Delft University of Technology

Master of Science Thesis

Flexible evacuation method

Minimize loss of life probability for a given flood threat

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Abstract

Some 60% of the Netherlands is prone to flooding and throughout time our country has experienced flooding problems. With an increasing population and on-going climate change, there is a growing attention for flood risk reducing measures. Evacuation is one such measure.

In case of a flood threat, evacuation can reduce loss of life by moving people to safe(r) locations. There are two basic evacuation strategies. The first concerns vertical evacuation where people will move inside the threatened area to a higher and dry place. The second concerns preventive evacuation where people will move from a threatened area to a safe location outside this area. Preventive evacuation leads in principle to a lower loss of life risk but, when unsuccessful (e.g. due to road blocking or insufficient time), people are more vulnerable to flooding than when evacuating vertically. It is noted that preventive evacuation requires significantly more time than vertical evacuation whilst the expected available time for evacuation in the Netherlands is often limited. Vertical evacuation as base strategy and using preventive evacuation as an additional option provided sufficient time is available is therefore considered most effective. More research however, is needed to establish the optimum evacuation strategy.

In this thesis, the flexible evacuation method is developed. The main objective of this method is to minimize the loss of life risk in case of a flood threat by, for an assumed available evacuation time, finding the optimum evacuation strategy as a combination of vertical and preventive evacuation.

Starting from the base strategy (vertical evacuation) the optimum strategy follows from the selection of zones for preventive evacuation. The prioritization of these zones is based on the loss of life risk when opting for the base strategy (assuming both sheltering at home and public sheltering). Zones ranking highly in this prioritization, also referred to as critical zones, are characterized by a relatively high conditional flood probability, severe flood characteristics and/or poor possibilities for vertical evacuation. In case of preventive evacuation, the impact on traffic intensity with respect to the maximum road capacity is taken into account.

Prior to applying the flexible evacuation method to a case study on Rotterdam North, a simplified example study is carried out to test the potential of the method. As part of this case study an inventory is made of capacities for public sheltering and sheltering at home for neighbourhoods in Rotterdam North. The capacity for sheltering at home is found to be abundantly available in all neighbourhoods. There is only limited capacity however, for public sheltering. Possibilities for preventive evacuation are investigated, including the impact of preventive evacuees from surrounding threatened areas.

The case study for Rotterdam North assumes a high-water level forecast and closure failure of the Maestlantkering. The optimum evacuation strategy is determined for a number of available evacuation times. Four potential dike failure locations, each with its own conditional failure probability, are considered. Per potential dike failure location one flood scenario based on the water level forecast is assumed. The optimum strategy results in a significant reduction of the expected loss of life as compared with 100% vertical or 100% preventive evacuation. This reduction increases when the available evacuation time increases.

Based on a sensitivity analysis the impact of changes in specific parameters (flood probability, road capacity, available evacuation time, water depth and public sheltering capacity) and boundary

conditions is investigated. The prioritization of zones for preventive evacuation was found to be rather insensitive especially to parameter changes when evenly applied over all zones. However, a change in available evacuation time or road capacity does impact on the optimum strategy as the maximum outflow capacity of the threatened area is affected. In case the road capacity is smaller or the available time shorter than forecasted, may increase the expected loss of life since people may be exposed to the flood whilst evacuating. It is therefore recommended to take account of the uncertainty in actual available evacuation time by incorporating probabilities and consequences into the flexible evacuation method. For the same reason decision time by authorities, in case of a flood threat, should be minimized.

The flexible evacuation method is considered to have potential for improving the current flood risk approach. Valuable time can be saved during the warm phase (when there is an actual flood threat) if preparatory work is carried out during the cold phase (when there is no flood threat). If during the warm phase one failure location appears to be (extremely weak), or some zones started already evacuating preventively, the model can quickly adapt to such new boundary conditions. Also changes in available evacuation time, for example due to postponing an evacuation call, can be handled. By taking risk reducing measures for zones that are critical in the prioritization, e.g. by improving public sheltering facilities, the expected loss of life in case of a flood threat can be reduced.

Preface

This thesis is written as the final step for completion of the Master of Science degree in Hydraulic Engineering at Delft University of Technology. Research for this thesis was supported by HKV-consultants, the Municipality of Rotterdam and the Hydraulic Engineering section at Delft University of Technology.

First of all, I am grateful to the members of my graduation committee: Matthijs Kok, the chairman of my committee, for the positive attitude and valuable feedback about my work. Bas Kolen for his expertise and enthusiasm for the research topic and the extraordinary support provided during the research. Nick van Barneveld for his interest from start to end, and for taking the view from the perspective of the municipality of Rotterdam. And Mark Voorendt, for all support and feedback to my research.

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Contents

1 Research Description

1.1 Research Introduction

One third of the Netherlands is location below sea level and a relatively large part (some 60%) of the Netherlands is flood prone. As a consequence there is always a thread of flooding. Throughout time, our country has experienced flooding problems of which the disaster of 1953 is most well-known. The flooding problems can arise from storm surges as well as high-water levels in the many rivers that flow through the Netherlands on their way to the sea.

In order to protect the millions of citizens from the consequences of flooding, the Netherlands have some 3500 kilometers of primary flood defenses. Figure 1 shows the maximum water levels that are predicted should these flood defenses fail. As can be seen, in some areas water depths exceeding 6 m can be reached. Many of these areas are found east of Rotterdam.

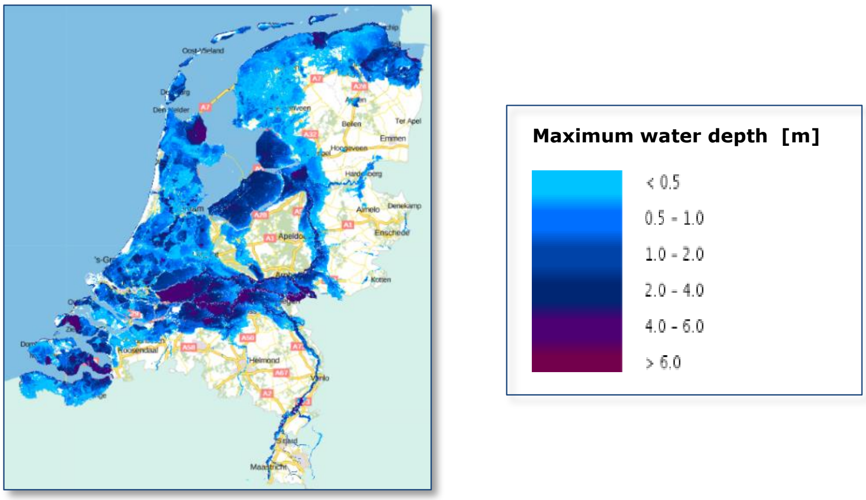

Figure 1: Maximum water depth in the Netherlands (LIWO)

Although the probability of flooding is considered to be small, the consequences of a flood can be severe, especially in highly populated areas. The storm surge of 1953 is the last major flood in the Netherlands with some 2000 square kilometers of land flooded and more than 1800 fatalities. After this disaster the Delta Commission was installed with the task of preparing a flood protection plan. They introduced strict requirements for flood defenses and introduced location dependent safety norms. These safety norms are based on pre-defined water levels that can occur once in so many years which the defense systems should be able to withstand.

Since the beginning of 2017 a multi-layer safety approach has been incorporated in the Delta program with the overall objective of reducing the loss of life probability due to flooding (Kok et al., 2017). The approach consists of three layers: 1) prevention 2) spatial planning and 3) crisis management. Also, new safety norms were introduced that are based on the probability of failure of flood defenses. It is now recognized that dike failure can also occur at lower water levels by taking into account several dike failure mechanisms.

