the EMC, regardless of the number of simultaneously flooded hospitals, "shelter in place with additional measures" results in the least fatalities, followed by "shelter in place without additional measures", then "accept" and finally "preventive evacuation".

Table 5.27: Fatalities at the EMC and other hospitals threatened by the "Parksluizen 1" and "Parksluizen 2" scenario. The number of simultaneously flooded average-sized Dutch hospitals is set to 20

Flood strategy	Fatalities EMC	Fatalities average-sized Dutch hospital	# affected average-sized Dutch hospitals	Total fatalities
Shelter in place with additional measures	18,8	7,1	20	160
Shelter in place without additional measures	83,4	31,3	20	709
Accept	125,2	46,9	20	1064
Preventive evacuation				
25 evacuations, incl. 1 flood	195,3	73,2	20	1660
25 evacuations, no flood	n/a	39,1	12	469
Total				2129

5.5 Sensitivity analysis

Equation 3.8 has been used to calculate the number of fatalities for "shelter in place with additional measures", "shelter in place without additional measures" and "accept". For "preventive evacuation", Equation 3.9 has been used. To gain insight into which parameters of these equations have the largest impact on the calculated number of fatalities, a sensitivity analysis is conducted. The total number of fatalities and the individual contributions of the patient groups with high, medium and low vulnerability are shown. For the sensitivity analysis, a fictitious hospital is used. The hospital has 1000 hospital beds. Table 5.28 contains the values specific to the patient groups. These values remain constant throughout the sensitivity analysis. In Tables 5.29 and 5.30, the values for the parameters of Equations 3.8 and 3.9 are listed respectively. The listed values are used, unless the parameter is varied for the sensitivity analysis. For Equation 3.8, the parameters t_j, t_m and f_j are varied individually. For Equation 3.9, the parameters f_{suc}, f_{fail}, e, and r are varied individually. First, the parameters are considered individually and are compared with each other once each parameter has been reviewed.

Table 5.28: Parameters for the patient group with high, medium and low vulnerability.

Patient group (i)	$N_{i,j}$ [#ppl]	v_i [-]
High ($i = 1$)	50	8
Medium ($i = 2$)	250	2
Low ($i = 3$)	700	0,14

Table 5.29: Parameters for the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept" (Equation 3.8).

Parameter	Value
Flood strategy factor f_j [-]	10
Time when maximum mortality rate is reached t_m [d]	4
Time when the flood ends t_j [d]	5

Table 5.30: Parameters for the flood strategy "preventive evacuation" (Equation 3.9).

Parameter	Value
Flood strategy factor f_{suc} [-]	1,5
Flood strategy factor f_{fail} [-]	40
Evacuation fraction e [-]	0,5
Number of evacuations relative to one flood r [-]	10
Duration of evacuation t_4 [d]	1

Time when the flood ends (t_j)
Figure 5.15 shows how the number of fatalities varies if the time when the flood ends varies from 0 (no flood) to 20 days. As the t_j increases, the number of fatalities increases as well. This trend is expected: longer exposure of patients to a flood results in more fatalities. For $t_j = 0$, the number of fatalities is 0, because without a flood, no fatalities are expected from this model. From $t_j = 0$ until $t_j = t_m$ ($t_m = 4$ in this instance) the curves are non-linear, which is explained by the mortality rate that increases until it reaches its maximum value at t_m. For $t_j > t_m$, the lines are linear, because the mortality rate is constant. When t_j reaches a value of approximately 7 days, all patients from the highly vulnerable patient group have died. Hence, the red line remains constant from that moment onward. As a result, the black line for the total number of fatalities becomes less steep from then onward. An increase of t_j results in a significant increase on the number of fatalities. The sensitivity is highest for $t_j > t_m$, until all patients from the highly vulnerable patient groups have died.

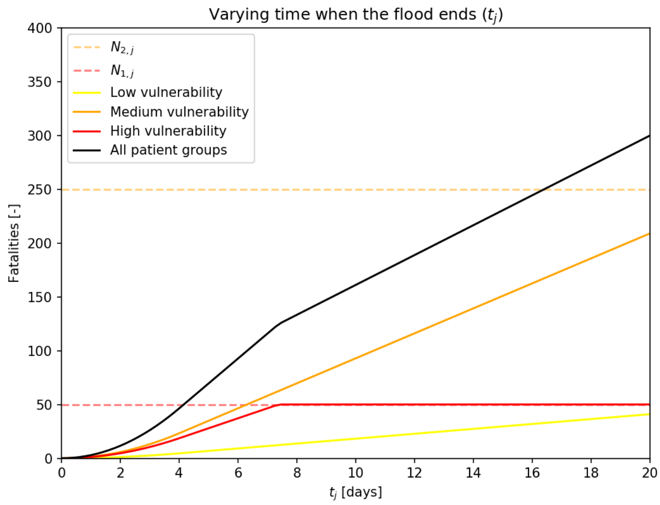


Figure 5.15: Sensitivity of the time when the flood ends (t_j).

Time when the maximum mortality rate is reached (t_m)
Figure 5.16 shows how the number of fatalities varies if the time when the maximum mortality rate is reached varies from 0 (immediate maximum mortality rate) to 20 days. A decreasing trend is found for an increase of t_m. This trend is expected, because for smaller values of t_m patients are sooner exposed to the maximum mortality rate than if t_m were large, resulting in more fatalities. The lines are linear for $t_m \leq t_j$ ($t_j = 5$ for this instance), because the equivalent duration ($\int_{t=0}^{t_j} m_j(t)dt$, also see Figure 3.15) linearly depends on t_m. Once $t_m > t_j$, the dependence of the equivalent duration on t_m is defined by $1/t_m$. The number of fatalities is most sensitive for small values of t_m. As t_m increases, the sensitivity reduces.

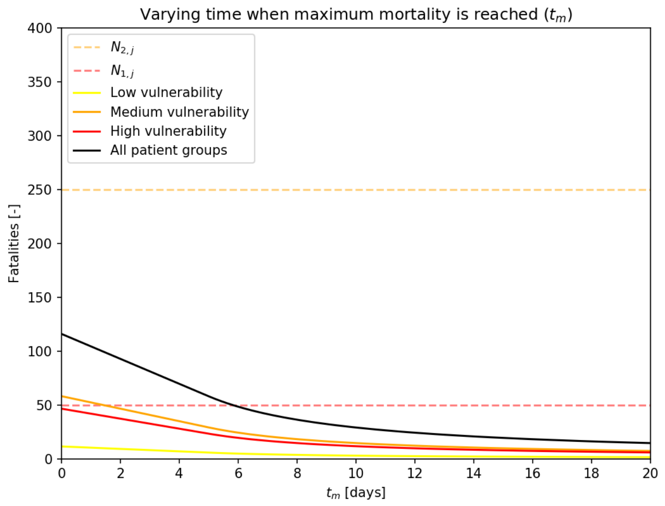


Figure 5.16: Sensitivity of the time when maximum mortality is reached (t_m).

Flood strategy factor (f_j)

Figure 5.17 shows how the number of fatalities varies if the flood strategy factor varies from 0 (no mortality rate) to 50. A larger flood strategy factor results in a higher mortality rate. As a result, the number of fatalities increases for larger values of f_j. If $f_j = 0$, the mortality rate is 0, resulting in 0 deaths. Equation 3.8 linearly depends on f_j, explaining why the plotted lines are linear. Once all patients from the highly vulnerable patient group have died, at approximately $f_j = 18$, the slope of the black line (total number of fatalities) decreases. The number of fatalities is sensitive to the parameter f_j. The sensitivity is highest for low values of f_j. In conclusion, comparing the time when the flood ends (t_j), the time when the maximum mortality rate is reached (t_m) and the flood strategy factor (f_j), it is found that Equation 3.8 is most sensitive to t_j, followed by f_j and finally t_m.

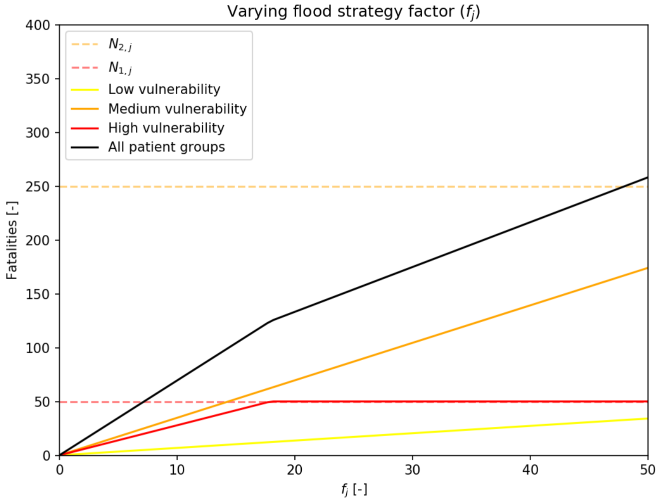


Figure 5.17: Sensitivity of the flood strategy factor (f_j).

Flood strategy factor for successful preventive evacuation (f_{suc})

Figure 5.18 shows how the number of fatalities changes if f_{suc} is varied. For increasing values of f_{suc}, the mortality rate for successful preventive evacuation increases, resulting in an increased number of fatalities. Equation 3.9 linearly depends on f_{suc}, explaining why the plotted lines are linear. The parameter f_{suc} is applied to all patients that are able to successfully evacuate preventively. Out of r preventive evacuation, $(r-1)$ evacuations are successful because no flood occurs. In addition, the one time that a flood occurs, a part of the patients can successfully evacuate preventively (defined by the evacuation fraction). For every preventive evacuation, all patients are evacuated. Therefore, many patients are affected by f_{suc}. Equation 3.9 is sensitive to f_{suc}.

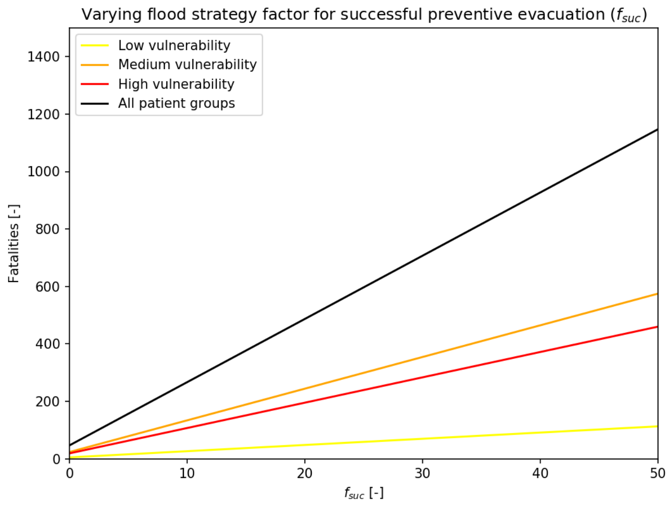


Figure 5.18: Sensitivity of the flood strategy factor for successful preventive evacuation (f_{suc}).

Flood strategy factor for unsuccessful preventive evacuation (f_{fail})

Figures 5.19 and 5.20 both show how the number of fatalities changes if f_{fail} is varied. Figure 5.20 has the same scale for the y-axis as Figure 5.18 to facilitate comparison of these parameters. Figure 5.19 is zoomed in to enable analysis of the effects of f_{fail}. Equation 3.9 linearly depends on f_{fail}, explaining why the plotted lines are linear. The effect of f_{fail} is limited, because this parameter is only applied to the part of the patients that is unable to evacuate successfully, defined by $(1 - e)$. This group is patients is relatively small. Therefore, Equation 3.9 is not very sensitive to f_{fail}.

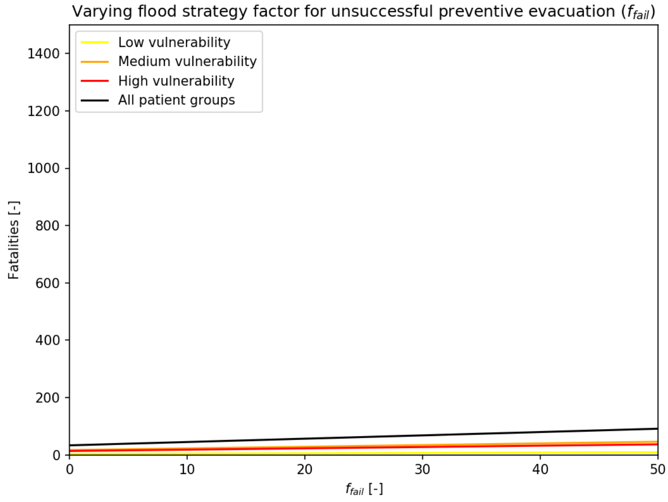


Figure 5.19: Sensitivity of the flood strategy factor for unsuccessful preventive evacuation (f_{fail}) with the same scale for the y-axis as f_{suc}.

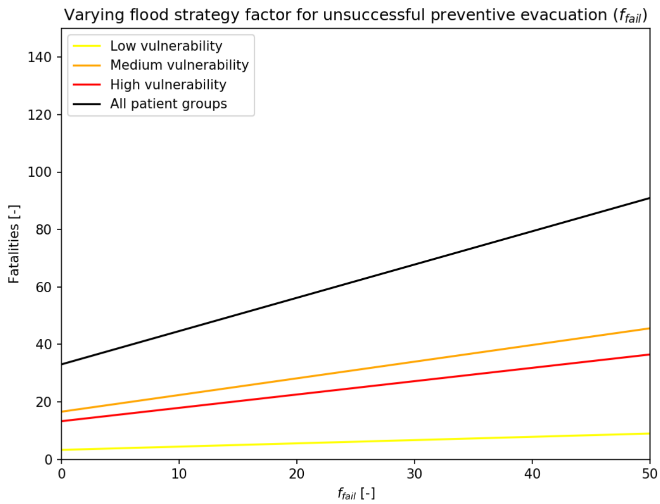


Figure 5.20: Sensitivity of the flood strategy factor for unsuccessful preventive evacuation (f_{fail}) with zoomed in y-axis.

Evacuation fraction (*e*)
Figure 5.21 shows a decreasing trend if e increases. This trend is as expected, because a larger evacuation fraction implies that more patients are able to evacuate successfully. The corresponding flood strategy factor f_{suc} is lower than f_{fail}, that is applied if evacuation is

unsuccessful. Hence, the number of fatalities decreases for larger values of e. The number of fatalities does not reach 0 for $e = 1$, because even successful preventive evacuation causes (a limited amount of) fatalities. Equation 3.9 linearly depends on e. Therefore, the lines in Figure 5.21 are also linear. The sensitivity of Equation 3.9 to e is limited.

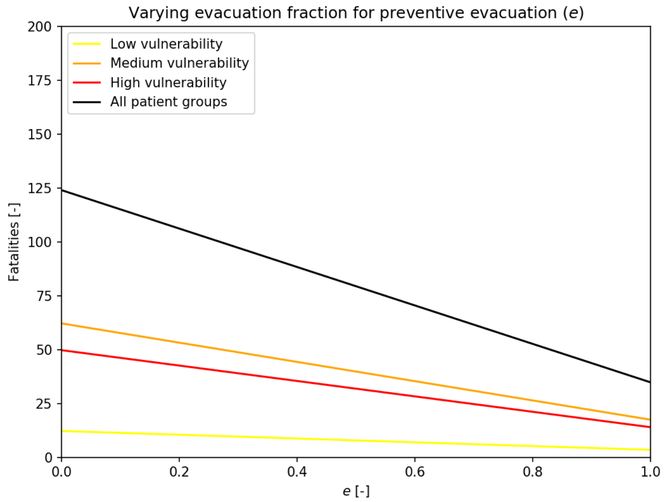


Figure 5.21: Sensitivity of the evacuation fraction (e).

Number of preventive evacuations relative to one flood (r)

Figure 5.22 depicts how the number of fatalities increases if r is increased. As previously mentioned, out of r preventive evacuations, a flood occurs only once. In other words, for every additional preventive evacuation above $r = 1$ no flood occurs, meaning that evacuation is successful. Successful preventive evacuation has a limited contribution if f_{suc} is small, like the value $f_{suc} = 1,5$ that was assumed for this instance. If f_{suc} is larger (for instance $f_{suc} = 15$, see Figure 5.23), the Equation 3.9 becomes more sensitive to r.

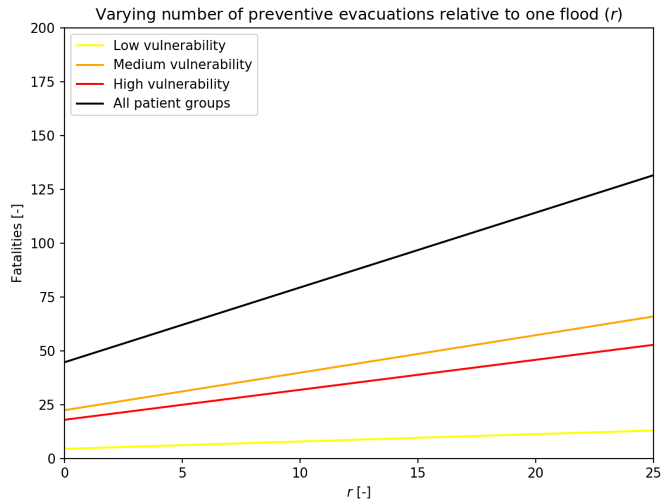


Figure 5.22: Sensitivity of the number of preventive evacuations relative to one flood (r) for $f_{suc} = 1,5$.

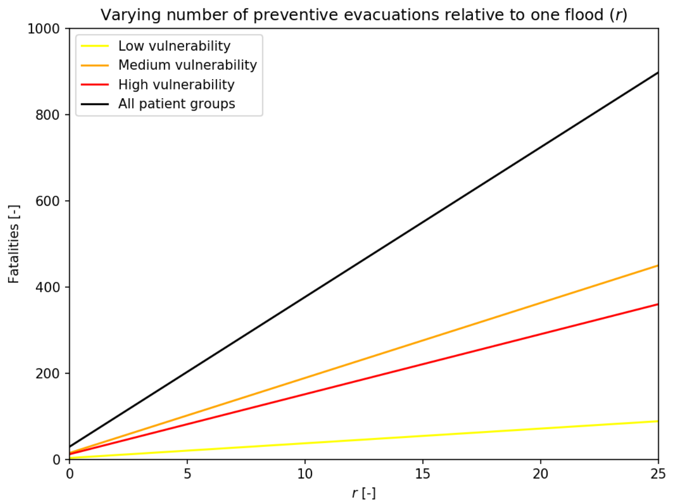


Figure 5.23: Sensitivity of the number of preventive evacuations relative to one flood (r) for $f_{suc} = 15$.

In conclusion, the sensitivity of Equation 3.9 to the flood strategy factor for successful (f_{suc}) and (f_{fail}) unsuccessful preventive evacuation, the evacuation fraction (e), and the number of evacuations relative to one flood (r) was compared. The parameter f_{suc} is found to be the most sensitive parameter. In addition, f_{suc} also influences the sensitivity of Equation 3.9 to r. The parameter r is very sensitive for high values of f_{suc}, while the opposite is true for small values of f_{suc}. The parameter f_{fail} is significantly less sensitive than f_{suc}, because this parameter is only applied to a relatively small part of patients. However, in calculations it was found that the contribution of f_{fail} to the number of fatalities is larger than the contribution of f_{suc}, because a higher value is chosen for f_{fail} than for f_{suc}. The parameter e determines the influence of f_{suc} and f_{fail} on the number of fatalities. For this sensitivity analysis, $e = 0,5$ was used to balance the influence of f_{suc} and f_{fail}. The sensitivity of Equation 3.9 to e is limited.

5.6 Costs

The types of costs associated with physical flood damage to the hospital and the implementation of flood strategies are collected per flood strategy via the phase 2 interviews. Based on the identified types of costs, a qualitative estimation of the costs is made in terms of "low", "medium" and "high".

Shelter in place with additional measures
First, damage to the hospital has to be accounted for. Despite taking additional measures, damage cannot be ruled out. Furthermore, investing in additional measures costs money. Especially investments in spatial adaptation measures for the hospital and its surroundings are associated with very high investment costs. Investing in additional measures also increases the upkeep costs, which may consist of maintenance and practise exercises. Therefore, additional measures increase the upfront and running costs. Discharging patients in anticipation of the flood saves money. Overall, this flood strategy is expected to be most expensive. Investments in spatial adaptation measures contribute the most to the costs. The costs for this flood strategy are labelled "high".

Shelter in place without additional measures
Damage to the hospital should be considered. Compared to "shelter in place with additional measures", the damage will be more extensive, thus these costs will be higher. However, the costs due to damages are not expected to be higher than the investment costs required for spatial adaptation measures for "shelter in place with additional measures". Moving equipment to elevated locations costs money, because more and specialised personnel is required to move the equipment. Overall, the costs for this flood strategy are labelled "medium".

Accept
There are no costs related to the implementation of this flood strategy. The main type of cost to be considered is the damage to the hospital. This type of costs is expected to be extensive, but the overall costs are expected to be lowest of the four flood strategies. The costs for this flood strategy are labelled "low".

Preventive evacuation
A specific type of costs for this flood strategy is transport costs. Patients also have to be taken up by another hospital. However, the associated costs are expected to be similar to the cost of care at the original hospital. Evacuation procedures have to be practised repeatedly, which adds to the running costs. It is assumed that no measures are taken at the hospital to mitigate the damages to the hospital. As a result, the associated costs will be extensive. The costs for this flood strategy are labelled "medium".

5.7 Comparing fatalities and costs

Figures 5.24 and 5.25 provide an overview of the costs (on the x-axis) and fatalities (on the y-axis) per flood strategy for the RdGG and EMC respectively. Comparing these figures, it becomes apparent that the number of fatalities for the EMC is much higher than for the RdGG for every flood strategy. For the RdGG, more expensive flood strategies result in less fatalities. For the EMC, this is only true if the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept" are regarded. "Preventive evacuation" is more costly than "accept", but results in more fatalities.

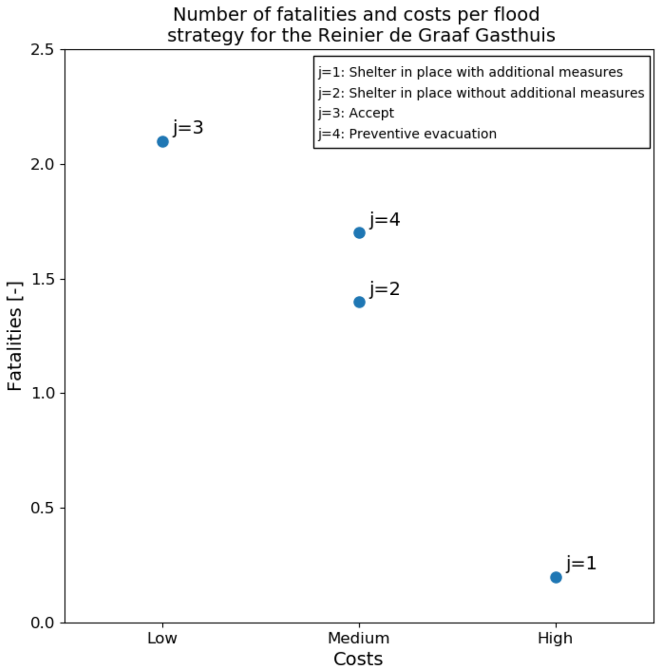


Figure 5.24: Number of fatalities at the RdGG caused by the flood scenario "Precipitation 1000", "Precipitation 100", "Precipitation 10" or "Regional 100" and costs per flood strategy.

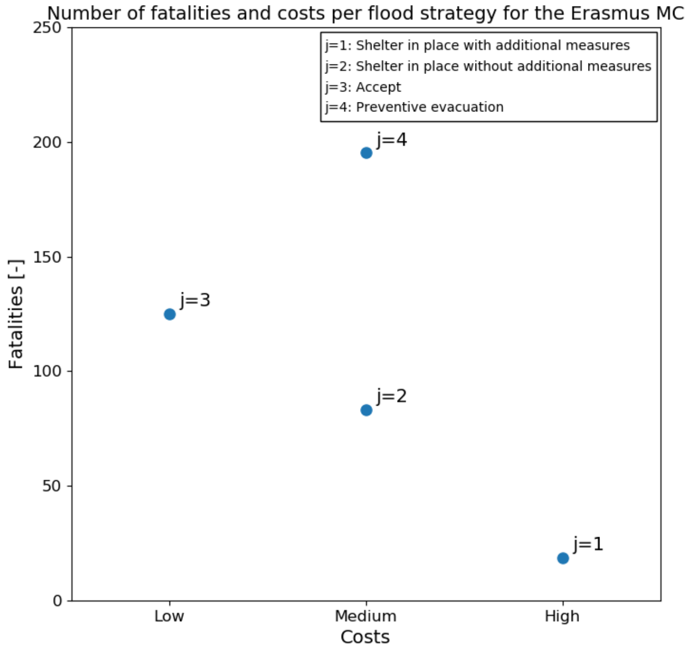


Figure 5.25: Number of fatalities at the EMC caused by the flood scenario "Parksluizen 1" or "Parksluizen 2" and costs per flood strategy.

5.8 Evaluation

The phase 2 interviews were used to evaluate the results and underlying assumptions of the assessment of hospitals' flood preparedness.

Patient groups: The participants agreed on the division of patients into groups with varying vulnerability. The percentages and vulnerability factors used were approved. Also the subsequent number of fatalities, given a certain flood strategy, was deemed plausible. It was recommended to use hospital departments rather than percentages when that information is available.

Series system for continuity of healthcare: The participants indicated that a hospital is unable to function properly if any of the proposed flood preparedness indicators fail:

"As a hospital you are nothing without all the departments. (...) Just like a body, so to speak: if the heart does not beat, the rest does not work either." [participant 7]

Especially the utilities were deemed important. Failure of the utilities is expected to initiate many cascade effects. Nevertheless, the series system for continuity of healthcare does not represent the reality. If facilities fail, the quality of healthcare decreases, but hospital employees are said to become resourceful under dire circumstances. Therefore, assuming immediate failure of the continuity of healthcare is too drastic. The participants were could not provide alternatives for the development the mortality rate over time or an indication of a maximum mortality rate.

Quantitatively supporting decision-making: The participants stated that quantifying flood impact could support the decision-making of flood strategies. To create credibility, presenting the underlying assumptions are just as important as the outcome. The quantitative outcomes could possibly stimulate investments in flood coping measures. An interview participant from the phase 2 interviews stated that patient safety is always prioritised in flood strategy decision-making. This statement was also confirmed by several interviewees from the phase 1 interviews. Hence, the interviewees consider the number of fatalities to be more important than the costs associated with flood strategies.

"Patient safety is the most important criterion for this decision [between flood strategies]." [participant 7]

"I think that the focus is on people during every consideration. They are always the most important, above money, above reputation, and so forth" [participant 4]

6. Stakeholder engagement

First, stakeholders are identified that are relevant for the preparation or execution of flood strategies (Section 6.1). The identified stakeholders are then described in detail in Section 6.2. From the identified stakeholders, a selection is made per flood strategy on who *could* be involved in the implementation (see Section 6.3). Next, the stakeholders are categorised per flood strategy (Section 6.4). Categorisation results in recommended actions regarding the involvement of stakeholders per flood strategy. Next, the current and desired stakeholder engagement for flood strategy implementation is discussed in Section 6.5. Subsequently, a selection is made of stakeholders that *should* be engaged per flood strategy (Section 6.6). Finally, the phase 2 interviews are used to obtain views from experts with lived experience on how these stakeholders can be engaged (Section 6.7).

6.1 Identification

The identification of stakeholders is supported by the phase 1 interviews and hospital tours. The Executive Board of a hospital is appointed as principal stakeholder. Hospitals are the focus of this research and the Executive Board is the controlling body. Only stakeholders who engage in direct interaction with the hospital's Executive Board are listed. The other stakeholders are disregarded. The Executive Board is also included in the stakeholder analysis. The principal stakeholder and other identified stakeholders are depicted in Figure 6.1.

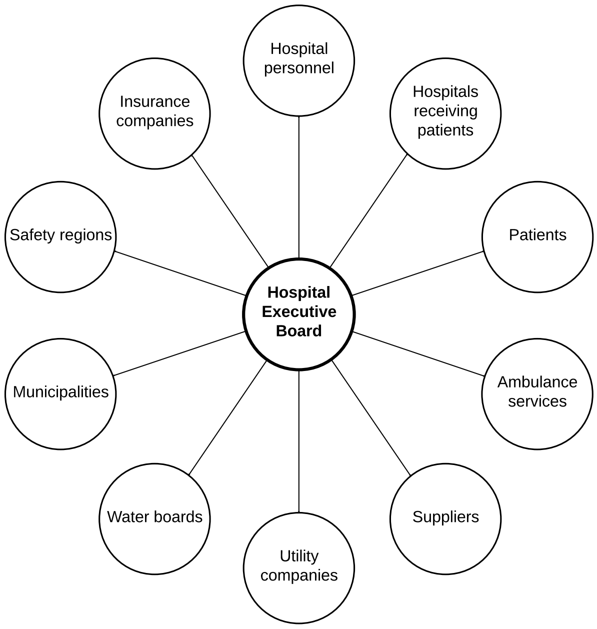


Figure 6.1: Principal stakeholder and stakeholders who engage in direct interaction with the principal stakeholder.

6.2 Assessment

After identification, the stakeholders are assessed to obtain a clear view of their role, influence, resources, perceived problems and the actions that are required from them to improve flood preparedness of hospitals.

Hospital Executive Board
The Executive Board of a hospital makes decisions on hospital level. During crises, they take part in the crisis management team. Their priorities are the safety of the hospital's personnel and patients. Every hospital has limited funds, leading to dilemmas on how these should be spent. The Executive Board is more likely to use their funds to solve "daily problems", rather than problems with a return period of decades years or more (Kolen et al., 2017). However, to improve flood preparedness of hospitals, acknowledgement of flood risk and impact is a must, while investments may be required.

Hospital personnel
The hospital personnel is responsible for patient care. Their priorities are the patients' and their own safety. They play a pivotal role in healthcare. If organised, through unions for instance, personnel can exert pressure on the Executive Board. Their main resources is medical knowledge. There is a shortage of personnel in the Dutch healthcare sector, which is expected to increase during the coming years. This shortage results in a high workload.

To improve flood preparedness of hospitals, the hospital personnel should (be enabled to) continue providing healthcare during floods.

Hospitals receiving patients
In case the decision is made to evacuate a threatened hospital, other hospitals play a key role in the continuity of healthcare by taking up patients from that hospital. Their most important resources are their medical knowledge and patient capacity. Potential hurdles may be the accessibility of these hospitals just before or during a flood, their capacity or that the receiving hospital is under threat of being flooded too. To improve the flood preparedness, hospitals should coordinate the distribution of patients and make agreements in advance.

Patients
Patients require medical care. Patient well-being is one of the top priorities of hospitals. The main problem from the view of the patients is their vulnerability. Floods may have a disastrous impact on this group. From the point of view of flood preparedness, it would be best for the independent patients to leave the hospital when a flood is imminent. This allows hospital personnel to focus on healthcare-dependent patients.

Ambulance services
Ambulance services provide acute care and transport for patients. They enable flood strategies that rely on transportation of patients. Their main resources are medical knowledge and ambulance vehicles. To improve flood preparedness, an abundance of ambulances is required to enable quick transport of vulnerable patients if necessary. However, ambulance services face staff shortages and a limited number of ambulances. In addition, hospitals may be inaccessible just before and during a flood.

Suppliers
"Suppliers" is an umbrella term for all types of suppliers that deliver goods to hospitals. The supplies that are delivered are essential for the continuity of healthcare. Hospitals have stocks, but for some items, such as food, these are limited. A shortage of stocks makes hospitals vulnerable to floods and is a determining factor for choosing flood strategies. To improve flood preparedness of hospitals, stocks should be increased so that hospitals can continue operations without deliveries for a few days. Alternatively, the hospitals should remain accessible for deliveries. However, on the supplier side, additional problems may occur if the distribution centre is flooded or when there is no personnel available during floods.

Utility companies
Utility companies provide essential services to hospitals, like drinking water, electricity and sewerage. If these services become unavailable due to a flood, they have to be taken over by local systems at the hospital. Such systems can usually last for a limited time. Therefore, to improve flood preparedness, continuity or quick recovery of the utility services is important. The main problem perceived by utility companies during floods is large-scale damage to infrastructure. This infrastructure is expensive and time-consuming to replace. Besides hospitals, there are many more users (who may also fulfil a vital role) that are simultaneously cut-off from utilities. Failure of utilities may cause cascade effects. Restoring utilities is a large task for utility companies.

Water boards
There are 21 water boards in the Netherlands. Water boards look after the water quality and safety. They are tasked with maintaining dykes in their region and have the responsibility to prevent and reduce floods from regional water systems. Therefore, any flood is considered undesirable. Water boards can also take on an informative role, warning other institutions

about expected flood levels. In addition, water board levy their own taxes, making up a large portion of their financial resources. To contribute to hospital preparedness, water boards could share knowledge on floodproof spatial adaptation. Furthermore, they could inform hospitals of flood characteristics in emergency situations to facilitate decision-making.

Municipalities
Municipalities are responsible for spatial planning. Spatial planning plays an important role in the prevention of floods and in reducing the consequences. In this context, the municipality can adopt rules to force spatial adaptation. Municipalities also inform and warn the population if there is a flood threat. To perform their duties, municipalities need money. This money mainly comes from government funding and taxes. Municipalities will see the flooding of hospitals as undesirable, given their responsibilities regarding water safety, general safety and public health. To improve flood preparedness of hospitals, municipalities should make use of their regulatory power in relation to spatial planning to force spatial adaptation at hospitals.

Safety regions
There are 25 safety regions in the Netherlands. Safety regions make agreements with hospitals about flood disaster management in advance. During a flood disaster, the safety regions have a coordinating role. Mayors of all municipalities within the region are part of the board of a safety region. Usually, the mayor of the largest municipality is the chair of the board. Safety regions are for the most part financed by the municipalities. A small part is financed by the government. The main problem perceived by safety regions is the disruption of healthcare continuity in the region during a flood. The interviewed flood expert from RWS expressed their concern that no crisis organisation seems to be prepared for flood events with a return period of more than 10 years. Flood preparedness of hospitals can be improved by also preparing for such events.

Insurance companies
Floods often result in large economical damages. In some cases, flood insurance for buildings is possible in the Netherlands. However, buildings located in outer dyke areas are not eligible for flood insurance. Damage resulting from the failure of a primary river or dyke is also excluded. This is mainly due to the fact that insurance companies do not have the funds to cover the damage. The government may partially compensate damages in some cases. This governmental compensation is covered by an act that provides compensation in case of damages due to disasters, in Dutch: Wet tegemoetkoming schade bij rampen (WTS). Floods from the sea are officially excluded from this act. However, the government has indicated that it would also grant compensation for such disasters. Only damage resulting from failure of a secondary dyke or heavy precipitation may be covered by insurance companies. Regarding floods, the focus lies on collective care by the government to prevent floods and reduce their consequences. The principle of collective care is translated into flood protection safety standards. Only in a limited number of cases collective care belongs to insurance companies. Individual care of the building always partially remains with the owner. Building owners are not sufficiently aware of their own responsibility for flood damage and are not incentivised to prepare their buildings for floods (Dekker et al., 2020). In other words: insurance companies appear not to impose requirements with regard to the flood preparedness of buildings, or more specifically, hospitals. Therefore, this stakeholder is disregarded.

6.3 Relevant stakeholders per flood strategy

As discussed in Section 2.3, four flood strategies are highlighted in this research: "shelter in place with additional measures", "shelter in place without additional measures", "accept" and "preventive evacuation". As the implementation of these four flood strategies involves different actions, the selection of stakeholders, whose engagement is required for implementation, varies. A selection is made of which stakeholders *could* be engaged for the implementation of each flood strategy (Table 6.1). The selection of stakeholders is based on the literature study in Section 2.2, where a number of stakeholders and their responsibilities were discussed. Furthermore, during the phase 1 interviews, it was asked which stakeholders are currently involved in the implementation of flood measures (Appendix B). Lastly, characteristics of the previously identified stakeholders (Section 6.2) further add information about which stakeholders could be engaged per flood strategy. Stakeholders for whom it is reasonable to assume that they have no role in the implementation of a specific flood strategy are excluded. For "shelter in place with additional measures" and "shelter in place without additional measures", hospitals receiving patients and ambulance services are not engaged. These stakeholders come into play when patients need to be transported and re-accommodated, which is irrelevant when sheltering in place. For "accept", it is assumed that no actions are taken to prepare for the flood. Therefore, it is assumed that no stakeholders are engaged for the implementation of this flood strategy. Although it is unrealistic to expect that no stakeholders are engaged at all, the flood strategy "accept" serves as a benchmark to compare other flood strategies. For "preventive evacuation", suppliers and utility companies are deemed superfluous when leaving the hospital. As discussed in Section 3.5, insurance companies are not engaged in any flood strategy.