Although the focus in the multi-layer approach is on the first layer, prevention against flooding, the possibility of flooding can never be completely ruled out. In a highly populated delta such as the Netherlands, with an increasing population and taking into account climate change, there is a growing attention for risk reducing measures. As part of spatial planning (the second layer), public shelter facilities can be considered and areas are designated that can be used for water buffering if needed. Also, in the planning of new buildings the possibility of flooding is often taken into account. Evacuation, as part of the third layer, is a measure to potentially reduce loss of life in case of a flood threat (Kolen, 2013). In case of a threat or incident, evacuation can be described as the process of moving people from a potentially dangerous location to a less dangerous location (Helsloot and Alphen, 2008).

Regarding evacuation, two basic types can be defined: preventive evacuation (moving people from a threatened area to a safe location outside the threatened area) and vertical evacuation (evacuation inside the threatened area to a higher and dry place). Research by Kolen (2013), showed that focusing on preventive evacuation may result in putting people at risk when the onset of actual dike failure is uncertain and time available is limited. People, for example, could get blocked in traffic and may be more vulnerable to the consequences of flooding. Kolen concluded that it is preferred to focus on vertical evacuation and use preventive evacuation only as an additional measure when sufficient time is available. People who evacuate vertically have to cope with the flood event on their own and need to survive in the threatened area often under primitive circumstances (e.g. due to fall out of utilities).

It is the task of authorities to facilitate self-reliance of people and inform them clearly about possible strategies and consequences. The Ministry of Safety and Justice (2014) proposed basic principles for large-scale evacuation which are, within the context of "Water & Evacuatie" specified further (Oberije and Rosmuller, 2017). Furthermore, the website "overstroomik.nl" has been launched with the objective of increasing people's awareness and helping them to prepare for and cope with a flood event, if this would occur. Further research however, is needed to find the optimum evacuation strategy as a mix of vertical and preventive evacuation in case of a flood treat whilst taking into account the uncertainty of available evacuation time and flood probabilities.

1.2 Problem Statement

Evacuation can be an important measure for reducing loss of life in case of a flood threat. Although the loss of life reduction resulting from evacuation seems straightforward, in practice, the effectiveness of evacuation strategies is variable since it depends on many (uncertain) elements, e.g. flood scenario, available time for evacuation, required time for evacuation, infrastructure, etc. Decision makers, both authorities and citizens, must deal with these uncertainties (Kolen, 2013). They carry great responsibility as wrong evacuation decisions may put people at higher risk, for example when preventive evacuees are exposed to be flood while moving (in their car).

During a large-scale flood threat, the emergency assistance that can be provided by authorities is limited (Kolen, 2013) as the available capacity for so doing may be insufficient. Responses by people at threat are therefore most likely difficult to control. Each person or a group of persons will act according to their own interpretation of the threat with the, in their opinion, appropriate measures (Helsloot and Ruiterberg, 2004). Their risk perception however, is not necessarily the best (Terpstra, 2009). Hence, there is a need to make people aware of the risks of flooding and the risks of preventive and/or vertical evacuation.

Two important parameters for evacuation planning include available and required time for evacuation (Barendregt, 2005 and Jonkman, 2007). When the available time for evacuation is less than time needed, people may be unprepared during a flood and a large number of fatalities can be expected. Therefore, evacuation must be complete before the onset of flooding (Rijkswaterstaat, 2014). If time can be saved during the lead phase, the effectiveness of evacuation can be increased significantly (Kolen and Helsloot, 2012).

In the case of a flood threat the emergency documents as currently used by the authorities mainly focus on preventive evacuation. In these documents, optimistic threats and impact scenarios are used deterministically based on old safety norms. Research shows however, that in case of a flood threat in the Netherlands, focusing on vertical evacuation and use preventive evacuation as an additional measure if time is available may be more effective for reducing expected loss of life. Regarding this point, it is noted that more research is needed to locally implement vertical evacuation as an effective strategy (Delta program, 2017).

Preventive evacuation leads in principle to a lower loss of life risk but, when unsuccessful (e.g. due to road blocking or insufficient time), people are more vulnerable to flooding than when evacuating vertically. It is noted that preventive evacuation requires significantly more time than vertical evacuation whilst the expected available time for evacuation in the Netherlands is often limited. Therefore, only a fraction of the people under threat can evacuate preventive safety (defined as *evacuation fraction*) as shown in Figure 2. By prioritization of preventive evacuation for people with the highest loss of life risk, the overall expected loss of life may be minimized. More research is needed for implementation of this prioritization.

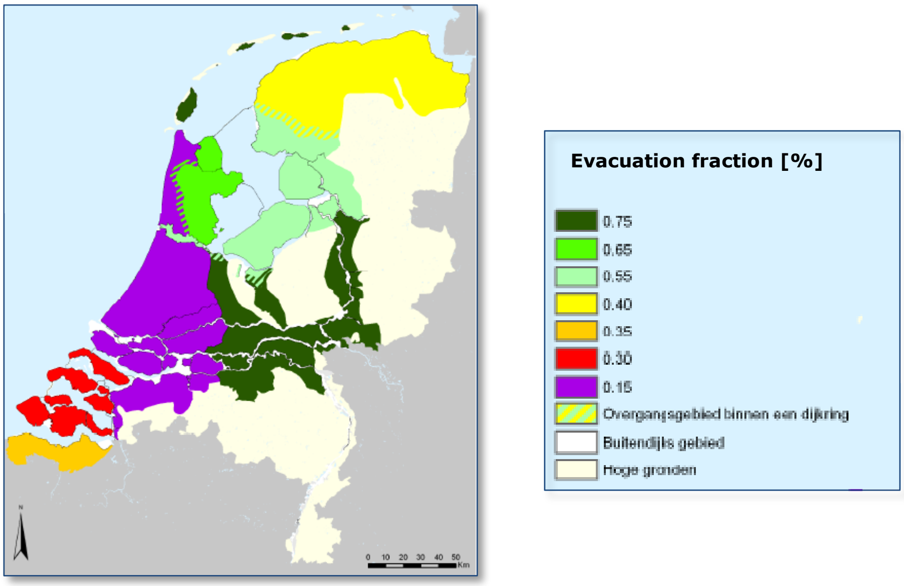

Figure 2: Average feasibility of preventive evacuation in the Netherlands (Kolen et al., 2013)

1.3 Research Question

The following research question is defined for this MSc. Thesis:

In case of a flood threat and given a call for evacuation, what is the optimum evacuation strategy by a combination of vertical and preventive evacuation, in order to minimize the risk for loss of life?

1.4 Research Objectives

The following main objective is defined for this MSc. Thesis:

To develop a method, which results in the minimum risk for loss of life for a given flood threat and available time, by separately determining the evacuation type for all zones within the threatened area.

The following four sub objectives are defined to support this main objective:

1. Carry out a literature study for the subjects of evacuation strategies, dike failure probabilities and flood scenarios.

2. Develop a generic method to quantify effectiveness of evacuation types (preventive and vertical) based on a given flood threat and available time

3. Prepare and investigate results of a simplified example study

4. Investigate possibilities for preventive and vertical evacuation (both sheltering at home and public sheltering) in Rotterdam North, and apply the method as developed on a case study in Rotterdam North

1.5 Research Scope

In the case of a flood threat, evacuation can reduce loss of life. Evacuation however, will have a severe impact on both economy and society. In this study an evacuation call is assumed to be given. In other words, the economic question as well as the societal impact of evacuation is left out of this research. Given the call for evacuation, the available time for evacuation is determined and the selection of the optimum evacuation strategy is in this study based solely on minimizing the expected loss of life whilst excluding other potential factors (such as economic impact and societal disruption).