Table 6.1: Overview of which stakeholders could be engaged per flood strategy.

Stakeholder	Shelter in place with additional measures	Shelter in place without additional measures	Accept	Preventive evacuation
Hospital Executive Board	•	•	○	•
Hospital personnel	•	•	○	•
Hospitals receiving patients	○	○	○	•
Patients	•	•	○	•
Ambulance services	○	○	○	•
Suppliers	•	•	○	○
Utility companies	•	•	○	○
Water boards	•	•	○	•
Municipalities	•	•	○	•
Safety regions	•	•	○	•
Insurance companies	○	○	○	○

Engaged: •
Not engaged: ○

6.4 Stakeholder categorisation

The stakeholders are categorised to enable making recommendations on their engagement in improving flood preparedness of hospitals. The categorisation is done through the PIA matrix by Murray-Webster and Simon (2006). For each stakeholder selected in the previous section, their current power, interest and attitude regarding the implementation of each flood strategy is assessed. Power relates to the ability to influence an organisation. This may be through credibility, resources or position. Stakeholders are labelled influential (+) or insignificant (-). Interest describes whether a stakeholder will take on an active (+) or passive (-) role in a project. Attitude is used to describe the view of the stakeholder. This is subdivided into backers (supporters) (+) and blockers (those who oppose the project) (-) (Murray-Webster & Simon, 2006). These three characteristics lead to eight possible categories, which are depicted in Figure 6.2 and described in Table 6.2. The stakeholders are categorised per flood strategy in Tables 6.3 to 6.5.

Table 6.2: The eight stakeholder categories from Murray-Webster and Simon (2006) and their characteristics.

Category	Power (+/-)	Interest (+/-)	Attitude (+/-)	Recommended actions
Saviour	+	+	+	Keep satisfied.
Friend	-	+	+	Use as confidant or sounding board.
Saboteur	+	+	-	Engage in order to disengage.
Irritant	-	+	-	Needs to be engaged early on to prevent hindrance of the process.
Sleeping giant	+	-	+	Needs to be actively engaged to support to process.
Acquaintance	-	-	+	Keep informed.
Time bomb	+	-	-	Needs to be understood to prevent negative involvement.
Trip wire	-	-	-	Needs to be understood to prevent making a mistake.

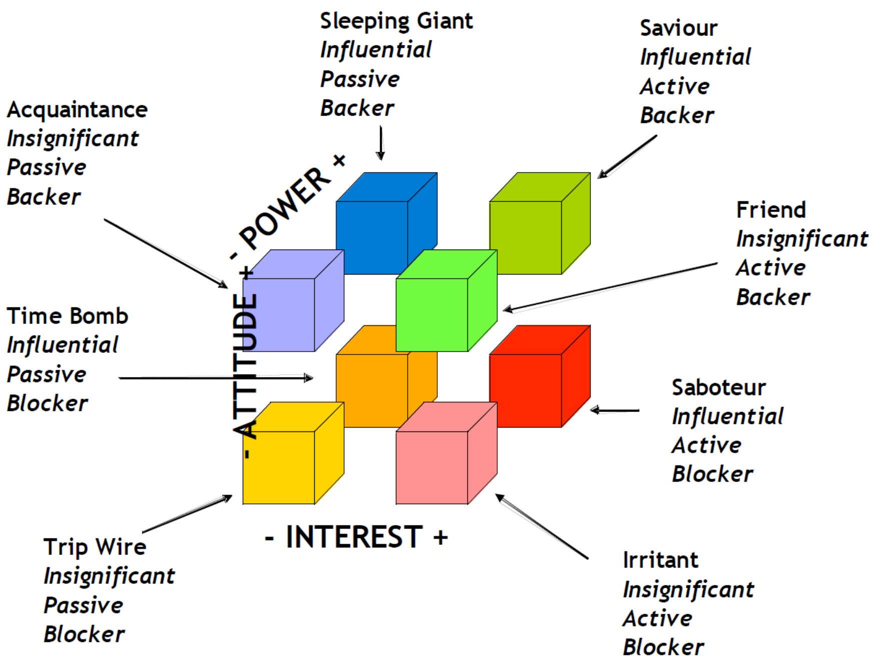


Figure 6.2: PIA matrix by Murray-Webster and Simon (2006), used to categorise stakeholders.

Shelter in place with additional measures

Regarding power, stakeholders with significant resources or regulatory powers receive a "+". Patients are assumed to have relatively little power, especially on an individual level. Only municipalities and safety regions are assumed to take on an active role in the implementation because of their responsibilities and interests. Water boards share these responsibilities and interests, but have so far focused on preventing floods on a larger scale than hospitals. Hospitals often overlook flood risk. All stakeholders are assumed to support this flood strategy to reduce the number of fatalities.

Table 6.3: Categorisation of stakeholders based on their power, interest and attitude toward the flood strategy "shelter in place with additional measures".

Stakeholder	Power (+/-)	Interest (+/-)	Attitude (+/-)	Category
Hospital Executive Board	+	-	+	Sleeping giant
Hospital personnel	+	-	+	Sleeping giant
Patients	-	-	+	Acquaintance
Suppliers	+	-	+	Sleeping giant
Utility companies	+	-	+	Sleeping giant
Water boards	+	-	+	Sleeping giant
Municipalities	+	+	+	Saviour
Safety regions	+	+	+	Saviour

Shelter in place without additional measures

Regarding power, stakeholders with regulatory powers receive a "+". Compared to "shelter in place with additional measures", less preparations are made. Therefore, stakeholders like suppliers, utility companies and water boards have less power. Only municipalities and safety regions are assumed to take on an active role in the implementation because of their responsibilities and interests. All stakeholders are assumed to support this flood strategy, since it leads to reduction of the number of fatalities.

Table 6.4: Categorisation of stakeholders based on their power, interest and attitude toward the flood strategy "shelter in place without additional measures".

Stakeholder	Power (+/-)	Interest (+/-)	Attitude (+/-)	Category
Hospital Executive Board	+	-	+	Sleeping giant
Hospital personnel	+	-	+	Sleeping giant
Patients	-	-	+	Acquaintance
Suppliers	-	-	+	Acquaintance
Utility companies	-	-	+	Acquaintance
Water boards	-	-	+	Acquaintance
Municipalities	+	+	+	Saviour
Safety regions	+	+	+	Saviour

Accept
No stakeholders have to be engaged to implement this flood measure. Therefore, no stakeholder categorisation can be carried out.

Preventive evacuation
Stakeholders with critical resources or who are involved in decision-making are classified as powerful. Hospitals often overlook flood risk. Only municipalities and safety regions are assumed to take on an active role in organising preventive evacuation. For many stakeholders, evacuation has become the standard response if faced with a flood threat. The attitude towards this strategy is positive for all stakeholders considered.

Table 6.5: Categorisation of stakeholders based on their power, interest and attitude toward the flood strategy ”preventive evacuation”.

Stakeholder	Power (+/-)	Interest (+/-)	Attitude (+/-)	Category
Hospital Executive Board	+	-	+	Sleeping giant
Hospital personnel	+	-	+	Sleeping giant
Hospitals receiving patients	+	-	+	Sleeping giant
Patients	-	-	+	Acquaintance
Ambulance services	+	-	+	Sleeping giant
Water boards	+	-	+	Sleeping giant
Municipalities	+	+	+	Saviour
Safety regions	+	+	+	Saviour

6.5 Current and desired stakeholder engagement

Based on the stakeholder assessment and categorisation, an overview can be created of the current and desired level of stakeholder engagement for implementation of flood strategies at hospitals. A bullseye diagram is used for visual representation. Stakeholders that are (to be) closely engaged are located at the centre of the diagram. Lower degrees of engagement are located further from the centre. In addition, a distinction is made between influencers, decision makers, contributors and users. For the flood strategy ”accept” no bullseye diagram is given, because this flood measure does not require any stakeholder engagement. The bullseye diagrams for the remaining three flood strategies are shown in Figures 6.3 to 6.5.

Regarding the stakeholders’ current engagement, the principal stakeholder (the Executive Board of the hospital) is at the core of the diagram. Hospitals receiving patients are currently at a co-think level, since a network to distribute patients over hospitals already exists. During the COVID-19 pandemic, the so-called Landelijk Coördinatie Centrum Patiëntenspreiding (LCPS) was established. As per 1 July 2023 it has been integrated with the Landelijk Netwerk Acute Zorgketens (LNAZ), a national network organisation for acute healthcare. Patients are currently not involved in implementing flood strategies and are therefore at the co-know level. The other stakeholders are currently located at the co-operate level. This is based on their passiveness (low interest) or the lack of current communication between hospitals and these stakeholders on implementing flood strategies.

The desired stakeholder engagement is based on the stakeholder categorisation. It is desirable to engage the sleeping giants more closely, except for the hospitals receiving patients. This stakeholder is already at the desired engagement level. The saviours also have been more closely engaged, because of the combination of high power and positive attitude. Acquaintances are not further engaged.

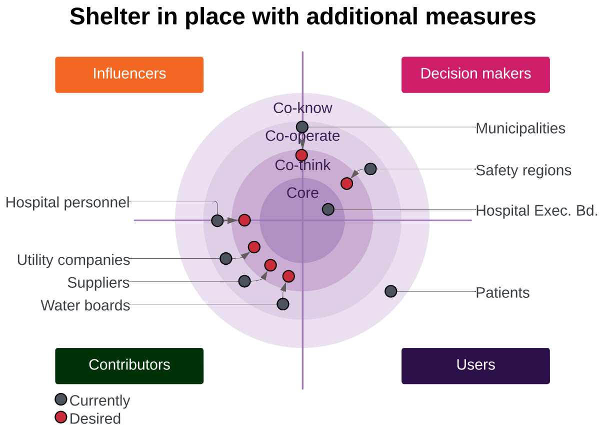


Figure 6.3: Bullseye diagram of the current and desired stakeholder engagement for implementation of "shelter in place with additional measures" at hospitals.

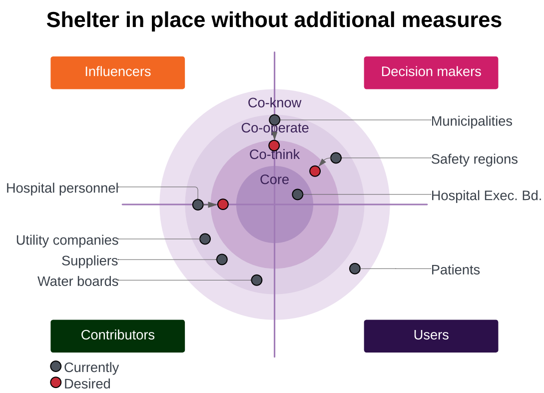


Figure 6.4: Bullseye diagram of the current and desired stakeholder engagement for implementation of "shelter in place without additional measures" at hospitals.

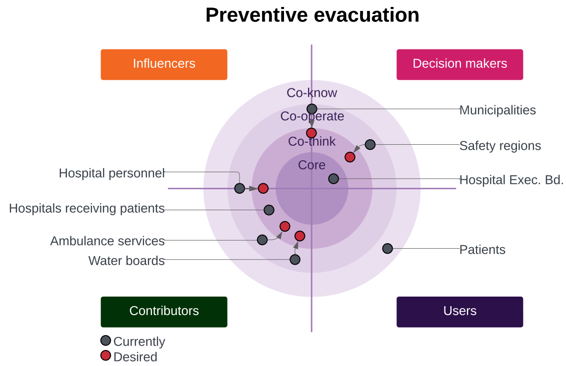


Figure 6.5: Bullseye diagram of the current and desired stakeholder engagement for implementation of "preventive evacuation" at hospitals.

6.6 Selecting stakeholders per flood strategy

Based on the desired stakeholder engagement and the phase 2 interviews, a selection is made per flood strategy of stakeholders that *should* be engaged. Stakeholders that are at "co-operate" or closer to the centre of the bullseye diagrams should be engaged for the implementation of flood strategies. Stakeholders further from the centre of the bullseye (at "co-know") were categorised as "acquaintance" by the PIA matrix. Therefore, it is reasoned that these stakeholders have too little influence and resources to contribute to the implementation of flood strategies at hospitals. Keeping these stakeholders informed is sufficient (hence: "co-know"). The resulting list of stakeholders that should be engaged per flood measure is shown in Table 6.6.

Table 6.6: Overview of which stakeholders should be engaged per flood strategy.

Stakeholder	Shelter in place with additional measures	Shelter in place without additional measures	Accept	Preventive evacuation
Hospital Executive Board	●	●	○	●
Hospital personnel	●	●	○	●
Hospitals receiving patients	○	○	○	●
Patients	○	○	○	○
Ambulance services	○	○	○	●
Suppliers	●	●	○	○
Utility companies	●	●	○	○
Water boards	●	●	○	●
Municipalities	●	●	○	●
Safety regions	●	●	○	●

Engaged: ●
Not engaged: ○

6.7 Experts' view on stakeholder engagement

The phase 2 interviews were used to obtain the views of experts with lived experience on how the selected stakeholders can be engaged. The two main opinions were to enforce engagement through legislation and to create awareness. The different proposed methods are briefly discussed and pros and cons according to the experts are highlighted.

Enforcing engagement through legislation can be achieved in several ways. A government body can be appointed to take on a coordinating role to engage stakeholders. Another option is to assign controlling power to a government body. Investments in flood strategies could also be subsidised. In such cases, requirements can be imposed on engagement of specific stakeholders and acquiring a certain level of flood preparedness. Directly approaching politics can be used to achieve legislation. This method also comes with an advantage:

"If you want to use legislation, this [directly approaching politics] is the shortest route to achieve that." [participant 6]

An advantage of enforcing engagement through legislation is that, in theory, success is guaranteed once the legislation comes into force. Downsides of using legislation are the costs and the duration of implementing new laws. In addition, hospitals already have to comply with many rules:

"In terms of obligations, hospitals already have so much to do. (...) But I do think that we will see this [flooding at hospitals] more often, so that it [making emergency plans with other stakeholders

mandatory] can certainly be asked of hospitals. And once you have the agreements, they are there, so then you can use them." [participant 7]

Awareness can be created on several levels: the public and important stakeholders. The advantage is that people become informed about the problem and who needs to be engaged for the solution, leading to a sense of urgency. However, this method is unpredictable and requires a lot of time to succeed. One interviewee described how awareness should be used:

"What works well, is that the subject is brought to attention in a structured way over a number of years. (...) One creates or seizes moments to discuss the theme of interest." [participant 6]

These two methods for stakeholder engagement contain aspects that are also mentioned in the literature (Olejniczak et al., 2020). A first aspect that can be recognised, is using an *authority tool* that relies on obeying the law. The view that investments in flood strategies could be subsidised is described as an *incentive tool*. The method of creating awareness is described by the so-called *capacity tool*. This tool implies providing information to steer decisions.

7. Discussion

In this chapter, the methods and results from this research are discussed. First, it is discussed how quantitative assumptions may influence the calculated number of fatalities. Then the selection of the cases and interview participants is discussed. Next, limitations of this studies are discussed. The general applicability of the method, given the assumptions and limitations discussed, is reviewed. Finally, the scientific contribution of this research is addressed.

7.1 Number of fatalities

Two different equations were proposed to calculate the number of fatalities. One equation was proposed for the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept". Another equation was proposed for "preventive evacuation".

The outcomes of the equation for the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept" are influenced most by the assumed duration of the flood and the mortality rate. Regarding the flood duration, for the RdGG case, a short duration of 0,5 to 1 day was assumed, based on the expected conditions during a flood. The RdGG can be flooded as a consequence of a breach in a regional flood defence or by heavy precipitation. For both types of floods, it is reasoned that the extent of the flood and the flood depth are limited. Therefore, the hospital remains relatively easily accessible. In addition, the RdGG is the only hospital flooded during these flood scenarios and no densely populated areas are flooded. Therefore, rescue efforts can focus on saving the RdGG. Hence, using a short duration was deemed justifiable. However, if the actual flood duration were to be longer, the number of estimated fatalities would be significantly underestimated. For the EMC case, a longer flood duration was assumed: 3 to 5 days. The EMC can only be flooded as a consequence of a breach in a primary flood defence. The storm that causes the breach threatens a large part of the Dutch coastal area, including 33 hospitals, and causes storm damage to infrastructure. Multiple breaches are expected to occur, flooding many of these hospitals. In this research it was assumed that only one breach can occur simultaneously, which means that if the EMC is flooded, three other hospitals are also flooded. If the duration of the flood is underestimated, the actual number of fatalities will be higher than calculated. The equation for "preventive evacuation" does not depend on duration. Hence, a longer flood duration would mean that the number of fatalities for the flood strategy "preventive evacuation" does not increase. Therefore, the flood strategy that yields the least fatalities may change. Regarding the mortality rate of the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept", the used values are based on sources from the literature and expert judgement. A higher mortality rate results in more fatalities. Although the mortality rates of the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept" could in reality be different than was assumed in this report, it is expected that the mortality rate for "shelter in place with additional measures" will be the lowest of these three flood strategies and "accept" will have the highest mortality rate, because of the expected conditions in the hospital during a flood. Hence, the order of least to most fatalities is not expected to change between these three flood strategies.

The equation for "preventive evacuation" is sensitive to the mortality rate for successful preventive evacuation, because this mortality rate affects the largest group of people. The sensitivity of the mortality rate for unsuccessful preventive evacuation is lower, because it affects fewer patients. However, because this mortality rate is assumed to be higher than for successful preventive evacuation, the impact on the number of fatalities is still significant. The sensitivity of the number of evacuations relative to one flood increases with higher values of the mortality rate for successful preventive evacuation. The evacuation fraction rate determines the influence of the two mortality rates, but has a relatively limited effect on the number of fatalities. Because this equation is sensitive to a number of parameters that also influence each other's sensitivity, this equation is less robust than the equation for "shelter in place with additional measures", "shelter in place without additional measures" and "accept". For both the RdGG and EMC cases, a low mortality rate was assumed for successful preventive evacuation. As discussed, this assumption has a significant influence on the calculated number of fatalities. The current assumption makes the model less sensitive to the assumption of the number of evacuations relative to one flood. The mortality rate for unsuccessful preventive evacuation currently contributes most to the number of fatalities. Other values may significantly change the calculated number of fatalities.

The assumption that only one breach occurs simultaneously is unrealistic in the EMC case and limits the number of simultaneously flooded hospitals. By choosing a higher number of simultaneously flooded hospitals, it was shown that the number of fatalities does increase for all flood strategies. However, the order of flood strategies in terms of fatalities did not change.

The number of fatalities of the EMC (ranging from 18,8 to 195,3) is much higher than for the RdGG (ranging from 0,2 to 2,1). The high number of fatalities at the EMC is due to the duration of exposure of patients to the flood that lasts for several days and the low evacuation fraction. The EMC is a large hospital that has a capacity of 1200 beds. Hence, many patients are exposed if the EMC is flooded, resulting in more fatalities compared to a smaller hospital. The relatively long exposure duration and low evacuation fraction are caused by the large extent of the flood and significant flood depth. Many other hospitals are simultaneously threatened or flooded and a large densely populated area is also flooded. For the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept", the rescue efforts and resources have to be divided and accessing the hospital is difficult. As a result, the exposure duration is long, causing many fatalities. During "preventive evacuation", many people and hospitals are simultaneously evacuating. Infrastructure becomes congested and evacuation resources have to be divided. As a consequence, the evacuation fraction for the EMC is low, resulting in a high number of fatalities.

7.2 Selection of cases and interview participants

The two hospitals that were selected for the case study are located relatively close to each other. Although the cases differ in some of their characteristics, it could be that for hospitals in other parts of the Netherlands other flood preparedness indicators than the indicators used in this report are essential when assessing flood preparedness and deciding on flood strategies.

Five interviews were held for the phase 1 interviews. It can be argued that data saturation has therefore not been achieved. However, the number of people per hospital who possess the knowledge to answer the interview questions (see Appendix B) is limited. Therefore, the number of suitable participants from the two selected hospitals is low.

The phase 1 interviews aimed to find factual information. However, during key informant interviews it is unavoidable that personal bias is introduced. For the phase 2 interviews two doctors with flood experience were asked for their opinion, which inherently introduces personal bias. Furthermore, these experts have also worked at the same hospital. Therefore, there is a risk of obtaining a one-sided or incomplete view. The number of Dutch hospitals with flood experience is limited, which makes including a varied view difficult.

7.3 Limitations & general remarks

In this research, a number of assumptions was made. In addition, during the research factors were discovered that could not be included, but presumably influence the results or applicability of this thesis. Limitations and general remarks are organised per theme and briefly discussed.

7.3.1 Data quality

- The flood scenarios from the LIWO are based on elevation maps. Over time, hospitals are renovated, changing the elevation of the hospital and its terrain. Because of such renovations, the reported flood depth may not always be accurate.
- The flood scenarios from the LIWO contain maximum flood depths, which are outputs of flood simulation models. These models may contain uncertainties that can influence the resulting flood depths. The availability of hospital facilities is based on the flood depths from the LIWO. Therefore, uncertainty in the maximum flood depths introduces inaccuracies in the availability of hospital facilities, which can affect the quantitative outcomes of this studies.

7.3.2 Flood preparedness indicators

- Separate flood preparedness indicators were presented in this research, but the it should be acknowledged that these indicators are connected and depend on one another. Some indicators share facilities. For instance, water is relevant for stocks and utilities. In addition, failure of one indicator may cause cascade effects to occur, leading to failure of other indicators.

- As researcher, by selecting certain flood preparedness indicators and leaving out others, a simplified version of reality is depicted. The decisions behind the developed model introduce bias for selecting a flood strategy, even though the outcome is not determined by the researcher.
- Because a series system was assumed where failure of one flood preparedness indicator results in the disruption of the continuity of healthcare, it could be argued that only the weakest link is of interest. However, to find the weakest link, all flood preparedness indicators should be considered.

7.3.3 Flood scenarios and impact

- The probability of occurrence of the scenarios have not been taken into account in this research. However, the combination of the expected flood impact and probability of occurrence of a flood plays a significant role in the decision whether to invest in a certain flood strategy.
- The vulnerability of a hospital to a flood changes if other critical flood levels are assumed for facilities inside the hospital or accessibility to hospitals for suppliers.
- This research shows that hospital suppliers may be flooded by a different flood scenario than the hospital. These scenarios have not been accounted for. However, combining these scenarios with the scenarios that threaten hospitals yields a more complete view of the availability of supplies that have to be delivered to the hospital.
- In this research it was assumed that if a flood occurs, supplies will continue as long as the company and route to the hospital are available. Another factor that should be considered, is whether employees of suppliers will to come to work during a flood.

7.3.4 Mortality rate

- Only patients are assumed to die at hospitals during a flood. Other groups of people have been disregarded (such as staff and visitors). This assumption results in an underestimation of the total number of fatalities.
- Although the flood depth is used implicitly to determine the number of fatalities, in combination with the serial system used in this research, the expected difference in fatalities for different flood depths is not reflected. A series system was proposed to determine the failure of continuity of healthcare care at hospitals. If the critical flood level of a hospital function is exceeded, the function fails. If a hospital function fails, the associated indicator fails, resulting in failure of healthcare care continuity. Subsequently, an increased mortality rate is assumed to be applicable and the number of fatalities is calculated with a formula. The flood depth is not an input to this formula, but is used implicitly, as stated. In the case of the RdGG, the number of fatalities is equal for all flood scenarios (precipitation events with varying degrees of severity and a breach in a regional dyke), despite the fact that the flood depth varies from 0,15m to 0,76m. The number of fatalities for flood scenarios with a relatively small flood depth are expected to be lower than for flood scenarios with a larger flood depth. For example, a precipitation event with return period of 10 years that results in 0,15m flood depth is expected to result in less fatalities than a flood resulting from a regional dyke

breach that causes a flood depth of 0,76m. Hence, the expected influence of the flood depth on the number of fatalities is not accounted for by this research. Therefore, it is recommended to explore how this influence can be included, for example, by explicitly including the flood depth in the function that calculates the number of fatalities. In addition, the series system always assumes the most pessimistic scenario: failure of a single function already results in failure of the continuity of healthcare. Alternatively, a parallel system could be assumed, where multiple functions or indicators need to fail before the continuity of healthcare is assumed to have failed. This recommendation can be also be addressed in a future research.

- Regardless of which flood preparedness indicator fails, a single mortality rate is used per flood strategy. Individual contributions from flood preparedness indicators to the mortality rate would allow for more detailed insights. These individual contributions cannot be substantiated with the current knowledge.
- A mortality rate has been assumed per flood strategy. However, mortality rates and their development over time may also differ per hospital or type of flood.
- The evacuation fraction from the LIWO is used. This fraction is related to the ability of the entire population to leave an area before a flood arrives and is only applicable for breaches in primary flood defences. The evacuation fraction for hospitals may differ from these assumed values. Firstly, special vehicles, such as ambulances, are required to carry out the evacuation. If multiple hospitals are simultaneously threatened, the ambulances will have to be divided over the hospitals, slowing down the evacuation process. In addition, some hospital patients have increased vulnerability. Therefore, extra precautions are required during evacuation, slowing down the process even more. It is expected that the used evacuation fractions overestimate the actual evacuation fractions for hospitals. If the actual evacuation fractions for hospitals are lower, the expected number of fatalities presented in this report for the flood strategy ”preventive evacuation” is underestimated.

7.3.5 Costs

- Not all costs have been considered. The phase 2 interviews confirmed that the total costs are difficult to estimate, since there is not fixed set of costs that should be considered. In this research, costs due to damage to the hospital and the costs of implementation of flood strategies have been included. Examples of other types of costs that could be considered are the number of lost hours of operation, absence of staff or loss of life.

7.3.6 Stakeholder engagement

- The stakeholders were identified based on interviews, two cases and literature. If other hospitals are considered, it could be that additional or other stakeholders appear relevant for the implementation of flood strategies.
- Selecting stakeholders is not an indisputable or absolute decision. The applied steps were used to analyse the stakeholders as clearly as possible to subsequently make a

substantiated decision. Even though the result is a list of stakeholders per flood strategy, the details behind the selection (for instance: the desired degree of engagement) should be taken into account.

- No stakeholders were identified that oppose the implementation of flood strategies. Many stakeholders are passive, which may explain why implementation is still lacking. Nonetheless, the analysis suggests that implementation of flood strategies would be effortless, once stakeholders become active. It can be questioned whether this would be the case.
- No interviews were held with the identified stakeholders. Interviews might result in additional information that can be relevant for the decision on who should be engaged for the implementation of each flood strategy. It may even result in the identification of additional possibly relevant stakeholders.
- Only two methods for stakeholder engagement were recommended by the expert from the phase 2 interviews. However, many more methods exist for this purpose. It cannot be ruled out that more methods are suitable for achieving stakeholder engagement in the context of implementing flood strategies. The fact that only two phase 2 interviews were held is assumed to be the cause of identifying only a limited number of recommended methods for stakeholder engagement.

7.4 Applicability to other hospitals

The two hospitals that were selected experience different kinds of floods: a breach in a primary flood defence, a breach in a regional flood defence and precipitation events. In addition, the developed methods proved to be applicable to cases where only one or multiple hospitals are simultaneously threatened and flooded. Also, the stakeholders that were selected for the implementation of flood strategies are relevant for both cases. Therefore, the method is expected to be applicable to other hospitals too. However, by studying only two hospitals, the applicability of the method that was developed could only be verified to a limited extent. To ensure that the methods of this research are generally applicable to all hospitals in the Netherlands, more hospitals with other characteristics than the RdGG and EMC should be studied.

7.5 Scientific contribution

In Chapter 2, a number of research gaps were identified. The scientific contributions of this research are addressed.

Indicators have previously been used to assess flood risk and impact (Batica & Gourbesville, 2014; Miranda et al., 2023; Phongsapan et al., 2019; World Health Organization, 2015), but a set of indicators that can be used to assess flood preparedness of hospitals was lacking. In addition, the direct impact of floods has been studied (Kolen et al., 2017; Van Beek et al., 2015), but the indirect impact had not been mapped. This studies proposed six flood preparedness indicators that also take into account the dependency of hospitals on services that are externally supplied.

Previous studies have looked into (quantitative) flood strategy decision-making for hospitals (Kolen, 2013, 2023; McGinty et al., 2017; Zane et al., 2010). However, such decision-making models have not been previously applied to specific hospitals. This research provides a detailed overview of fatalities and cost estimations per flood strategy to facilitate decision-making of flood strategies.

The literature review showed that many sources acknowledge that flood preparedness at hospitals must be achieved through engagement of external stakeholders (Adelaine et al., 2016; Krause et al., 2023; Ministry of Infrastructure and Water Management, 2023a; Rattanakanlaya et al., 2021; Van Eijk, 2022; World Health Organization, 2017). However, no research was found that stated which stakeholder should be involved. This research makes recommendations on which stakeholders should be involved per flood strategy. In addition, medical experts who have experience hospital floods were asked for their view on how stakeholders could be engaged. These expert opinions are a first step towards creating a policy where relevant stakeholders are actively engaged for the implementation of flood strategies at Dutch hospitals.

8. Conclusions and recommendations

In this thesis flood preparedness indicators were identified that represent a set of functions that is essential to the continuity of healthcare of hospitals. A method was developed to quantitatively assess hospitals' flood preparedness based on these indicators. This assessment method enables decision-making between flood strategies, which can be implemented to improve flood preparedness. Stakeholders who are relevant for the implementation of flood strategies were identified and selected per flood strategy. Interviews were held with experts in the area of hospitals floods to obtain recommendations on the engagement of the selected stakeholders. In this chapter, the conclusions and recommendations from this thesis are presented.

8.1 Conclusions per research question

To answer the main research question, four sub-questions were created. These sub-questions are answered first.

8.1.1 Sub-question 1: Which flood preparedness indicators are relevant for contributing to the choice of flood strategies implemented by Dutch hospitals?

Four flood strategies were considered in this research: "shelter in place with additional measures", "shelter in place without additional measures", "accept" and "preventive evacuation". From the literature and phase 2 interviews, it became apparent that the characteristics of the flood strategy "preventive evacuation" significantly differ from the other flood strategies. Because this flood strategy involves leaving the hospital, other functions are important than for the other flood strategies, where it is decided to stay at the hospital. For preventive evacuation, the following flood preparedness indicators are selected:

- Availability of modes of transport for patients
- Having prepared emergency management plans
- Availability of sufficient and qualified personnel

For the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept", the flood preparedness indicators below are selected:

- Availability of critical equipment
- Having sufficient supplies in stock
- Availability of utilities
- Having prepared emergency management plans
- Availability of sufficient and qualified personnel

8.1.2 Sub-question 2: What is the flood impact on Dutch hospitals given their level of flood preparedness?

The flood impact was analysed for the Reinier de Graaf Gasthuis (RdGG) and Erasmus Medical Centre (EMC). The direct and indirect impact were derived for each flood scenario that threatens the hospital by determining critical flood depths for each hospital facility. The availability of suppliers was also considered for these flood scenarios. This type of analysis has not been conducted previously in other researches. The hospital facilities were grouped per flood preparedness indicator. A series system was assumed where failure of a facility leads to the failure of the corresponding indicator. If any flood preparedness indicator fails, it was assumed that the hospital fails. The impact of the flood was subsequently quantified by the number of deaths and types of costs. The overview of failing flood preparedness indicators, the number of deaths and costs per flood scenario enables hospitals to make substantiated and specific choices for investments in flood strategies to increase flood preparedness. Such investments are focused on achieving extended availability of flood preparedness indicators, lowering mortality rates or shorter duration of exposure to a flood.

The number of fatalities and costs per flood strategy were determined for the RdGG. These results are applicable to the four scenarios considered (”Precipitation 1000”, ”Precipitation 100”, ”Precipitation 10” and ”Regional 100”), because during all four scenarios, the continuity of healthcare at the RdGG is disrupted. The number of fatalities for the RdGG is relatively limited, ranging from 0,2 to 2,1 fatalities depending on the flood strategy. The number of fatalities is low because the flood depth and extent of the flood are limited. Furthermore, the duration of exposure of patients to the flood is short, being one day or less. In summary, ”shelter in place with additional measures” results in 0,2 fatalities and the costs are ”high”. ”Shelter in place without additional measures” results in 1,4 fatalities and the associated costs are labelled ”medium”. The flood strategy ”accept” results in the most fatalities: 2,1. However, it is the least expensive strategy. Lastly, ”preventive evacuation” yields 1,7 fatalities and the costs are labelled ”medium”. These results show that investing in flood strategies results in a lower number of fatalities. The interview participants from the RdGG and EMC agreed that only the well-being of patients is considered when deciding on flood strategies and that costs do not play a role. If only the number of fatalities is considered, ”shelter in place with additional measures” is the ”best” flood strategy for the RdGG, because it results in the least fatalities.

The number of fatalities and costs per flood strategy were also determined for the EMC. Both flood scenarios that were considered (”Parksluizen 1” and ”Parksluizen 2”) result in disruption of the continuity of healthcare at the EMC. The number of fatalities for the EMC ranges from 18,8 to 195,3, depending on the flood strategy, which is much higher compared to the RdGG. The relatively high number of fatalities is caused by the large flood depths and flood extent that results from a breach in a primary flood defence. In addition, multiple hospitals and many houses are simultaneously threatened or even flooded. Therefore, the patients are expected to be exposed to the flood for several days. Lastly, the EMC is much larger than the RdGG. Hence, the number of exposed patients is higher, resulting in more fatalities compared to the RdGG. ”Shelter in place with additional measures” results in the least fatalities (18,8), but is the most expensive strategy. ”Shelter in place without additional measures” yields 83,4 fatalities and the costs are labelled ”medium”. Unlike at the RdGG, ”preventive evacuation” results in more fatalities than ”accept”. These strategies result in 195,3 and 125,3 fatalities respectively. The costs for ”preventive evacuation” are ”medium” and the costs for ”accept” are the lowest. When only the number of fatalities is considered,

”shelter in place with additional measures” is the ”best” flood strategy, because it yields the least fatalities. If all hospitals are considered that are simultaneously threatened by the same flood scenario as the EMC, the same conclusion can be drawn. The finding that sheltering in place may be a better strategy than preventive evacuation for densely populated areas with low evacuation fractions corresponds with other results in the literature (Balsari et al., 2016; Kolen, 2013).

Regarding the costs per flood strategy, it was found that for every flood strategy a degree of damage to the hospital building can be expected. The strategies ”shelter in place with(out) additional measures” focus on preventing failure of hospital functions. Therefore, the damage will be less when compared to the other flood strategies, but requires additional investments. Of the two shelter-in-place strategies, investing in additional flood measures reduces the damage the most, but also results in the highest investment costs. In addition, the running costs for upkeep of flood measures (for tangible assets and emergency plans) should be considered. It is assumed that there are no investment costs for the flood strategy ”accept”. For ”preventive evacuation”, transportation costs and costs for practising the evacuation procedures are additional expenses.

The flood preparedness assessment of the RdGG and EMC revealed that several suppliers also supply other hospitals in the region. The companies Evides (drinking water), ZorgserviceXL (medical supplies), Combi-Ster (sterilsation of medical equipment) and Linde Gas (medical gases) were found to supply up to approximately 40 hospitals. It is uncertain whether failure due to flooding of these companies can be compensated by other suppliers and what the subsequent impact will be on the regional healthcare system. However, interviews and tours at hospitals revealed that certain supplies (such as food), are delivered to hospitals multiple times per day. Failure of the corresponding suppliers can cause immediate shortage at hospitals on a regional scale.