Regarding the economic question, research by Veerhuis (2017) has shown that evacuation may be economic for flood probabilities of around 10%. For this research a human life is expressed as a monetary value. Figure 3 shows an example of the development of an evacuation decision over time as extracted from the research by Veerhuis. When the value of this decision is below 1, represented by the red dotted line, the call for evacuation is considered worthwhile (in this example from day 4). This thesis contributes to the decision model by estimating the expected loss of life parameter for different moments of decision making. The thesis also establishes how best to evacuate for different moments of decision making.

It should furthermore be noted that the flexible evacuation method of this thesis is a further development of the strategy builder as introduced by Kolen (2014), being an approach for large scale evacuation that affects multiple areas in case preventive evacuation capacities and emergency assistance is limited.

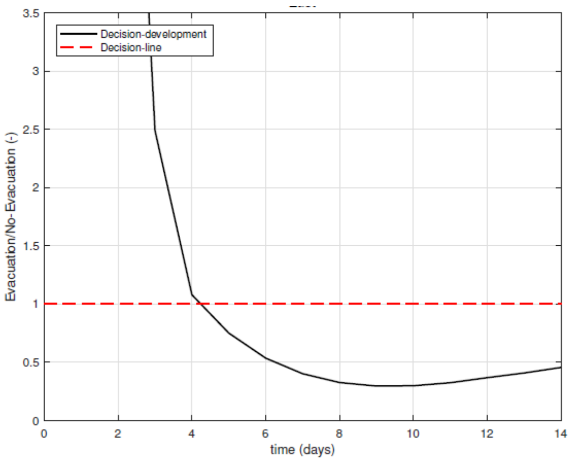

Figure 3: An example evacuation decision over time (Veerhuis, 2017)

1.6 Research Outline

This report starts with a general introduction on flood threat in the Netherlands and evacuation as part of the multi-layer safety approach. The introduction is followed by a research description. Chapter 2 summarizes relevant theory and background information regarding evacuation strategies. Chapter 3 presents a flexible evacuation method to quantify effectiveness of evacuation strategies for a given flood threat and available evacuation time. Besides, in this chapter an example study is performed and analyzed. In chapter 4 the flexible evacuation method is applied for a case study for Rotterdam North. In chapter 5 conclusions and recommendations are given for improving the developed method and case study results.

2 Theory and Background Information

2.1 Introduction

In the Netherlands, flood threats are dealt with by using a risk based approach. The fundamentals of such an approach are based on the well-known risk formulation:

$$Risk = Probability * Consequences$$

The risk based approach for a simple dike ring is illustrated in Figure 4. In order to reduce the probability or consequences of flooding a multi-layer safety approach is considered, which includes the following three layers (Kok et al., 2017):

1. *Prevention*: prevent a flood to occur by preparations prior to an actual flood threat

2. *Spatial planning*: reduce the potential impact of a flood by spatial planning prior to an actual flood threat

3. *Crisis management*: measures to reduce the impact of a flood in case an actual flood threat

Regarding this approach, prevention is considered to be most important. Evacuation as part of crisis management, however, is considered to be a crucial measure for reducing the current or future flood risk (Kok et al., 2017).

Figure 4: Graphical representation of the risk based approach (VNK, 2015)

Section 2.2 will discuss the overall uncertainties regarding evacuation planning. Section 2.3 will explain the effectiveness of different types of evacuation strategies and section 2.4 will discuss the flood probability which includes the theory of conditional dike failure probabilities using fragility curves and a basic approach to deal with flood scenario probabilities.

2.2 Key evacuation elements

Evacuation can be defined as the movement of people (evacuees) from a dangerous location to a less dangerous location because of a threat or incident (Helsloot and Alphen, 2008). The following phases can be described in an evacuation process (based after: Kolen and Helsloot, 2012):

- *Phase 0*: This phase represents the a normal-life situation prior to the recognition of a threat. During this phase, also denominated as the *cold phase*, one can gather valuable information which is required during a period of threat.

- *Phase 1*: The period of detection and recognition of a threat

- *Phase 2*: The phase during which evacuation decisions are taken and implemented

- *Phase 3*: The actual evacuation period. Evacuation should be complete before the onset of flooding (Rijkswaterstaat, 2014)

- *Phase 4*: The period during which people in the exposed areas may be dependent on their own (or only get limited assistance)

  (Note that phases 2 -4 are denominated as the *warm phase*.)

The effectiveness of the evacuation process is strongly dependent on the following four (uncertain) elements): *threat and impact*, *decision making by authorities*, *environment and traffic infrastructure* and *citizens response* (Kolen, 2013). These elements are discussed in the upcoming sections.

2.2.1 Threat and impact

A flood threat is recognised when high hydraulic loads on flood defences, mainly described by water level [m] or river discharge [m^3/s], are forecasted. Corresponding dike failure probabilities can be described by means of fragility curves (as discussed in section 2.4.2).

Information on the potential impact of an upcoming flood event is essential for effective evacuation planning. The characteristics of a flood in exposed areas can be described in terms of water depth, flow velocity and rise speed of the water. A range of possible flood events can be described in terms of scenarios (below normative, normative, above normative or extreme) and is dependent on the dike failure location, elevation of the area behind the failure location and volume of water flowing into the area behind the dike (Kok et al., 2017). Since water level forecasts and dike strengths are uncertain, many flood scenarios can be considered. The impact of a flood scenario is dependent on the number of people located in the affected area(s), possible fall-out of utilities and possibilities for evacuation in the threatened areas. The relation between flood characteristics and people’s safety is discussed in more detail in section 2.3.2.

Regarding *phase 3* (the actual evacuation period), the available and required evacuation time heavily impact on the effectiveness of the evacuation. A schematic representation of the available and required evacuation time is shown in Figure 5. In this example the available time for evacuation exceeds the required time for complete (preventive) evacuation as shown by the blank space just before onset of flooding. The available time for evacuation as compared to the actual required time, which are both highly uncertain, can be classified in terms of *optimistic* or *pessimistic* (Kolen and Huizinga, 2017).

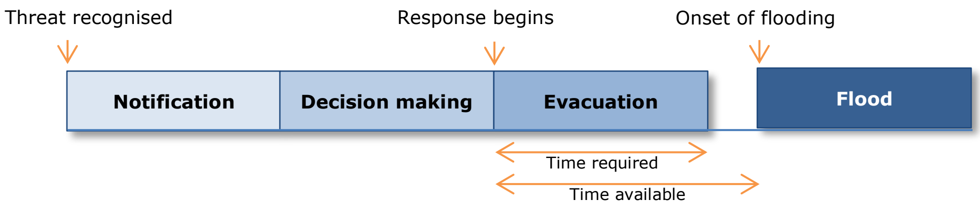

Figure 5: Representation of the time required and available for evacuation (after: Barendregt and van Noortwijk, 2004)

2.2.2 Decision making by authority

During the transition phase, decisions will have to be made and communicated to the public without losing precious time. First priority in the case of a large-scale flood threat is saving people's life's (Rijkswaterstaat, 2014). Possible evacuation types that can be applied are:

- *Preventive evacuation:* The organisation and horizontal movement of people from a potentially threatened area to a safe location outside the threatened area prior to the onset of the flood. The fraction of inhabitants able to evacuate preventive successfully is defined as the evacuation fraction.