8.1.3 Sub-question 3: Which stakeholders should be involved per flood strategy in the process of implementing flood strategies for Dutch hospitals?

Stakeholders were identified through interviews and the literature. An initial selection of stakeholders was made per flood strategy. Each stakeholder was categorised based on their power, interest and attitude, which resulted in recommended actions for engagement per stakeholder per flood strategy. It was found that in principle all stakeholders have a positive attitude towards implementing flood strategies. However, most stakeholder take on a passive role. This passiveness is often caused by unawareness of flood risks, the lack of sufficient (human) resources or the experience that one already has to meet many important obligations on a daily basis. Other stakeholders should be actively engaged more closely to achieve active participation in implementing flood strategies. Patients were excluded based on their passiveness, low influence and lack of resources to contribute to the implementation of flood strategies at hospitals. The selection of stakeholders per flood strategy is depicted in Table 8.1. The Executive Board of a hospital, hospital personnel, water boards, municipalities and safety regions should be involved for the implementation of any of the flood strategies. The flood strategy ”accept” is the exception, because this strategy involves taking no measures. Therefore, it is desirable that any of these stakeholders take the lead in engaging the other stakeholders required for the implementation of flood strategies.

Table 8.1: Overview of which stakeholders should be engaged per flood strategy.

Stakeholder	Shelter in place with additional measures	Shelter in place without additional measures	Accept	Preventive evacuation
Hospital Executive Board	•	•	○	•
Hospital personnel	•	•	○	•
Hospitals receiving patients	○	○	○	•
Patients	○	○	○	○
Ambulance services	○	○	○	•
Suppliers	•	•	○	○
Utility companies	•	•	○	○
Water boards	•	•	○	•
Municipalities	•	•	○	•
Safety regions	•	•	○	•

Engaged: •
Not engaged: ○

8.1.4 Sub-question 4: How can relevant stakeholders be engaged for the implementation of flood strategies according to experts with lived experience?

During the phase 2 interviews two medical expert with flood experience at hospitals shared their view on how relevant stakeholders could be engaged. No consensus was found on a single ”best” method. Instead, two methods were proposed: enforcing engagement through legislation and creating awareness. These two methods for stakeholder engagement contain aspects that are also mentioned in the literature (Olejniczak et al., 2020): using the law, an incentive or providing information to steer decisions. According to the experts, the advantage of enforcing engagement through legislation is that, in theory, success is guaranteed once the legislation comes into force. However, the experts also mentioned that the costs of enforcement, the duration of implementing new laws and the experience that hospitals already have to meet many obligations are downsides. The stated advantage of creating awareness is that broad support is created, resulting in willingness to be engaged. However, this method is said to be unpredictable and requires a lot of time to succeed.

8.1.5 Main research question: How can flood preparedness of hospitals in the Netherlands be assessed and improved?

The four sub-questions contributed to answering the main research question. *SQ1* and *SQ2* addressed the assessment of flood preparedness of hospitals in the Netherlands. Essential hospital functions can be categorised based on the flood preparedness indicators. The availability of these indicators during floods can be used to quantitatively assess flood preparedness in terms of fatalities and types of costs. The outcomes of the assessment can be used to compare flood strategies that can be implemented to contribute to flood preparedness. The answers to *SQ3* and *SQ4* revealed that for every flood strategy, except for "accept", at least the Executive Board of a hospital, hospital personnel, water boards, municipalities and safety regions should be engaged to realise the implementation of flood strategies. Experts with lived experience recommended to engage stakeholders through legislation or creating awareness. In conclusion, flood preparedness has been assessed, enabling decision-making regarding flood strategies. By engaging the right stakeholders for the implementation of these flood strategies, the flood preparedness of hospitals in the Netherlands can be improved.

8.2 Recommendations

The discussion (see Chapter 7) and conclusions result in recommendations for future research. These recommendations are listed below.

- Adding more cases to the case study, especially for hospitals in other parts of the Netherlands, can verify whether the proposed methods are generally applicable to Dutch hospitals. It is recommended to select hospitals with varying causes of flooding, evacuation fractions and numbers of simultaneously threatened hospitals.
- To estimate the number of fatalities per flood strategy more accurately, it is recommended to calibrate the proposed fatality equations based on historical flood events at hospitals. For the flood strategies "shelter in place with additional measures", "shelter in place without additional measures" and "accept", it is recommended to focus on calibrating the flood duration and mortality rates for flood strategies. For the flood strategy "preventive evacuation", it is recommended to prioritise calibrating the mortality rates for successful and unsuccessful preventive evacuation.
- Regarding the availability of suppliers, future research could focus on the vulnerability of the regional healthcare system to supplier failure during floods. It is recommended to consider all scenarios that can flood suppliers and to prioritise suppliers that distribute supplies to multiple hospitals.
- In this thesis, it was assumed that the evacuation fraction from the LIWO is applicable to hospitals. It is recommended to look into the validity of this assumption.
- The views of two experts with lived experience on methods for stakeholder engagement were discussed. It is recommended to further look into methods or policies that can be used to engage stakeholders for the implementation of flood strategies at hospitals.

References

Actueel Hoogtebestand Nederland. (n.d.). *AHN - kwaliteitsbeschrijving*. Retrieved August 29, 2024, from https://www.ahn.nl/kwaliteitsbeschrijving

Adelaine, S. A., Shoaf, K., & Harvey, C. W. C. (2016). An Assessment of Collaboration and Disasters: A Hospital perspective. *Prehospital and Disaster Medicine*, *31*(2), 121–125. https://doi.org/10.1017/s1049023x16000066

Algemeen Hoogtebestand Nederland. (n.d.). *AHN Viewer*. Retrieved November 7, 2024, from https://www.ahn.nl/ahn-viewer

Balsari, S., Patrick, K., Perry, K., & Leaning, J. (2016). *The Surge After the Storm*. Harvard T.H. Chan School of Public Health.

Barten, D. G., Fijten, M. H., Gaakeer, M. I., Klokman, V. W., Mortelmans, L. J., Van Osch, F., Peters, N. A., Wijnands, J. J., Tan, E. C., & Boin, A. (2022). Three decades of hospital evacuations in the netherlands: A scoping review. *International Journal of Disaster Risk Reduction*, *81*, 103252. https://doi.org/10.1016/j.ijdrr.2022.103252

Batica, J., & Gourbesville, P. (2014). Flood resilience index - methodology and application. In *11th international conference on hydroinformatics*. City University of New York. https://academicworks.cuny.edu/cgi/viewcontent.cgi?article=1432&context=cc_conf_hic

Bergman, T. J., & Beehner, J. C. (2015). Measuring social complexity. *Animal Behaviour*, *103*, 203–209. https://doi.org/10.1016/j.anbehav.2015.02.018

Blanchette, R. A. D. G. E., Van Bree, E. M., & Bierens, J. J. (2023). Hospital disaster preparedness in the netherlands. *International Journal of Disaster Risk Reduction*, *93*, 103778. https://doi.org/10.1016/j.ijdrr.2023.103778

Bocanegra, R. A., & Francés, F. (2021). Assessing the risk of vehicle instability due to flooding. *Journal of Flood Risk Management*, *14*(4). https://doi.org/10.1111/jfr3.12738

CBS. (2024a). *CBS Statline - Gezondheid, leefstijl, zorggebruik en -aanbod, doodsoorzaken; vanaf 1900*. Retrieved September 2, 2024, from https://opendata.cbs.nl/#/CBS/nl/dataset/37852/table?ts=1718096952036

CBS. (2024b). *CBS Statline -Ziekenhuisopnamen; sterfte, urgentie, diagnose-indelingen CCS en VTV*. Retrieved September 2, 2024, from https://opendata.cbs.nl/#/CBS/nl/dataset/84522NED/table?ts=1718098858581

Cumiskey, L., Priest, S. J., Klijn, F., & Juntti, M. (2019). A framework to assess integration in flood risk management: implications for governance, policy, and practice. *Ecology and Society*, *24*(4). https://doi.org/10.5751/es-11298-240417

Dekker, G., Wullems, B., & Chan, P. (2020). *Verantwoordelijkheden bij risico's van extreem weer in een veranderend klimaat: Verkenning verantwoordelijkheden en ontwikkelagenda* (P20053). Utrecht, nl, Ambient Advies B.V.

Den Heijer, F., Podt, M., Bosch-Rekveldt, M., De Leeuw, A., & Rijke, J. (2023). Serious gaming for better cooperation in flood defence asset management. *Journal of Flood Risk Management*, *16*(3). https://doi.org/10.1111/jfr3.12910

Erasmus MC Foundation. (n.d.). *Erasmus MC Daktuinen*. Retrieved November 11, 2024, from https://erasmusmcfoundation.nl/erasmus-mc-daktuinen/

Evans, B., Lam, A., West, C., Ahmadian, R., Djordjević, S., Chen, A., & Pregnolato, M. (2024). A combined stability function to quantify flood risks to pedestrians and vehicle occupants. *The Science of The Total Environment*, *908*, 168237. https://doi.org/10.1016/j.scitotenv.2023.168237

Harbers. (2022). *Eindadvies Beleidstafel wateroverlast en hoogwater*. Retrieved September 16, 2024, from https://open.overheid.nl/documenten/ronl-a246ee801362b8b75afb770bc4f7d429cc30301b/pdf

HKV lijn in water. (2017). *Quick Scan Overstromingsrisico Ziekenhuizen: Kwetsbaarheidsanalyse overstromingen Erasmus MC* (PR3483.10).

HKV lijn in water. (2020). *Mijn waterrisicoprofiel*. Retrieved August 28, 2024, from https://mijnwaterrisicoprofiel.nl/

Jones Taylor, G. A., & Blake, B. J. (2015). Key informant interviews and focus groups. In M. De Chesnay (Ed.), *Nursing research using data analysis* (pp. 153–166). Springer Publishing Company. https://books.google.nl/books?hl=nl&lr=&id=g6qgBQAAQBAJ&oi=fnd&pg=PA153&dq=key+informant+interviews+qualitative+data&ots=RIWtwWJ_pP&sig=K29AkTi_BmUfsgSPPDd3xnw-vEw#v=onepage&q=key%20informant%20interviews%20qualitative%20data&f=false

Kennisportaal Klimaatadaptatie. (n.d.). *Vitale en Kwetsbare functies*. Retrieved September 13, 2024, from https://klimaatadaptatienederland.nl/kennisdossiers/vitale-kwetsbare-functies/

Kennisportaal Klimaatadaptatie. (2021). *Algemene informatie over de risicodialoog*. Retrieved January 31, 2024, from https://klimaatadaptatienederland.nl/risicodialoog/routekaart-risicodialoog/algemene-informatie/

Klopstra, D., & Kok, M. (2009). *Van neerslag tot schade* (PR1116). HKV lijn in water.

Kok, M., Huizinga, H. J., Vrouwenvelder, A. C. W. M., & Barendregt, A. (2004). *Standaardmethode2004 schade en slachtoffers als gevolg van overstromingen* (DWW-2005-005). Ministry of Infrastructure; Water Management.

Kolen, B. (2013). *Certainty of uncertainty in evacuation for threat driven response. Principles of adaptive evacuation management for flood risk planning in the Netherlands* [Doctoral dissertation, Radboud University Nijmegen]. https://repository.ubn.ru.nl/bitstream/handle/2066/115713/115713.pdf

Kolen, B. (2023). *Overstromingsrisico analyse Nederland ziekenhuizen: Kennisalliantie slachtoffers en evacuatie* (PR3591.70) (Unpublished). HKV lijn in water.

Kolen, B., Groot, S., & Bierens, J. (2017). *Synthese quick-scan ruimtelijke adaptatie voor ziekenhuizen: Op basis van 3 pilots voor overstromingen en extreme neerslag* (PR3483.10). HKV lijn in water.

Krause, S., Joel, E., Schaum, C., Bäumer, J., Rücker, N., Wienand, I., Sturm, C., Jahn-Mühl, B., Geiger, M., Fekete, A., Van Der Heijden, S., Heinzel, C., & Sandholz, S. (2023).

Water safety planning for healthcare facilities for extreme events. *Journal of Water and Health*, *22*(1), 77–96. https://doi.org/10.2166/wh.2023.102

Lamine, H., Lamberti-Castronuovo, A., Singh, P., Chebili, N., Zedini, C., Achour, N., Valente, M., & Ragazzoni, L. (2023). A qualitative study on the use of the hospital safety index and the formulation of recommendations for future adaptations. *International Journal of Environmental Research and Public Health*, *20*(6), 4985. https://doi.org/10.3390/ijerph20064985

Landelijk Netwerk Acute Zorg. (2024). *Kwaliteitskader Risicomanagement, Crisisbeheersing en OTO 3.0: Samen voorbereid op rampen en crises*. Retrieved October 9, 2024, from https://www.lnaz.nl/oto/kwaliteitskader-risicomanagement-crisisbeheersing-en-oto-3.0

McGinty, M., Burke, T. A., Resnick, B., Barnett, D. J., Smith, K. C., & Rutkow, L. (2017). Decision processes and determinants of hospital Evacuation and Shelter-in-Place during Hurricane Sandy. *Journal of public health management and practice*, *23*(1), 29–36. https://doi.org/10.1097/phh.0000000000000404

Mens, M., De Grave, P., Noordhuis, R., & Van Veggel, W. (2024). *Huidige watergerelateerde klimaatrisico's in nederland: Een inventarisatie voor de thema's waterveiligheid, waterkwantiteit en waterkwaliteit* (11210323-002-BGS-0003). Deltares.

Ministry of Infrastructure and Water Management. (2018). *Overstromingsrisico's in nederland: Voorlopige overstromingsrisicobeoordeling en aanwijzing van gebieden met potentieel significant overstromingsrisico in het kader van de Europese Richtlijn Overstromingsrisico's (ROR) 2e cyclus: 2016 – 2021*.

Ministry of Infrastructure and Water Management. (2023a). *National Delta Programme 2024: Now for the future*. Retrieved January 19, 2024, from https://english.deltaprogramma.nl/documents/publications/2023/09/19/delta-programme-2024-english

Ministry of Infrastructure and Water Management. (2023b, September 13). *Deltabeslissing waterveiligheid*. Retrieved January 29, 2024, from https://www.deltaprogramma.nl/themas/waterveiligheid/deltabeslissing

Miranda, F., Franco, A. B., Rezende, O., Da Costa, B. B. F., Najjar, M., Haddad, A. N., & Miguez, M. (2023). A gis-based index of physical susceptibility to flooding as a tool for flood risk management. *Land*, *12*(7), 1408. https://doi.org/10.3390/land12071408

MultiBel. (2022). *Reinier de Graaf Ziekenhuis*. Retrieved August 16, 2024, from https://www.multibel.eu/nl/portfolio-items/reinier-de-graaf/#:~:text=Er%20werken%20bij%20het%20Reinier,dat%20beschikt%20over%20481%20bedden.

Murray-Webster, R., & Simon, P. (2006). Making sense of stakeholder mapping. *PM World Today*, *8*(11).

Nationale Intensive Care Evaluatie. (2023). *Basisgegevens IC units 2023*. Retrieved August 16, 2024, from https://www.stichting-nice.nl/datainbeeld/public?subject=BASIC&year=2023&hospital=-1&icno=0

NOS. (2024, September 2). *Noodweer leidt tot overlast, water weggepompt in ziekenhuis doetinchem*. Retrieved November 20, 2024, from https://nos.nl/artikel/2535587-noodweer-leidt-tot-overlast-water-weggepompt-in-ziekenhuis-doetinchem

Olejniczak, K., Śliwowski, P., & Leeuw, F. (2020). Comparing behavioral assumptions of policy tools: Framework for policy designers. *Journal of Comparative Policy Analysis Research and Practice*, *22*(6), 498–520. https://doi.org/10.1080/13876988.2020.1808465

Phongsapan, K., Chishtie, F., Poortinga, A., Bhandari, B., Meechaiya, C., Kunlamai, T., Aung, K. S., Saah, D., Anderson, E., Markert, K., Markert, A., & Towashiraporn, P. (2019). Operational flood Risk index mapping for disaster risk reduction using earth observations and cloud computing technologies: a case study on Myanmar. *Frontiers in Environmental Science*, *7*. https://doi.org/10.3389/fenvs.2019.00191

Rattanakanlaya, K., Sukonthasarn, A., Wangsrikhun, S., & Chanprasit, C. (2021). Improving flood disaster preparedness of hospitals in Central Thailand: Hospital personnel perspectives. *Journal of Clinical Nursing*, *31*(7-8), 1073–1081. https://doi.org/10.1111/jocn.15971

Rentschler, J., Klaiber, C., Tariverdi, M., Desjonquères, C., & Mercadante. (2021). *Frontline: Preparing healthcare systems for shocks, from disasters to pandemics.* Washington, DC, The World Bank. https://www.worldbank.org/en/news/feature/2021/04/13/frontline-preparing-healthcare-systems-for-shocks

Stevens Van Dijck. (n.d.). *Reinier de Graaf Gasthuis Delft*. Retrieved August 16, 2024, from https://www.stevensvandijck.nl/portfolio/reinier-de-graaf-gasthuis-delft/#:~:text=Op%20het%20parkeerterrein%20tussen%20twee,Griekse%20symbool%20voor%20de%20geneeskunde.

Strijker, B., Asselman, N., De Jong, J., & Barneveld, H. (2023). The 2021 floods in the Netherlands from a river engineering perspective. *Journal of coastal and riverine flood risk*, *2*. https://doi.org/10.59490/jcrfr.2023.0006

Tarabochia-Gast, A. T., Michanowicz, D. R., & Bernstein, A. S. (2022). Flood risk to hospitals on the united states atlantic and gulf coasts from hurricanes and sea level rise. *GeoHealth*, *6*(10). https://doi.org/10.1029/2022gh000651

Toussaint, K. (2024, October 10). *How a tampa hospital withstood two massive hurricanes*. Retrieved November 20, 2024, from https://www.fastcompany.com/91207434/how-a-tampa-hospital-withstood-two-massive-hurricanes

Van Beek, G., Calon, M., Van Heumen, S., Traversari, A., & Verhoeff, O. (2015). Waterrobuustheid Nederlandse ziekenhuizen. *TNO*, (TNO 2015 R11234). Retrieved January 12, 2024, from https://publications.tno.nl/publication/34618516/IolCPy/TNO-2015-R11234.pdf

Van der Wal, W., Barten, D. G., Ketelings, L., Van Osch, F., Rao, M., Mortelmans, L., & Bierens, J. (2023). Addressing a climate emergency amidst the covid-19 pandemic: A mixed-methods study on a hospital evacuation during the 2021 european floods. *medRxiv (Cold Spring Harbor Laboratory)*. https://doi.org/10.1101/2023.02.02.23285386

Van Eijk, B. (2022). *Overstromingsrisico's bij ziekenhuizen* [Internship report]. Wageningen University & Research.