- *Vertical evacuation*: The organisation and movement of people to a dry and safe location within the threatened area and prior to the onset of the flood

  - *Shelter at home*: The organisation and movement of people to a dry and safe floor at private homes

  - *Public sheltering*: The organisation and movement of people to a designated collective shelter facility

- *Non-prepared evacuation*: Non-prepared sheltering at the moment of onset of flooding

Preventive and vertical evacuation are considered to be the main evacuation strategies and will be discussed in more detail, including their advantages and disadvantages, in section 2.3.1. The number of fatalities when applying evacuation strategies can be estimated by using the PBL model as commissioned by Planbureau voor Leefomgeving (Kolen et al., 2014). This will be discussed in more detail in section 2.3.3.

In this study two key assumptions related to decision making by authorities are made:

- A call for evacuation has been given (or is considered) and the available time for evacuation is determined

- In the case of a flood threat, the selected evacuation type per zone within the threatened area will be based solely on minimizing the expected loss of life for all areas combined

In reality decision making by authorities will include the economic impact and societal disruption of evacuation (strategies) as already mentioned in section 1.5. This may results in different boundary conditions. Furthermore it should be noted that decision makers must deal with the uncertainty in areas affected by flooding (and the extent of flooding) since dike failure locations are uncertain.

2.2.3 Environment and traffic infrastructure

The effectiveness of evacuation strategies is highly dependent on the physical environment and available infrastructure in an area. Examples are the following:

- Availability of roads and their capacities highly influence the number of people that can evacuate preventively during the transition phase.

- Availability of buildings suitable for accommodating large groups of people heavily impact on the possibilities for vertical evacuation through public sheltering. Boundary conditions for public sheltering are discussed in more detail in section 2.3.1.

- Availability of dry floors at private homes, taking into account maximum water depths during a flood, are key for possibilities of sheltering at home as part of a vertical evacuation strategy. This information can be obtained from the LIWO database (Rijkswaterstaat, 2015).

2.2.4 Citizens response

In the case of a flood threat, the response by the people (under threat) will impact on the effectiveness of selected evacuation strategies. The response by people is defined as all actions taken to prepare for a disaster and, during this disaster, with the intent of helping themselves and others to reduce the consequences (Helsloot and Ruitenberg, 2004). People tend to act according their own interpretations of the threat, which may not necessarily be correct (Terpstra, 2009). The authorities can offer information (by adequate communication) and to some extent manage the environment (for example, through traffic management and preparing public shelters). The response by citizens however, cannot be fully controlled and is therefore an uncertain element during a flood threat.

As discussed in section 1.2, preventive evacuation requires significantly more time than vertical evacuation whilst the expected available time for evacuation in the Netherlands is often limited. Therefore, vertical evacuation is considered as base strategy and preventive evacuation will be used as an additional option provided sufficient time is available. In this study it is assumed that people will act according to the base strategy and according to authority guidelines/decisions. however, it will also be investigated what happens when people evacuate preventively, independent of the base strategy and decisions by authority. Furthermore, in this study only self-reliant people are considered. Not self-reliant people (for example, people who are hospitalised or at prison) will not be considered since they will not be able to act themselves.

2.3 Effectiveness of evacuation

This section explains the effectiveness of evacuation strategies. Section 2.3.1 discusses the main strategies, preventive and vertical evacuation, in more detail. Section 2.3.2 threats the mortality functions as introduced by Jonkman (2007). In section 2.3.3, the PBL model will be discussed in which the method by Jonkman is expanded by specifying mortality functions for different situations of the people under threat.

2.3.1 Preventive and vertical evacuation

The previous section introduced the preventive and vertical evacuation strategies. This section will discuss both strategies in more detail as well as factors that must be taken into account when opting for these strategies.

When dry floors are present, sheltering at home can be considered, possibly in the home of neighbours, family and/or friends in case one's home is not suitable. People will need to survive often under primitive circumstances until rescued. Adequate communication with the public is required to make people aware of the vertical evacuation option. As a first step the website "overstroomik.nl" is launched which may increase people's awareness and help them to prepare for and cope with a flood event, if this would occur.

Public shelters can be used for sheltering large groups of people, if and when needed. Their primary function is to keep people safe in case of a flood threat. A secondary function of a public shelter is to provide a collective pickup point for evacuees and enable rescue workers to provide assistance more quickly and more efficiently. A public shelter can be very basic since people are expected to take care of themselves in times of disaster (and prepare themselves as if they would "go camping"). The presence of more facilities (e.g. electricity, medical supplies, sanitary facilities) will increase people's comfort, especially so if the rescue operation would take longer.

Regarding vertical evacuation (both sheltering at home and public sheltering) the following conditions and requirements have been defined (Kolen et al, 2015):

- The availability of dry locations of dry locations in houses and in public shelters need to be determined (e.g. per neighbourhood). Furthermore, the need for additional measures needs to be assessed (e.g. designation of public shelters and/or influencing spatial planning to create sufficient sheltering locations)

- Provision of information to the public about vertical evacuation should be added to generic information about risks

Preventive evacuation leads in principle to a lower loss of life risk but, when unsuccessful (e.g. due to road blocking and/or insufficient time), people are most vulnerable to the consequences of flooding. For preventive evacuation the available time in relation to the required time heavily impacts on the number of people at threat and hence on the effectiveness and feasibility of this strategy. When sufficient time is available, preventive evacuation generally leads to a minimum loss of life. In case the available time is insufficient, vertical evacuation is considered to be a more effective strategy. This is schematically shown in Figure 6.

In case of vertical evacuation (both sheltering at home and public sheltering), people stay (temporarily) in the threatened area and are preparing themselves as good as possible for the flood consequences. In comparison with preventive evacuation, the required time for vertical evacuation is significantly lower and hence the probability of vertical evacuees being exposed to the flood while moving (when people are most vulnerable) is low. On the other hand, vertical evacuees are more vulnerable during the flood than people who evacuated preventive successfully.

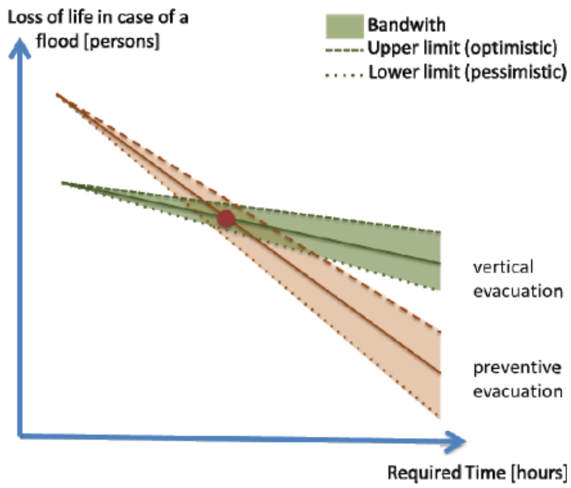

Figure 6: Qualitative representation of the effectiveness of vertical and preventive evacuation as a function of the required time (Kolen, 2013)

Research by Maaskant et al. (Maaskant et al., 2009) resulted in estimated evacuation fractions given a time frame of 0, 1, 2 or 3 days prior to the expected onset of a flood. The expected evacuation fraction is determined as well by taking into account time frame probabilities. Road capacities, expected intensity of the roads and time frame probabilities are taken into account. Results for certain areas are shown in Table 1. As can be seen, possibilities for preventive evacuation are in general limited when considering flood threats in the Netherlands, except for the upper river courses Maas and Rhine. The optimum evacuation strategy, by a combination of preventive and vertical evacuation, can be assessed after detection and recognition of a flood threat and can be implemented during the transition phase (Kolen, 2013).

Table 1: Estimated evacuation fractions for certain areas in the Netherlands, after (Maaskant et al., 2009)

	Expected	**3 days**		**2 days**		**1 day**		**0 days**	
Areas	Evacuation fraction	Evacuation	Probability	Evacuation	Probability	Evacuation	Probability	Evacuation	Probability
Southwest region with tidal inlets and islands	26%	-	-	52%	50%	0%	40%	0%	10%
Lower tidal courses of river Rijn and Maas	12%	-	-	59%	20%	0%	50%	0%	30%
Noord-Holland & Zuid-Holland	15%	45%	10%	25%	30%	0%	45%	0%	10%
IJsselmeer lake district	55%	-	-	78%	40%	60%	40%	0%	20%
Friesland & Groningen	42%	71%	20%	47%	50%	0%	15%	0%	10%
Upper river course Maas	76%	-	-	77%	50%	74%	40%	0%	10%
Upper river course Rijn	76%	79%	20%	77%	50%	67%	20%	0%	10%

2.3.2 Mortality functions

The effectiveness of evacuation strategies can be expressed in the number of fatalities. The standard approach for determining the number of fatalities is based on research by Jonkman (2009). Jonkman stated that mortality functions depend on the hydraulic characteristics of a flood. Based on these hydraulic characteristics (water depth, flow velocity and rise speed of the water), the following three zones can be distinguished:

- *Breach zone*: In general, due to the water inflow, high flow velocities are expected behind a dike breach. This may lead to collapse of buildings and instability of people exposed to the water flow.

- *Rapid rising water zone*: Due to rapid rising of the water people may not be able to reach a shelter at higher floors of a building or may not be able to properly prepare themselves and/or others. Rapid rising water is especially hazardous in combination with larger water depths.

- *Remaining zone*: Due to relatively low hydraulic characteristics better possibilities are expected for finding sheltering. Fatalities may occur amongst people who did not find shelter, or people who suffer from indirect consequences (drinking water, basic medicines, etc.) associated with (extended) sheltering.

A representation of the above zones is shown in Figure 7.

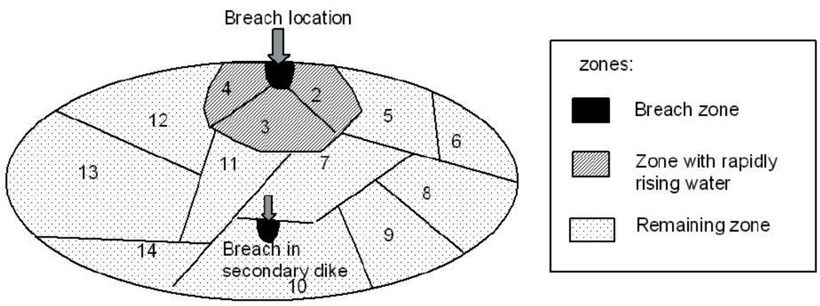

Figure 7: Representation of the breach zone, the rapid rising water zone and the remaining zone in the case of a flood threat (Jonkman, 2007)

Kolen et al. (2014) added the transition zone for flood characteristics between the rapid rising water zone and the remaining zone. In this study however, the transition zone will not be taken into account.

The mortality rate for the breach zone is assumed to be 100%. The mortality rate for the rapid rising water and remaining zones can be determined using the following lognormal distribution function (Jonkman, 2007):

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right)$$

where h is the water depth, and μ and σ are zone specific parameters. For the rapid rising water zone μ_N and σ_N are shown in Table 2 for the 2,5% confidence interval (lower bound), average and 97,5% confidence interval (upper bound).

Table 2: Zone specific parameters μ and σ for the average mortality function and for the lower and upper bound, after (Jonkman, 2007)

Mortality function	Remaining zone		Rapid rising zone	
	μ_N	σ_N	μ_N	σ_N
2,50% (lower bound)	8,76	2,94	1,69	0,36
Average	7,60	2,75	1,46	0,28
97,50% (upper bound)	6,45	2,55	1,34	0,23

Figure 8 shows the average mortality function (as formulated above) together with the lower and upper bounds based on actual observations, for the rapid rising water zone (a) and the remaining zone (b) as a function of the water depth (Jonkman, 2007).

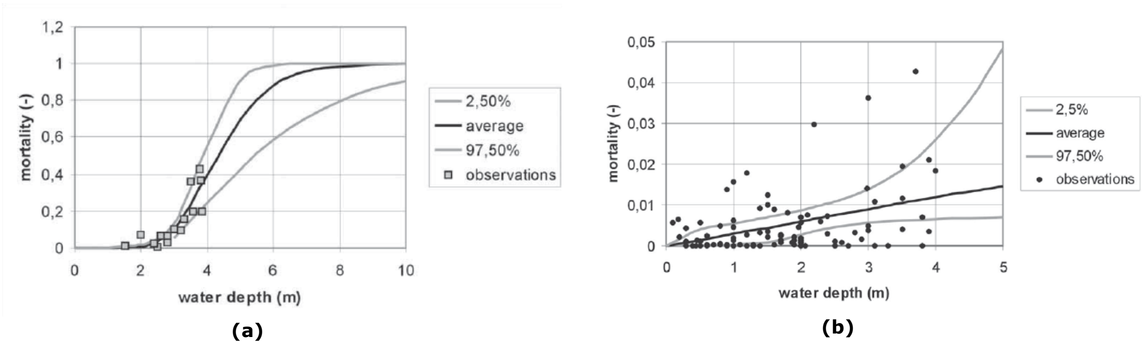

Figure 8: Average mortality function together with the lower and upper bound for the rapid rising zone (a) and the remaining zone (b) (Jonkman, 2007)

2.3.3 The PBL Model

Based on the representation of flood zones and corresponding mortality functions as described in section 2.3.2, the PBL model (Kolen et al. 2014) estimates the number of fatalities when applying evacuation strategies by taking into account local (flood) characteristics and the number of people involved. In this way the standard method by Jonkman (2007) is expanded by specifying mortality functions for different situations of the people under threat. This resulted in the following five categories:

- *Preventive evacuation*: Fatalities mainly caused by (stress and weather related) (traffic) accidents during evacuation. The mortality rate is considered to be 0,001% based on research of historical data.

- *Exposed to flood while evacuating preventively*: fatalities caused by unsuccessful preventive evacuation due to traffic overload, less available time than expected, etc. For people being exposed to the flood while in their car, the mortality rate is considered to be five times higher than the mortality rate by Jonkman, as discussed in section 2.3.2. For people being able to shelter in time, the mortality rate is assumed to be equal to the mortality rate for the category *people who stay at home and are not prepared*.

- *People in a shelter*: fatalities are caused by poor livability and limited provisions. Indirect consequences such as unavailability of (basic) medicines, violence and hypothermia are taken into account as well. The mortality rate is considered to be 0,05%.

- *People who stay at home and are prepared*: The mortality rate is characterized by the hydraulic characteristics and based on the lower bound of the lognormal distribution function by Jonkman (2007).

- *People who stay at home and are not prepared* (applicable for the do-nothing strategy): The mortality rate is characterized by the hydraulic characters and based on the upper bound of the lognormal distribution function by Jonkman (2007).

The above is summarized in Figure 9. Dependent on the evacuation strategy and hence the number of people per category, a loss of life estimation can be made for a given flood threat.