Van Hulst, B., & Blank, J. (2017). *Nederlandse ziekenhuizen te groot voor verdere schaalvoordelen* (No. 4749). Retrieved November 13, 2024, from https://www.ipsestudies.nl/wp-content/uploads/2021/10/Nederlandse-ziekenhuizen-te-groot-voor-verdere-schaalvoordelen.pdf

VieCurie Medisch Centrum. (2021, July 21). *Liveblog hoogwater VieCuri: Patiënten overgebracht naar Venlo*. Retrieved January 12, 2024, from https://www.viecuri.nl/nieuws/2021/juli/liveblog-maatregelen-oplopende-waterstand-maas/

Wijkhuis, V., & Van Duin, M. (2023). *Lessen uit crises en mini-crises: klimaatverandering en extreem weer*. Nederlands Instituut Publieke Veiligheid.

World Health Organization. (2015). *Hospital safety index: Guide for evaluators* (2nd ed.). https://www.who.int/publications/i/item/9789241548984

World Health Organization. (2017). *Flooding: managing health risks in the WHO European Region*. https://iris.who.int/handle/10665/329518

Zane, R., Biddinger, P., Hassol, A., Rich, T., Gerber, J., & DeAngelis, J. (2010). *Hospital evacuation decision guide* (No. 10-0009). Cambridge, MA, Abt Associates Inc.

Zhong, S., Cheng, Q., Huang, C., & Wang, Z. (2021). Establishment and validation of health vulnerability and adaptation indices under extreme weather events on the basis of the 2016 flood in anhui province, china. *Advances in Climate Change Research*, *12*(5), 649–659. https://doi.org/10.1016/j.accre.2021.07.002

A. List of assumptions

- For regional dykes, only one flood scenario will occur simultaneously. If a dyke is breached, it rules out that another breach will occur within that water system.
- With regard to primary dykes, only one breach is assumed to occur simultaneously.
- The elevation relative to ground level is used as the critical flood depth for each hospital facility.
- It is assumed that once the flood reaches the hospital, the maximum flood depth is immediately reached.
- For each supplier location, the level of the main entrance is used as the critical flood depth.
- For the transport of goods by road from suppliers' locations to the hospital a maximum flood depth of 0,20m is used.
- It is assumed that utility grids remain unaffected by floods, hence no critical flood depth is used.
- Regarding the duration of the unavailability of hospital functions once they have failed, it is assumed that recovery can only occur after the flood has receded or once new supplies are delivered.
- If any of the facilities that fall under a certain flood preparedness indicator fail, that particular indicator is considered to have failed.
- Failure of one flood preparedness indicator is assumed to cause disruption of the healthcare continuity.
- The number of affected patients is assumed to be equal to the number of hospital beds.
- The maximum mortality rate will be reached after four days.
- Only patients are affected by a flood.
- The hospital is full to capacity (in terms of patients) when a flood arrive, except for when the flood strategy "shelter in place with additional measures" is implemented. In that case, the patients with low vulnerability are discharged from the hospital before the flood arrives.
- The assumption is made that from the moment the flood reaches the hospital, the flood immediately reaches its maximum flood depth.
- The duration of preventive evacuation is one day.

B. Interview questions phase 1 interviews

General

- Does the hospital have experience with water nuisance as a result of flooding or extreme rainfall?

Logistics

- Which facilities that must be provided from outside the hospital are essential for continuity of healthcare? (For example: electricity, water, sewage, steam, gasses, food, needles, sterile equipment, medicines, patients and staff)
- Which parties are involved in the delivery of the externally supplied facilities?
- How and for how long is the hospital accessible during a flood? (For example, is there knowledge about water depth, flooding duration, supply routes and means of transport?)
- Which externally supplied facilities are threatened during a flood?

Spatial adaptation

- What considerations have been made in the design of the hospital regarding the placement of crucial facilities? Where are they located? (For example: backup generators, water, sewerage, steam, gasses, supplies, OR, ER, IC, ICT, elevator control)
- What measures have been taken in the immediate vicinity of the hospital?
- How often do functions fail under normal circumstances? (For example: OK, ER, delivery of goods)
- What requirements that have been imposed by the government with regards to flood measures for the hospital?
- Which parties have a say in drawing up flood measures?
- Which parties are involved in the implementation of flood measures?

Emergency plans

- What emergency plans are there for flooding?
- What emergency plans are there regarding shelter in place or evacuation of the hospital?
- Which parties need to be involved for the implementation of the emergency plans?
- To what extent do factors such as the number of deaths, money and reputation influence the choice of measures? Are there additional factors?

C. Interview questions phase 2 interviews

Flood preparedness indicators

- To what extent do you think the selected flood preparedness indicators cover the aspects that a hospital should consider when preparing for a flood?

Hospitals' flood preparedness evaluation

- How do you view the proposed classification of patient groups and their corresponding vulnerability factor?
- If one of the selected indicators fails, can it be assumed that the maximum mortality immediately applies?
  - If this is not the case: to what extent is the maximum mortality reached per flood preparedness indicator and what is the time dependency of this mortality?
- What are the estimated costs per flood measure?
- To what extent do you think does quantification of flood impact on hospitals aid flood measure decision-making at hospitals?

Stakeholder engagement

- Which parties should be involved per flood measure for the implementation?
- How should the decision-making for flood measures be secured? What are the corresponding pros and cons?
- How should stakeholders be engaged for the implementation of flood measures be secured? What are the corresponding pros and cons?

D. Reinier de Graaf Gasthuis case: indirect impact per flood scenario

Regional 100

This scenario is described in Chapter 5.

Precipitation 1000

Heavy precipitation events usually occur locally. Hence, it should be noted that it is unlikely that all suppliers and the hospital are flooded simultaneously as a consequence of precipitation. This remark applies to all precipitation scenarios discussed in this research.

Stedin
The precipitation leads to water accumulation in the street of the HV substation of approximately 0,20m at the façade of the building (see Figure D.1). However, the building is elevated 0,30m above ground level. The underground power grid is assumed to be unaffected by floods. Therefore, this event will not threaten the power supply.

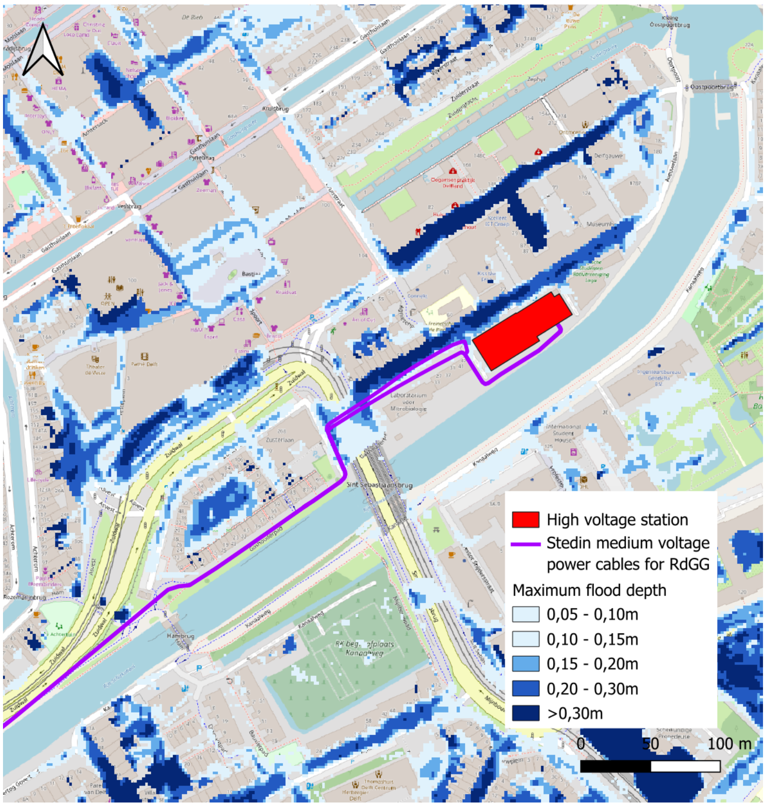


Figure D.1: Precipitation at the HV substation that supplies electricity to the RdGG. The depicted flood scenario is "Precipitation 1000". The building remains available.

Evides
The production location in Kralingen can experience some nuisance from such an extreme rain event: a flood depth of approximately 0,10m (or +4,80m NAP) is expected (see Figure D.2). Therefore, the operations are assumed to come to a halt. The water grid remains unaffected.

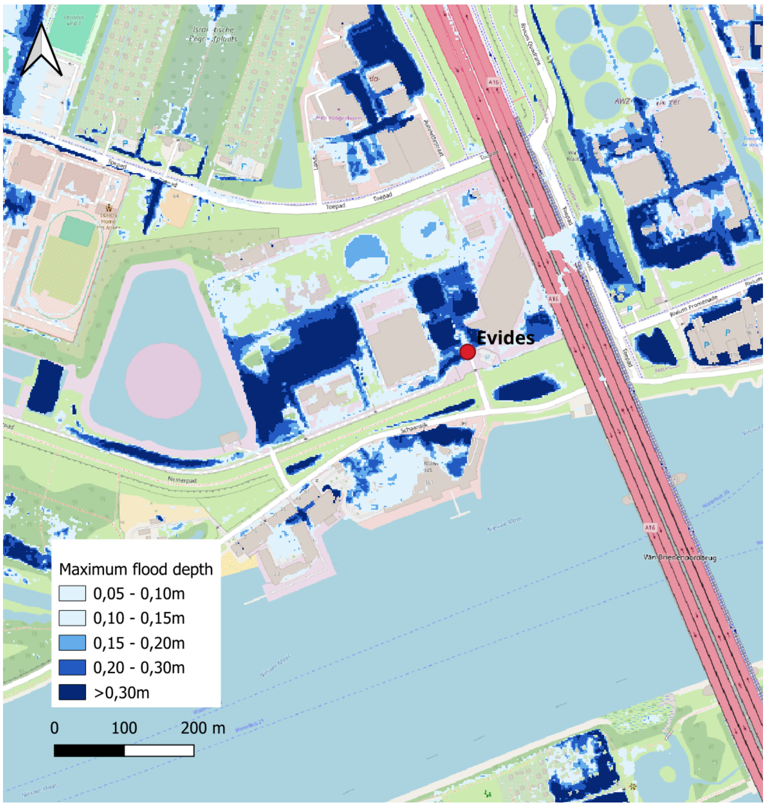


Figure D.2: Precipitation at the drinking water supplier Evides. The depicted flood scenario is "Precipitation 1000". The company is temporarily unavailable.

Delfluent

According to the LIWO, the water treatment plant is unaffected by the precipitation (see Figure D.3). It is assumed that the same applies to the underground sewage system.

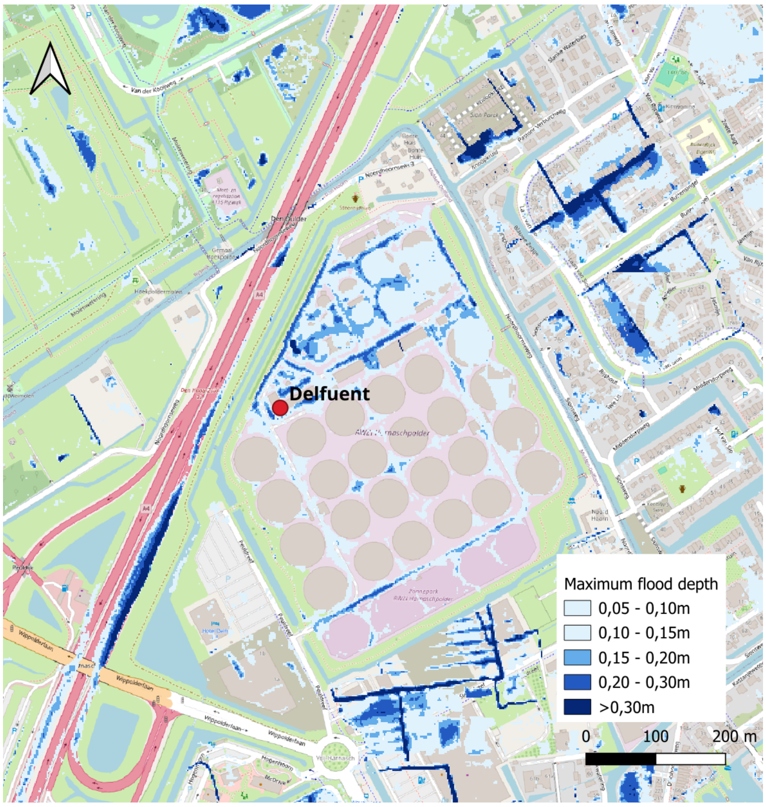


Figure D.3: Precipitation at the water treatment plan Delfuent. The depicted flood scenario is "Precipitation 1000". The plant remains available.

ZorgserviceXL
The company is not flooded by this scenario. However, on the route to the hospital, in the direct vicinity of ZorgserviceXL, flood depths of more than 0,30m are expected (see Figure D.4). Therefore, it is assumed that delivery of supplies is temporarily impossible. The road blockage is expected to last only several hours.

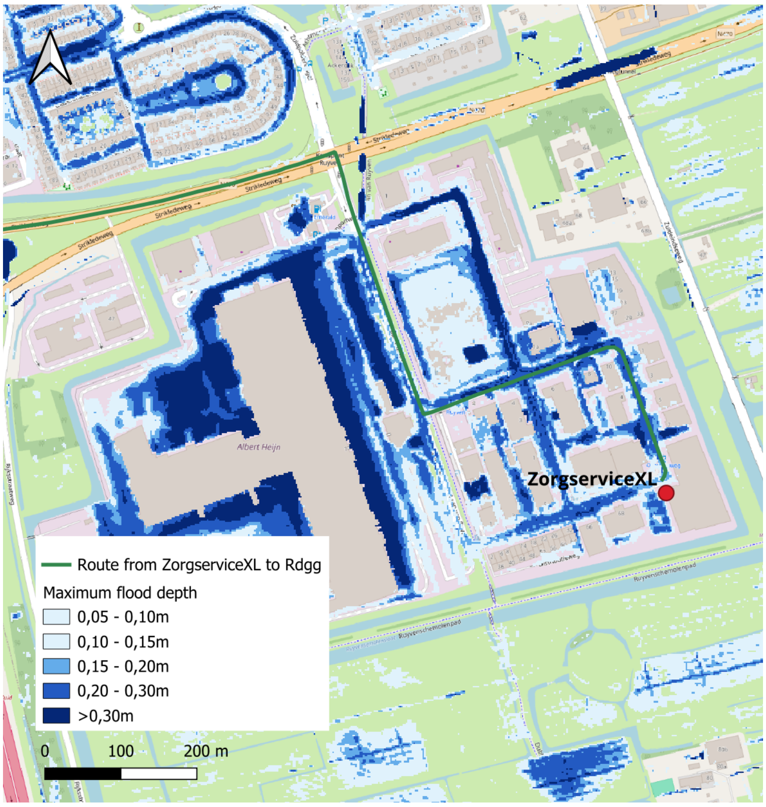


Figure D.4: Precipitation at ZorgserviceXL. The depicted flood scenario is "Precipitation 1000". Delivery is impossible due to flooded roads.

Combi-Ster
Combi-Ster is not threatened by a precipitation scenario. A part of the route to the hospital is flooded by more than 0,30m of water (see Figure D.5). This part cannot be avoided. Thus, it is expected that delivery will be interrupted for several hours.

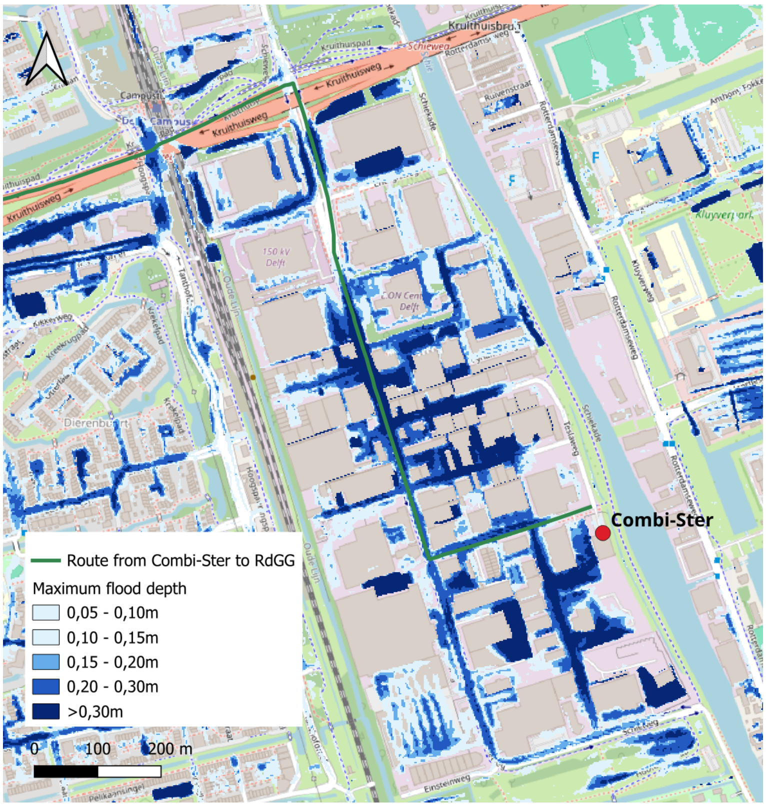


Figure D.5: Precipitation at Combi-Ster. The depicted flood scenario is "Precipitation 1000". Delivery is impossible due to flooded roads.

Linde Gas
The building is not flooded during such an event. The roads to the hospital are partly flooded, but by a maximum of 0,20m (see Figure D.6). Delivery can continue.

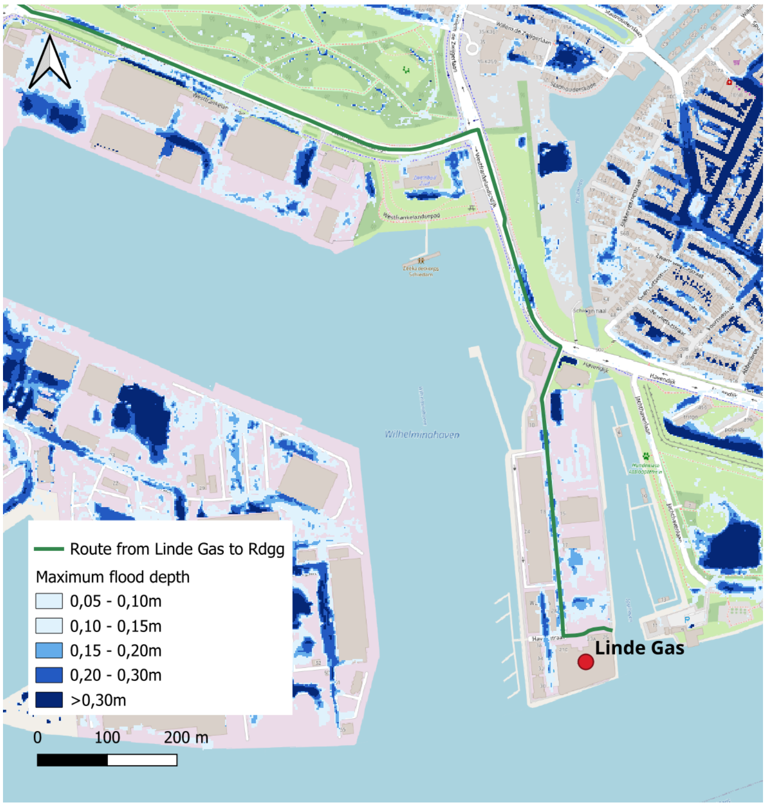


Figure D.6: Precipitation at Linde Gas. The depicted flood scenario is "Precipitation 1000". Delivery is can continue.

Fuel companies
Fuel can be delivered by several fuel companies. The hospital does not become isolated because of water accumulation caused by this precipitation event. Therefore, it is concluded that fuel delivery remains possible.

Personnel
For the "Precipitation 1000" scenario, it is expected that sufficient and and qualified personnel is available and able to reach the RdGG. The hospital remains accessible, since the access roads are flooded up to no more than 0,20m. Nevertheless, it may be possible that some employees are unable to reach the hospital due to local conditions.

Precipitation 100

Stedin
The precipitation leads to water accumulation in the street of the HV substation of approximately 0,15m at the façade of the building. However, the building is elevated 0,30m above ground level. The underground power grid is assumed to be unaffected by floods. Therefore, this event will not threaten the power supply.

Evides
The production site in Kralingen experiences water accumulation, but the buildings and water grid are not threatened (see Figure D.7). Hence, it is expected that water production can continue.

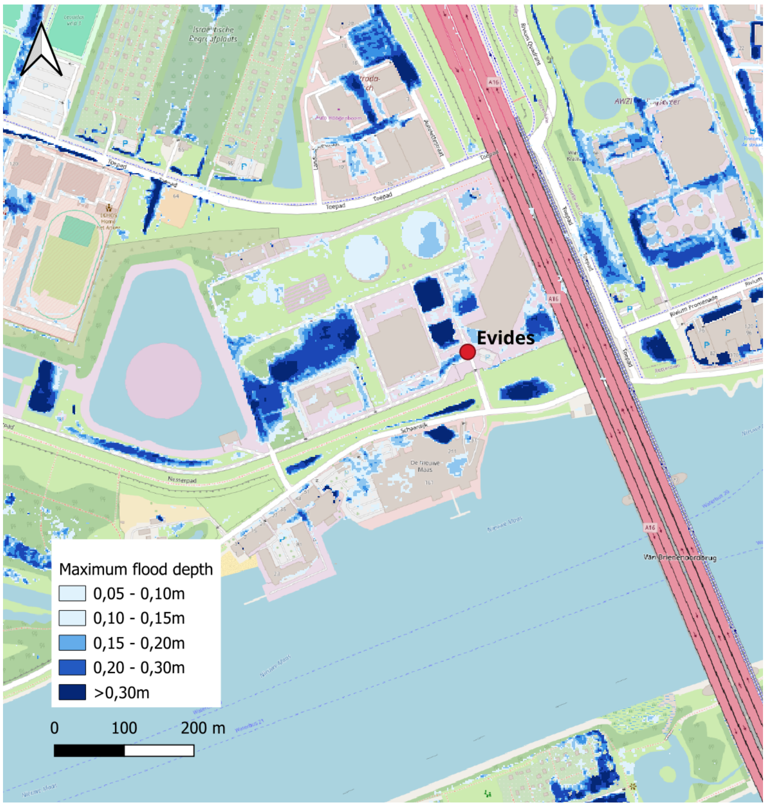


Figure D.7: Precipitation at the drinking water supplier Evides. The depicted flood scenario is "Precipitation 100". The company remains available.

Delfluent
The water treatment plant and the underground sewage system remain available.

ZorgserviceXL
The building is not flooded. The route to the hospital is partly flooded, but at most by 0,20m (see Figure D.8). Delivery is expected to continue.

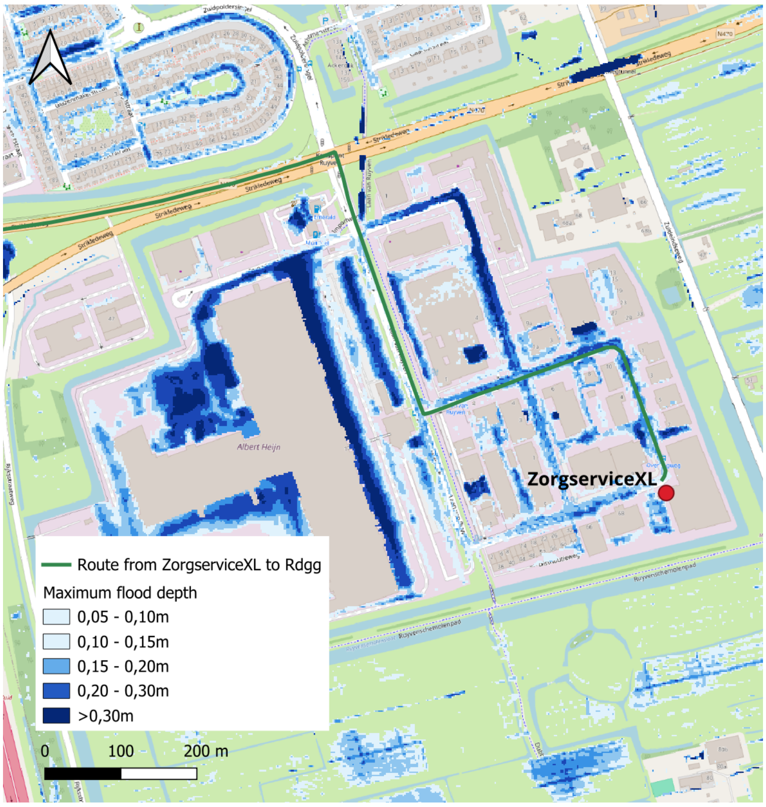


Figure D.8: Precipitation at ZorgserviceXL. The depicted flood scenario is "Precipitation 100". The company and road remain available.

Combi-Ster
The building is unaffected by the precipitation. However, a part of the route to the hospital is flooded by more than 0,30m of water (see Figure D.9). This part cannot be avoided. Thus, it is expected that delivery will be interrupted for several hours.

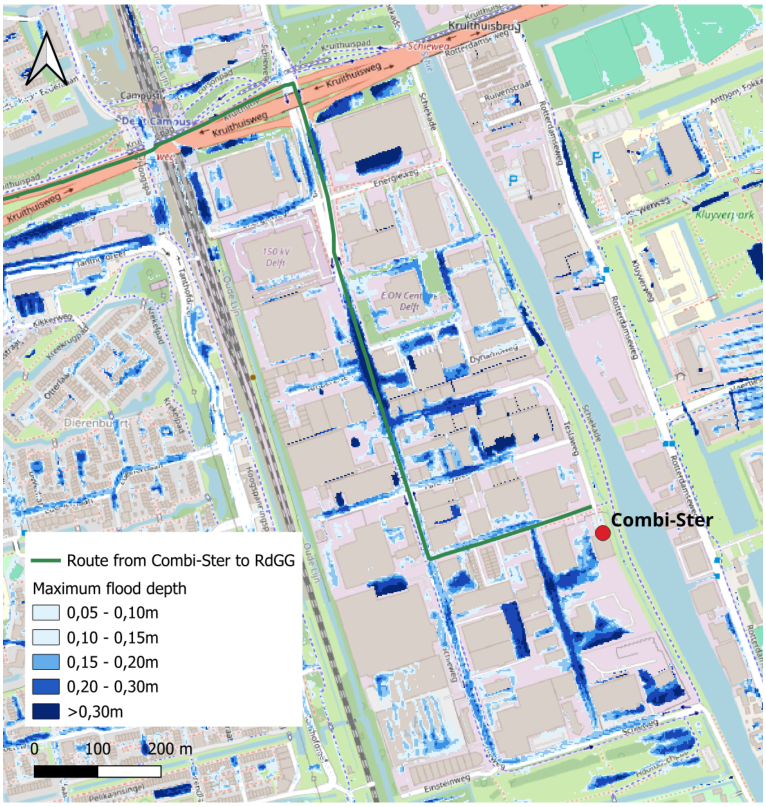


Figure D.9: Precipitation at Combi-Ster. The depicted flood scenario is "Precipitation 100". Delivery is impossible due to flooded roads.

Linde Gas
The building is not flooded during such an event. The roads to the hospital are partly flooded, but not more than 0,20m. Delivery can continue.

Fuel companies
Fuel can be delivered by several fuel companies. The hospital does not become isolated because of water accumulation caused by this precipitation event. Therefore, it is concluded that fuel delivery remains possible.

Personnel
For the "Precipitation 100" scenario, it is expected that sufficient and and qualified personnel is available and able to reach the RdGG. The hospital remains accessible, since the access roads are flooded up to no more than 0,20m. Nevertheless, it may be possible that some employees are unable to reach the hospital due to local conditions.

Precipitation 10

Stedin
This precipitation event does not cause water nuisance in the direct vicinity of the HV substation. The underground power grid is assumed to remain unaffacted by floods. The continuity of the power supply is not in danger.

Evides
Evides experiences water accumulation, but the buildings and water grid are not threatened. Hence, it is expected that water production can continue.

Delfluent
The water treatment plant and the underground sewage system remain available.

ZorgserviceXL
The building is not expected to be flooded. The route to the hospital is partly flooded, but no more than 0,20m. It is expected that deliveries can still take place.

Combi-Ster
The building remains unaffected by the rain. The route to the hospital is partially flooded, but no more than 0,20m (see Figure D.10). It is assumed that delivery can continue.

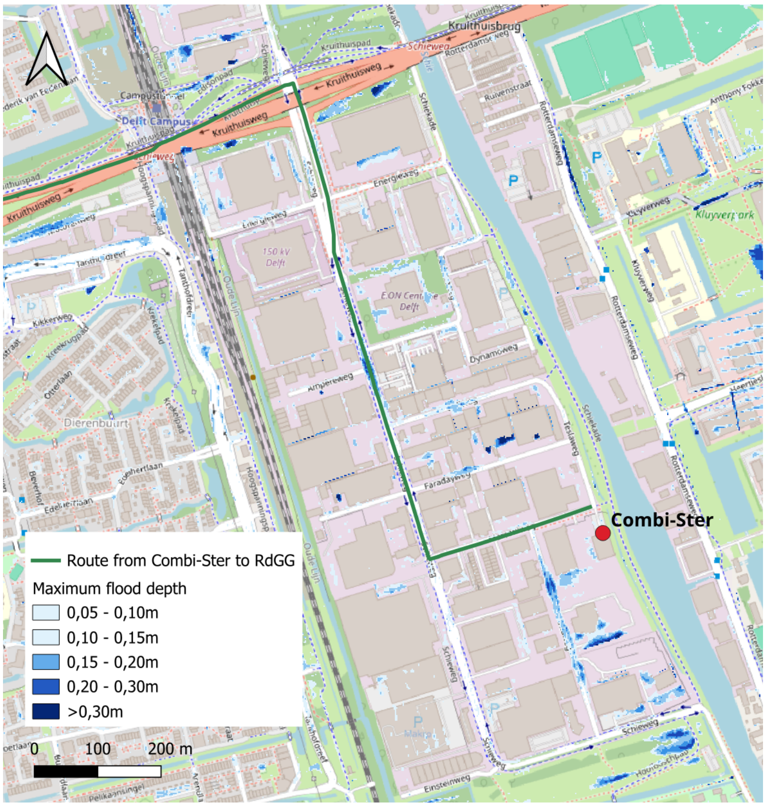


Figure D.10: Precipitation at Combi-Ster. The depicted flood scenario is "Precipitation 10". Deliver of supplies is possible.

Linde Gas
The building is not flooded during such an event, neither are the roads to the hospital. Delivery can continue.

Fuel companies
Fuel can be delivered by several fuel companies. The hospital does not become isolated because of water accumulation caused by this precipitation event. Therefore, it is concluded that fuel delivery remains possible.

Personnel
For the "Precipitation 10" scenario, it is expected that sufficient and and qualified personnel is available and able to reach the RdGG. The hospital remains accessible, since the access roads are flooded up to no more than 0,15m. Nevertheless, it may be possible that some employees are unable to reach the hospital due to local conditions.

E. Erasmus MC case: indirect impact per flood scenario

Parksluizen 1

Fuel companies - Stocks
As depicted in Figure E.1, the EMC becomes isolated due to the "Parksluizen 1" flood scenario. Similar to the "Parksluizen 2" flood scenario, the primary flood defence on the north side of the Meuse is breached at "Parksluizen". Either sides of the dyke (Westzeedijk) will be flooded. The dyke itself could provide access to the hospital, but may be damaged by the storm. Therefore, the availability of the road on top of the dyke cannot be guaranteed. Due to the isolation of the hospital, it is expected that no fuel company can reach the EMC to deliver fuel. All access roads to the EMC are flooded by more than 0,20 metres.

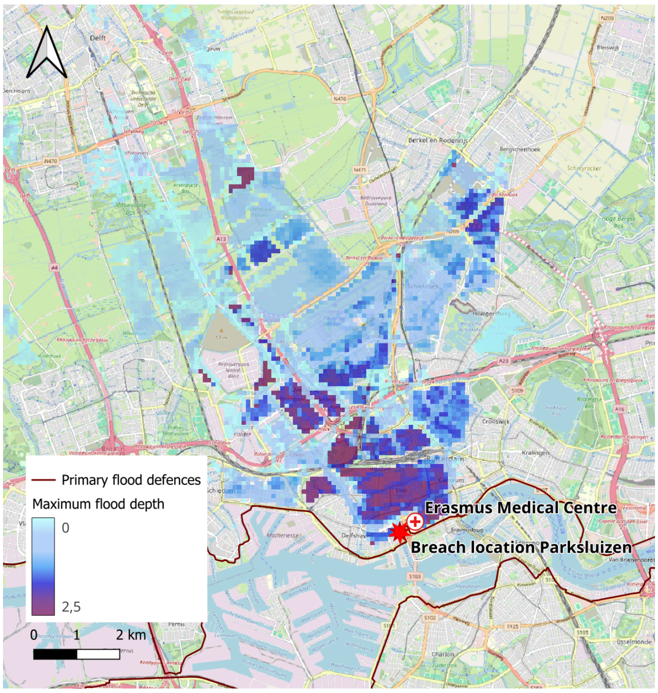


Figure E.1: Flood depth map resulting from a breach at Parksluizen. The depicted flood scenario is "Parksluizen 1". The EMC is expected to become isolated during this flood scenario.

Linen supplier (Nedlin Healthcare) - Stocks

Nedlin Healthcare supplies linen to the EMC. The company is located in Elsloo, in the province of Limburg. Nedlin Healthcare is not threatened by the "Parksluizen 1" flood scenario. However, the access road to the EMC is not available due to flooding (see Figure E.2) and no alternative routes are available due to isolation of the hospital.

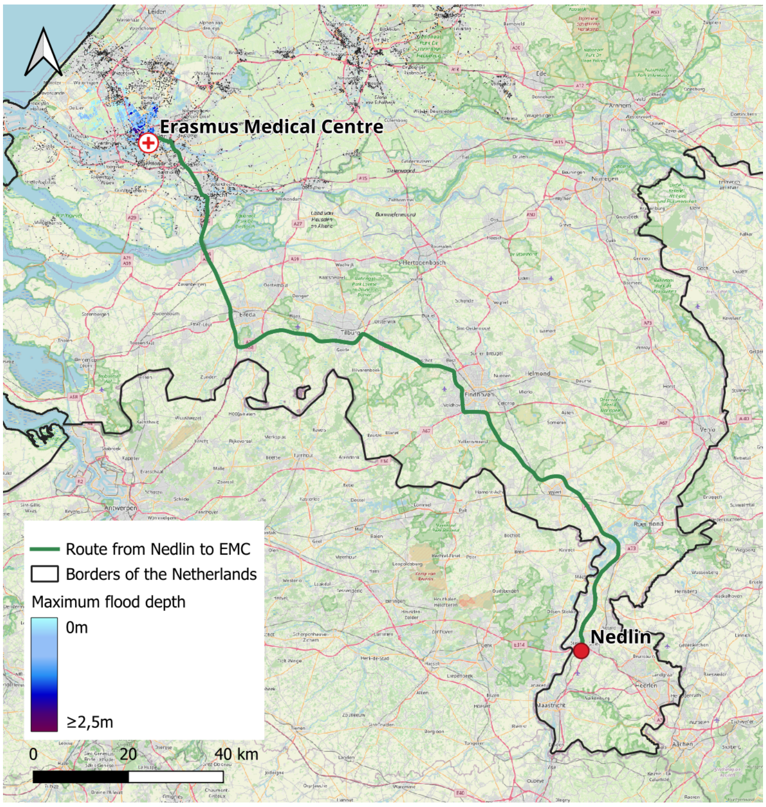


Figure E.2: Route from Nedlin Healthcare to the EMC. The depicted flood scenario is "Parksluizen 1". The route is inaccessible near the EMC.