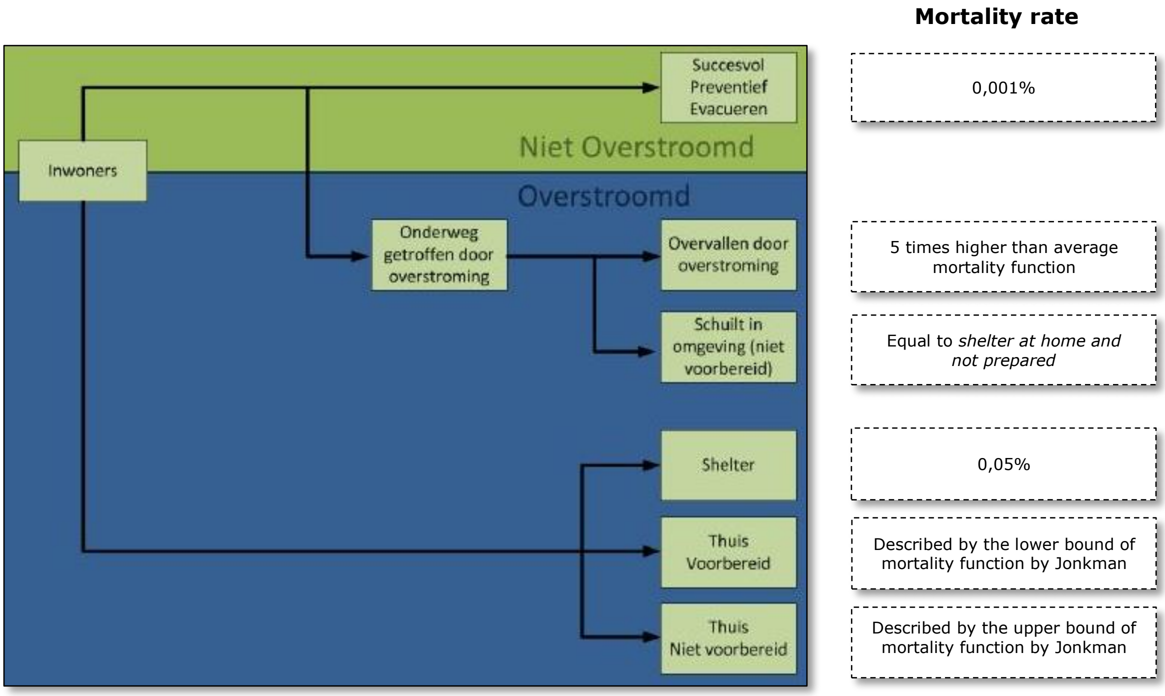

Figure 9: Representation of the PBL model together with the mortality rate (Kolen et al. 2014)

2.4 Flood probability

This section explains the flood probability. Section 2.4.1 discusses the failure probability of dike sections in general. Section 2.4.2 threats the fragility curves in more detail and in section 2.4.3, the location specific flood probabilities will be discussed.

2.4.1 Failure probability

In principle, flood defences fail when the strength of the structure is smaller than the load that acts on the flood defence (Jonkman, 2017). In the case of flood defences, the load is often expressed in water level [m + NAP] or river discharge [m^3/s] and the resistance is dependent on the design and condition of the flood defence. It should be noted that both the resistance against failure and the load parameter are uncertain and variable. Therefore, the resistance and load parameter are described by a probability density function, with a limit state function *Z* as follows:

$$Z = R - S$$

where R represents resistance against failure and S the load.

Failure occurs when $R<S$, i.e. when $Z<0$. The probability of failure, i.e. $P_f\,(Z<0)$, can be computed as follows (Jonkman, 2017):

$$P_f = P(Z < 0) = \int_0^{\infty} f_H(h) * F_R(h) dh$$

where $f_H(h)$ is the probability density function of the hydraulic load (water level) and $F_R(h)$ is the cumulative distribution of resistance given a certain hydraulic load level.

The probability density function $f_H(h)$ follows from a statistical analysis of hydraulic loads. The probability of exceeding a certain water level can be derived from this probability density function. The cumulative distribution function of resistance $F_R(h)$ is also called a *fragility curve* and indicates the conditional failure probability of a dike section given a certain water level.

In the VNK2 report (Rijkswaterstaat, 2015) failure probabilities of primary flood defences in the Netherlands are expressed per unit of time (per year). However, in the case of a given flood threat one wants to anticipate on this particular event, i.e. the conditional failure probability of the forecasted high water level is of key importance. In the next section fragility curves will be discussed.

2.4.2 Fragility curve

Fragility curves are often used as method for performing probabilistic calculations for dike failure. A fragility curve, which is normally represented as a cumulative distribution function, indicates the conditional failure probability of a dike section given a certain load level. This is particularly useful when one wants to anticipate (in this study by applying evacuations strategies) on a particular threat (forecasted high water level).

Different types of failure mechanisms can contribute to failure probabilities. For each failure mechanisms a fragility curve can be produced. The main mechanisms are summarized below (Kok et al., 2017):

- *Overflow and overtopping*: The water level exceeds the height of the dike crest (possibly in combination with wave overtopping) which may damage the inner slope of the dike, resulting in erosion and dike failure.

- *Macro instability*: Sliding of the inner and/or outer slopes of the dike because of water pressure differences caused by (high) water levels.

- *Micro instability*: Instability of the inner slope and/or outer slope because of seepage through the dike

- *Piping*: High water levels over a longer time period may lead to a water (and sediment) flow underneath the dike. This mechanism causes channels undermining the dike.

Fragility curves can relatively easily be produced and show, in a graphical way, the influence of water level on failure probability. The steeper the fragility curve, the higher the influence of water level on failure probability. When fragility curves of multiple failure scenarios are depicted in the same figure, one can easily see which failure mechanism(s) is/are critical for certain water levels. In a combined fragility curve critical failure mechanisms are considered per water level. An example is shown in Figure 10. As shown, in this case, the overtopping curve is the steepest which means that the failure probability for overtopping is most sensitive to water level changes. It can be seen that for lower water levels (*<NAP+2,6m*) piping is the leading failure mechanism whereas for higher water levels (*>NAP+2,6m*) overtopping mechanism is leading. Combining the two critical curves results in the combined fragility curve which takes account of multiple failure mechanisms.

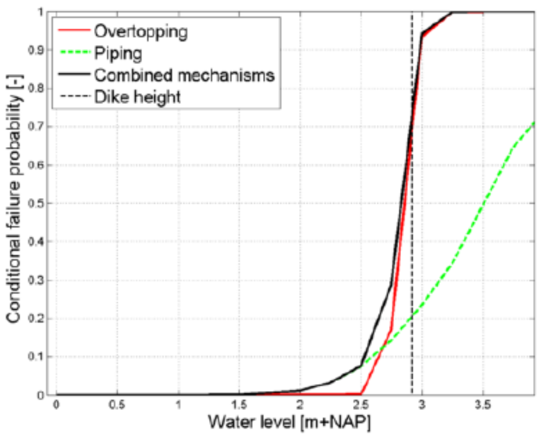

Figure 10: Example combined fragility curve for an uniform dike section taking into account the failure mechanisms overtopping and piping (Wojciechowska, 2015)

The relationship between failure probabilities and their consequences, in terms of flooding, is discussed in the following section.

2.4.3 Location specific flood probability

The relationship between dike failure and flood scenario(s) is best described by Jongejan and Maaskant (2015):

"A flood scenario is defined as a unique sequence of events following the failure of one or more flood defences, under specific high-water conditions. In reality, the number of potential flood scenarios is infinite. The infinite range of potential flood scenarios can be characterized by a limited set of representative flood scenarios. To define these representative flood scenarios (simply named scenarios hereafter), the water defence system is first divided into so-called consequence segments, each comprising one or more sections. Each consequence segment should be defined such that the flood pattern and consequences of flooding are relatively insensitive to the precise location of a breach within the segment"

The above principle is illustrated in a simple way in Figure 11. In this case, three dike segments are considered, each with their own flood pattern when failure occurs within these segments. As can be seen, as an example, flooding of area A can occur by failure of segments 1, 2 and/or 3, area B only floods by failure of segment 1 and area C does not flood at all. A comprehensive flood risk analysis takes account of flood scenarios assuming a single breach as well as scenarios assuming multiple breaches. The floods in New Orleans (2005), Thailand (2011) and also in the Netherlands (1953) were characterized by a large number of failure locations in the water defence system (Jonkman, 2016).

Probabilistic calculation techniques can be used to combine failure probabilities of individual sections to the probability of failure for a whole segment (Jongejan and Maastkant, 2015). When assuming multiple scenarios for flooding of a certain area, the overall flood probability equals the sum of the flood scenario probabilities (Kok et al., 2017). In this study, the same is assumed to be the case for conditional flood scenario probabilities.

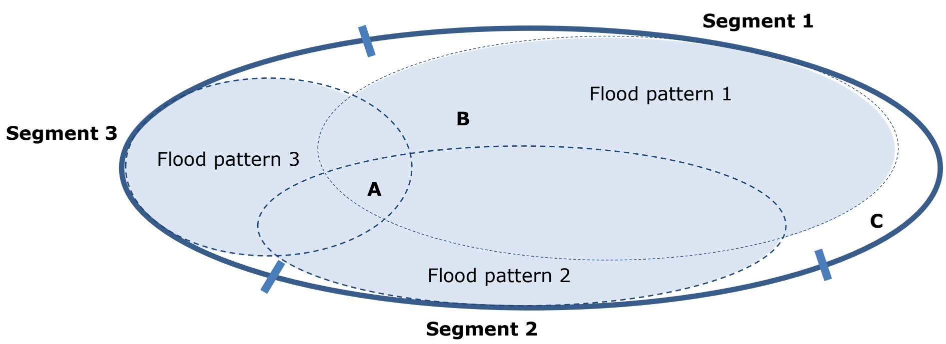

Figure 11: A simple representation of possible flood scenarios for a dike ring with three segments

3 Flexible evacuation method

3.1 Introduction

Imagine an area where people live and work located alongside a sea, lake or river. This area is normally protected from flooding by water defences, for example a dike. In case of a dike failure however, (part of) the area will be flooded and people will be at risk. In this chapter the development of a method to identify the optimum strategy for minimizing the expected loss of life will be discussed based on the "strategy builder" as introduced by Kolen (2014). The objective is to get insight into the risk of loss of life when applying different evacuation strategies given a water level forecast of the sea, lake or river. A second objective is to find the evacuation type per zone so as to minimize the risk of loss of life for the whole system (all zones combined). The method should furthermore be flexible, i.e. being able to deal with an uncertain and variable flood threat (in terms of available time and flood scenarios).

In this chapter the method will be applied using a simplified example (section 3.4) and in the end of the chapter three further example studies are summarized showing how parameter changes affect the outcome of the developed method (section 3.5).

3.2 Key elements

In this section key elements are discussed for the development of a flexible method to identify the evacuation type per zone with the objective to minimize the overall risk for loss of life.

- *Effectiveness of evacuation*: Information is required regarding the effectiveness, expressed in loss of life, of each evacuation type. The feasibility of a strategy (as a mix of evacuation types), is determined by the maximum outflow of evacuees taking into account possible boundary conditions. For example, if the outflow exceeds a certain limit, road blocking will occur in which case the loss of life may actually increase.

- *Conditional dike failure probability*: Flood defences fail when the water load caused by the water exceeds the strength or height of the defence structure. For a given water level forecast, the conditional dike failure probability can be represented by means of a fragility curve which shows the conditional failure probability as function of the water level per dike section.

- *Water level forecasts*: Recognition of a threat starts by forecasting water levels. Water level forecasts serve as input for conditional dike failure (and flood scenario) probabilities. Water level forecasts for the Netherlands are prepared daily by the Water Management Centrale Nederland (WMCN). In general, the accuracy of the water level forecasts will decrease with time.

- *Flood scenarios*: When a flood defence fails an area is likely to be flooded. The way the flooding propagates can be described using flood scenarios. A flood is characterised by the parameters: water depth, flow velocity and rise speed of the water. Although flood scenarios will be used, the actual development of these scenarios is not part of this study. For the Netherlands, possible flood scenarios as assumed to be known and can be extracted from the LIWO database (Rijkswaterstaat, 2015).

3.2.1 Effectiveness of evacuation

The first priority when dealing with an actual flood threat is saving people's lives (Rijkswaterstaat, 2014). Preventive evacuation leads in principle to a lower loss of life risk but, when unsuccessful (e.g. due to road blocking or insufficient time), people are more vulnerable to flooding than when evacuating vertically. To get more insight in the effectiveness of evacuation strategies (as a mix of vertical and preventive evacuation) two parameters are introduced: *loss of life* and *outflow of preventive evacuees*.

Loss of life

Loss of life, expressed as the number of fatalities, can be estimated using the PBL model as described in section 2.3.3. Loss of life is dependent on: the evacuation *zone (i)*, *evacuation type (j)*, *flood scenario (c)* and *evacuation time (t)* and can be expressed as follows:

$$\textit{Number of fatalities } L_i \textit{ for zone } i = F\,(\textit{evacuation type } j, \textit{flood scenario } c, \textit{lead time } t)$$

with

$$zone\ i = \begin{bmatrix} 1 \\ \vdots \\ m \end{bmatrix}, \quad evacuation\ type\ j = \begin{bmatrix} 1 \\ \vdots \\ n \end{bmatrix}, \quad flood\ scenario\ c = \begin{bmatrix} 1 \\ \vdots \\ z \end{bmatrix}, \quad lead\ time\ t = [hours]$$

Representation of the evacuation time as part of the lead time is illustrated in Figure 12 below. It should be noted that the effect of evacuation time limiting factors such as extreme weather conditions can be added if and when necessary.

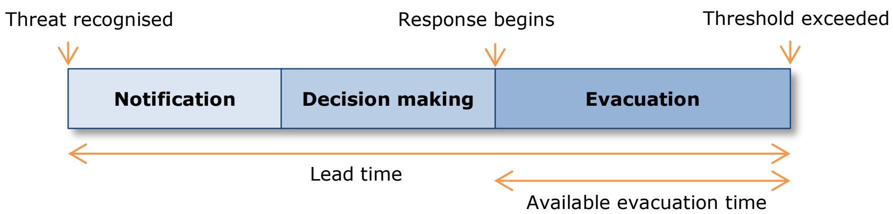

Figure 12: Representation of lead time and available evacuation time

Given an *available evacuation time (t)* and *flood scenario (c)*, values for loss of life for *zone (i)* and *evacuation type (j)* can be derived. It is assumed that for each zone has a single evacuation strategy applies, i.e. there is no mix of strategies within a zone. The value for loss of life for the whole system can then be obtained as the sum of the loss of life values for each zone as shown below:

$$Number\ of\ fatalities\ for\ the\ whole\ system = \sum_{i=1}^{m} L_i$$

The number of possible combinations assuming *m zones* and *n strategies is given by*:

$$Number\ of\ possible\ combinations = (n)^m$$

Outflow of preventive evacuees

For the outflow of preventive evacuees, it is assumed that most evacuees will travel by car. In this study two different road levels are considered: 1) roads within a zone and 2) the connecting roads in the system. Since evacuation is a measure to be executed before the water-level exceeds a certain threshold value (leading to a certain dike failure probability), it is not flood scenario dependent. The number of preventive evacuees for *zone (i)* depends on the *evacuation type (j)* and *available evacuation time (t)* as follows:

$$Inflow\ of\ preventive\ evacuees\ E_i\ for\ zone\ i\ to\ the\ connecting\ road = G(evacuation\ type\ j, evacuation\ time\ t)$$

The relation between the number of preventive evacuees and *evacuation time (t)* is illustrated in Figure 13. As can be seen, with increasing lead time more people can be preventively evacuated. In this case a linear development in time is assumed. The effect of a smaller road capacity is shown with the dashed blue line.