Medical gas supplier (Linde Gas) - Stocks
The company Linde Gas supplies the EMC with medical gases. The supplier is located in Schiedam and is not threatened by the "Parksluizen 1" flood scenario. The route from Linde Gas to the EMC is depicted in Figure E.3. The route near the hospital is inaccessible due to flooding, as the route crosses the breach location.

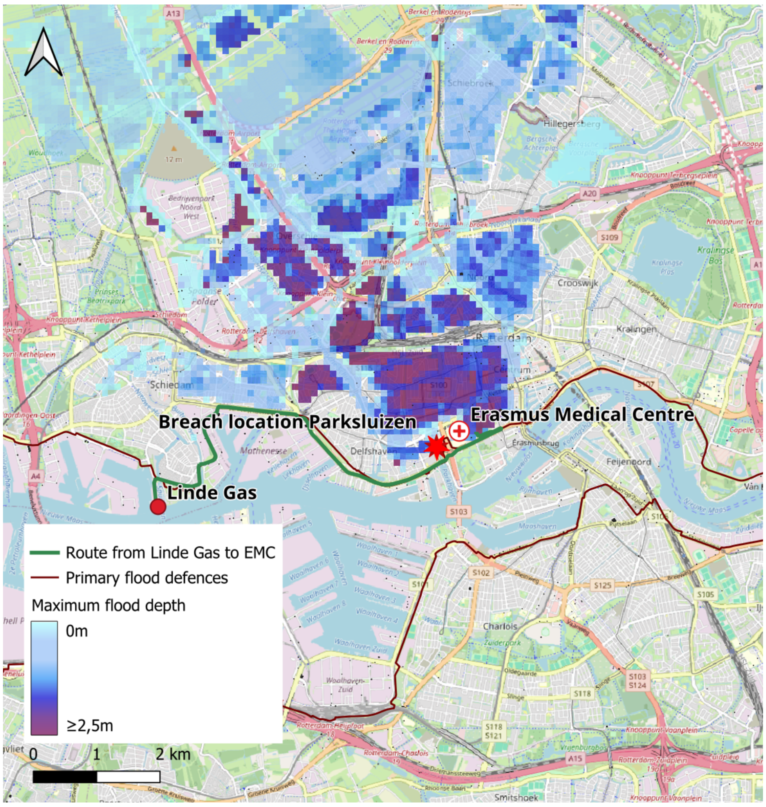


Figure E.3: Route from Linde Gas to the EMC. The depicted flood scenario is "Parksluizen 1". The route is inaccessible near the EMC.

Medical supplies (distribution centre) - Stocks

The EMC has its own distribution centre that stores and delivers medical supplies. The distribution centre is located on the other side of the river Meuse and cannot be flooded by the ”Parksluizen 1” flood scenario. However, during this scenario, the route near the EMC is flooded and therefore inaccessible (see Figure E.4).

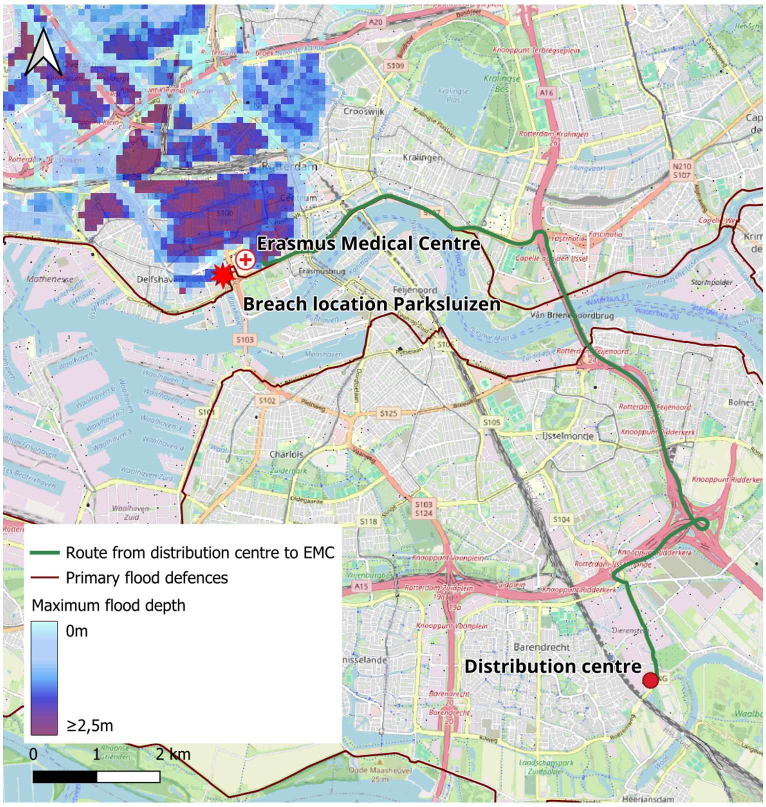


Figure E.4: Route from the distribution centre to the EMC. The depicted flood scenario is ”Parksluizen 1”. The route is inaccessible near the EMC.

Medicine supplier (Alliance Healthcare) - Stocks
Medicines are supplied by the company Alliance Healthcare, which is located in Veghel. This company is not threatened by any the "Parksluizen 1" flood scenario. Delivery of supplies cannot take place during the "Parksluizen 1" flood scenario, because the road near the hospital is flooded (see Figure E.5).

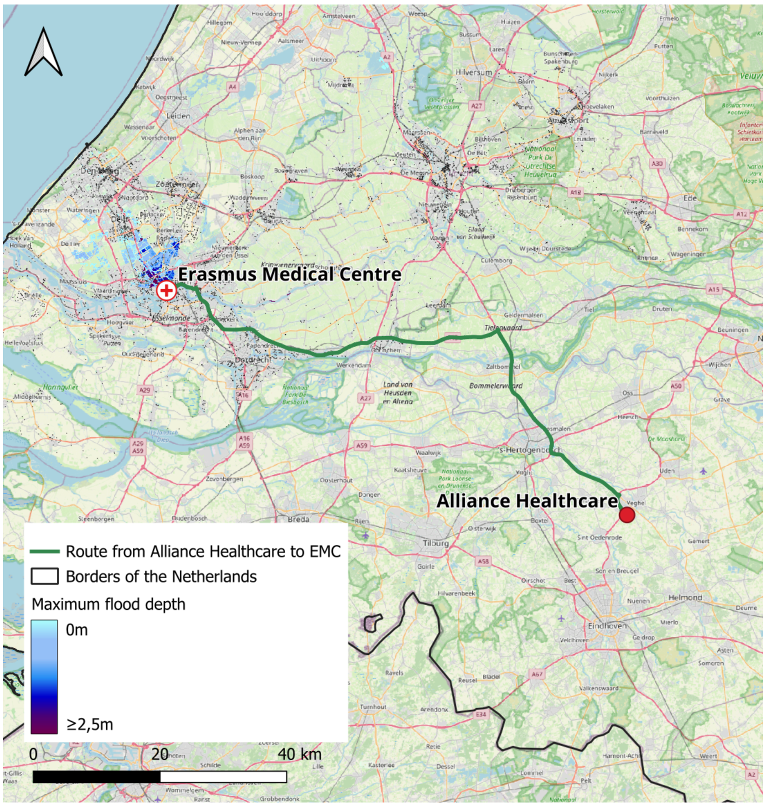


Figure E.5: Route from Alliance Healthcare to the EMC. The depicted flood scenario is "Parksluizen 1". The route is inaccessible near the EMC.

Drinking water supplier (Evides, Berenplaat) - Utilities
Drinking water is supplied by Evides by the production sites Berenplaat and Kralingen (Kolen et al., 2017). The production site Berenplaat cannot be flooded by the "Parksluizen 1" flood scenario. The water grid is assumed to remain unaffected by floods. Therefore, the supply of drinking water remains available.

Drinking water supplier (Evides, Kralingen) - Utilities
The production site Kralingen was previously analysed for the RdGG (see Appendix D). This location is not affected by the "Parksluizen 1" flood scenario. The water grid is assumed to remain unaffected by floods. Therefore, the supply of drinking water remains uninterrupted.

Electricity supplier (Stedin) - Utilities
The EMC has several connections to the power grid spread across the hospital terrain. The hospital has two 23KV connections, each connecting to a different power grid. In addition, there are three 10KV connections (Kolen et al., 2017). Although underground cables are assumed to remain unaffected by floods, the MV substations in the direct vicinity of the hospital are flooded during the "Parksluizen 1" flood scenario. Although no single critical flood level can be determined, it can be assumed that a flood depth of more than one metre in the vicinity of the EMC causes failure of the electricity supply.

Personnel - Personnel
For the "Parksluizen 1" flood scenario, it is expected that there will not be sufficient and qualified personnel available without implementation of specific measures. The flooded area is extensive, covering large densely populated parts of the city Rotterdam. The flood depth in these areas is also significant, reaching a flood depth of more than 1 metre. In addition, the hospital becomes isolated. These factors contribute to the assessment that personnel cannot reach the EMC.

F. Flood preparedness indicator sources

Table F.1: Sources per flood indicator.

Indicator	Sources
Critical equipment	Balsari et al. (2016); Barten et al. (2022); Batica and Gourbesville (2014); Kolen et al. (2017) McGinty et al. (2017); Rattanakanlaya et al. (2021); Rentschler et al. (2021); Tarabochia-Gast et al. (2022); Van Beek et al. (2015); Van der Wal et al. (2023); World Health Organization (2015); World Health Organization (2017); Zane et al. (2010); Zhong et al. (2021); Interview RdGG; Interview EMC
Stocks	Balsari et al. (2016); Batica and Gourbesville (2014); Kolen et al. (2017) McGinty et al. (2017); Rattanakanlaya et al. (2021); Rentschler et al. (2021); Tarabochia-Gast et al. (2022); Van Beek et al. (2015); Van der Wal et al. (2023); World Health Organization (2015); World Health Organization (2017); Zane et al. (2010); Zhong et al. (2021); Interview RdGG; Interview EMC; Interview RWS
Utilities	Balsari et al. (2016); Barten et al. (2022);

Continued on the next page.

Indicator	Sources
	Batica and Gourbesville (2014); Kolen et al. (2017) McGinty et al. (2017); Rattanakanlaya et al. (2021); Rentschler et al. (2021); Tarabochia-Gast et al. (2022); Van Beek et al. (2015); Van der Wal et al. (2023); World Health Organization (2015); World Health Organization (2017); Zane et al. (2010); Interview RdGG; Interview EMC; Interview RWS
Transport of patients	Balsari et al. (2016); Barten et al. (2022); Rattanakanlaya et al. (2021); Rentschler et al. (2021); Tarabochia-Gast et al. (2022); Van der Wal et al. (2023); World Health Organization (2015); World Health Organization (2017); Zane et al. (2010); Zhong et al. (2021); Interview RdGG; Interview EMC; Interview RWS
Accessibility	Balsari et al. (2016); Barten et al. (2022); Batica and Gourbesville (2014); Rattanakanlaya et al. (2021); Rentschler et al. (2021); Tarabochia-Gast et al. (2022); Van Beek et al. (2015); World Health Organization (2015); Zane et al. (2010); Interview RdGG; Interview EMC
Emergency management capacity	Balsari et al. (2016); Barten et al. (2022); McGinty et al. (2017); Rattanakanlaya et al. (2021); Rentschler et al. (2021); Van Beek et al. (2015);

Continued on the next page.

Indicator	Sources
	Van der Wal et al. (2023); World Health Organization (2015); Zhong et al. (2021); Interview RdGG; Interview EMC
Personnel	Balsari et al. (2016); Rattanakanlaya et al. (2021); Rentschler et al. (2021); Tarabochia-Gast et al. (2022); Van Beek et al. (2015); Van der Wal et al. (2023); World Health Organization (2015); World Health Organization (2017); Zane et al. (2010); Zhong et al. (2021)
Structural integrity	Barten et al. (2022); Van Beek et al. (2015); World Health Organization (2015); Zane et al. (2010); Zhong et al. (2021)
Financing	McGinty et al. (2017); Rattanakanlaya et al. (2021); Rentschler et al. (2021); World Health Organization (2015)
Patient capacity	Rentschler et al. (2021); Tarabochia-Gast et al. (2022); World Health Organization (2015); Zhong et al. (2021)
Safeguarding personnel's family	Rattanakanlaya et al. (2021); World Health Organization (2015)

Literature sources

Balsari, S., Patrick, K., Perry, K., & Leaning, J. (2016). *The Surge After the Storm*. Harvard T.H. Chan School of Public Health.

Barten, D. G., Fijten, M. H., Gaakeer, M. I., Klokman, V. W., Mortelmans, L. J., Van Osch, F., Peters, N. A., Wijnands, J. J., Tan, E. C., & Boin, A. (2022). Three decades of hospital evacuations in the netherlands: A scoping review. *International Journal of Disaster Risk Reduction*, *81*, 103252. https://doi.org/10.1016/j.ijdrr.2022.103252

Batica, J., & Gourbesville, P. (2014). Flood resilience index - methodology and application. In *11th international conference on hydroinformatics*. City University of New York. https://academicworks.cuny.edu/cgi/viewcontent.cgi?article=1432&context=cc_conf_hic

Kolen, B., Groot, S., & Bierens, J. (2017). *Synthese quick-scan ruimtelijke adaptatie voor ziekenhuizen: Op basis van 3 pilots voor overstromingen en extreme neerslag* (PR3483.10). HKV lijn in water.

McGinty, M., Burke, T. A., Resnick, B., Barnett, D. J., Smith, K. C., & Rutkow, L. (2017). Decision processes and determinants of hospital Evacuation and Shelter-in-Place during Hurricane Sandy. *Journal of public health management and practice*, *23*(1), 29–36. https://doi.org/10.1097/phh.0000000000000404

Rattanakanlaya, K., Sukonthasarn, A., Wangsrikhun, S., & Chanprasit, C. (2021). Improving flood disaster preparedness of hospitals in Central Thailand: Hospital personnel perspectives. *Journal of Clinical Nursing*, *31*(7-8), 1073–1081. https://doi.org/10.1111/jocn.15971

Rentschler, J., Klaiber, C., Tariverdi, M., Desjonquères, C., & Mercadante. (2021). *Frontline: Preparing healthcare systems for shocks, from disasters to pandemics.* Washington, DC, The World Bank. https://www.worldbank.org/en/news/feature/2021/04/13/frontline-preparing-healthcare-systems-for-shocks

Tarabochia-Gast, A. T., Michanowicz, D. R., & Bernstein, A. S. (2022). Flood risk to hospitals on the united states atlantic and gulf coasts from hurricanes and sea level rise. *GeoHealth*, *6*(10). https://doi.org/10.1029/2022gh000651

Van Beek, G., Calon, M., Van Heumen, S., Traversari, A., & Verhoeff, O. (2015). Waterrobuustheid Nederlandse ziekenhuizen. *TNO*, (TNO 2015 R11234). Retrieved January 12, 2024, from https://publications.tno.nl/publication/34618516/IolCPy/TNO-2015-R11234.pdf

Van der Wal, W., Barten, D. G., Ketelings, L., Van Osch, F., Rao, M., Mortelmans, L., & Bierens, J. (2023). Addressing a climate emergency amidst the covid-19 pandemic: A mixed-methods study on a hospital evacuation during the 2021 european floods. *medRxiv (Cold Spring Harbor Laboratory)*. https://doi.org/10.1101/2023.02.02.23285386

World Health Organization. (2015). *Hospital safety index: Guide for evaluators* (2nd ed.). https://www.who.int/publications/i/item/9789241548984

World Health Organization. (2017). *Flooding: managing health risks in the WHO European Region*. https://iris.who.int/handle/10665/329518

Zane, R., Biddinger, P., Hassol, A., Rich, T., Gerber, J., & DeAngelis, J. (2010). *Hospital evacuation decision guide* (No. 10-0009). Cambridge, MA, Abt Associates Inc.

Zhong, S., Cheng, Q., Huang, C., & Wang, Z. (2021). Establishment and validation of health vulnerability and adaptation indices under extreme weather events on the basis of the 2016 flood in anhui province, china. *Advances in Climate Change Research*, *12*(5), 649–659. https://doi.org/10.1016/j.accre.2021.07.002

G. Individual Double Degree study load specification

This thesis was written in partial fulfilment of the master's degrees in Civil Engineering (CE) and Construction Management & Engineering (CME) at the Delft University of Technology. The two programmes have been combined in an IDD. The added value of integrating two theses is that their contents can contribute to each other. This thesis is worth 40 EC, which consists of 30 EC for CE and 30 EC for CME, with a shared study load of 20 EC.

SQ1 and *SQ2* are part of CE. The CE part analysed the impact of floods on hospitals, given a certain level of flood preparedness, by modelling healthcare continuity at hospitals with a series system. The flood impact was quantified in terms of fatalities and types of costs. These results enabled comparison of flood strategies, which can be used to improve flood preparedness of hospitals. The corresponding results can be found in Chapters 4 and 5.

SQ3 and *SQ4* are part of CME. The CME part elaborated on the flood strategies, by focusing on which stakeholder should be engaged for the implementation of each flood strategy. Theories on stakeholder analysis, categorisation and engagement were used to come to a selection of stakeholders per flood strategy. Subsequently, expert interviews were used to obtain recommendations from experts with lived experience for the engagement of the selected stakeholders. These results are discussed in Chapter 6.

Overlap between the two programmes mainly resides with the identification of the stakeholders (part of *SQ3*), the case study and interviews. The case study and interviews were used as basis for answering all four SQs. The phase 1 interviews were used to obtain information about hospital facilities and their vulnerability, relevant for determining the flood impact, and to identify stakeholders. The phase 2 interviews were used to evaluate the method for assessment of hospitals' flood preparedness and for identifying experts' views on methods for stakeholder engagement. The cases and interviews are introduced in Chapter 3 and are used through the following chapters. The interview questions are listed in Appendices B and C.