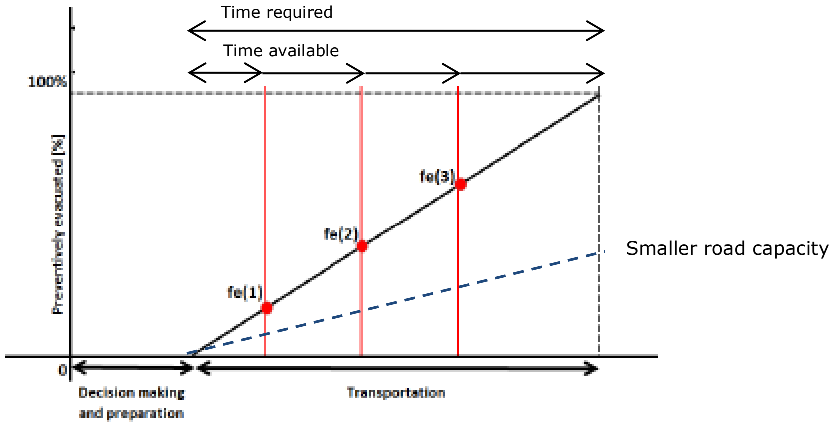

Figure 13: Relation between the number of preventive evacuees and available evacuation time

The inflow of evacuees (*IN*) from all zones to the connecting road in the system can be defined as follows for a given available *evacuation time (t)* and *evacuation type (j)* (after Kolen, 2013):

$$IN = \sum_{i=1}^{m} E_i$$

The maximum outflow is defined as *OUT* and is a system characteristic. In order to avoid the connecting road from blocking the following boundary condition exists:

$$IN + STORAGE \leq OUT$$

where

STORAGE = occupation of the connecting road at start of the evacuation and preventive evacuees from surrounded areas

$OUT = min\ (C_{road}, C_{exit})$

C_{road} *= road capacity without congestion for available evacuation time t*
C_{exit} *= capacity at road exit points for available evacuation time t*

In this study it will be attempted to find the evacuation strategy, as a combination of evacuation types per zone, which minimizes the probability of loss of life for the whole system given an available evacuation time and flood scenarios. The evacuation strategy must fulfil the boundary condition as described above to prevent road blocking.

A second boundary condition is that the number of people in a zone (N_i) is assumed not to exceed the capacity of the road(s) within that zone (C_i) for a given *evacuation time (t)* and *evacuation type (j)*, which is expressed by the following:

$$N_i \leq C_i$$

3.2.2 Conditional dike failure probability

Conditional dike failure information, which is represented through a fragility curve, is the second requirement for the generic method. As a water defence, e.g. a dike, cannot be assumed uniform over its full length, it is normally divided into sections whereby each section has homogeneous strength and loading properties. A fragility curve, which is usually represented as a cumulative distribution function, now indicates the conditional failure probability of a dike section given a certain load level. For the current study the water level is considered to be the only load variable. This assumption is representative for a river dike (Jonkman, 2017).

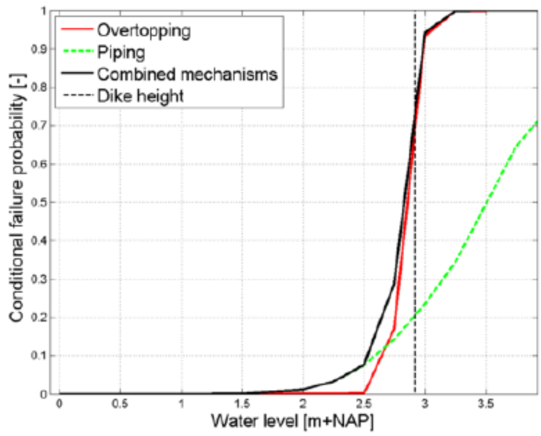

Figure 14: Example (combined) fragility curve for an uniform dike section taking into account the failure mechanisms overtopping and piping (Wojciechowska, 2015)

Based on the (combined) fragility curve (as shown in Figure 14) and assuming a certain water level, the conditional failure probability for each dike section can be predicted. In this study a dike failure always results in flooding. For each dike section various flood scenarios are possible when failure occurs, ranging from extreme to below normative. The extent of the flood depends on the water level upstream of the dike section (see also section 3.2.3 below).

$$Conditional\ failure\ probability\ Pf_y\ for\ dike\ section\ y = \ Fragility\ curve\ (water\ level\ h)$$

With

$$dike\ section\ y = \begin{bmatrix} 1 \\ \vdots \\ p \end{bmatrix}$$

More information on fragility curves can be found in section 2.4.2.

3.2.3 Water level forecast

A water level forecast predicts the water level as function of time, and is the third key element for the flexible evacuation method (note that this water level is upstream of the dike, i.e. in a river, lake or at sea). The water level as a function of time can be defined as $h = f(t)$ with h being the water level and t the time. Two simplified water level forecast are shown in Figure 15. The thick blue line represents the observed water level over time until *t=0* and the thin blue lines indicates the forecasted water levels from *t=0*. As explained in the previous section, a water level forecast can be used to determine the conditional failure probability of each dike section and thus the conditional probability for flooding. Besides, a water level forecast determines the possible extent of the flood since the height of the water determines the volume of water flowing into the threatened area when dike failure occurs. This is qualitatively shown in Figure 15. Flood scenarios and corresponding water levels can be prepared during the cold phase. The cold phase is defined as a phase without an actual flood threat. During the warm phase, when there is an actual flood threat, water level forecasts on which evacuation decisions must be made are of key importance.

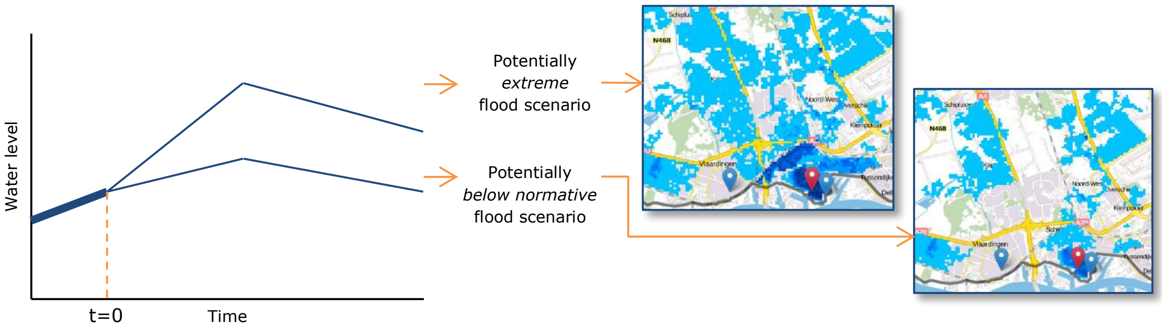

Figure 15: Qualitative relation between water level forecast and extent of potential flood scenario. Potential flood scenarios for dike failure at Vlaardingen used as examples (LIWO)

In reality, water level forecasts are made using an "ensemble" as shown in Figure 16. Ensembles are used to describe the uncertainty of water level forecasts. The red curves to the right of the vertical line (*t=0*) correspond to a range of possible water levels as function of time, each corresponding to a certain probability of occurrence. For this reason, the extent of flood scenarios can be linked to a certain probability. As can be seen in Figure 16, the uncertainty increases over time. An ensemble can be used to construct a representative water level forecast with a certain range of uncertainty. For simplicity reasons, in this study a single water level forecast will be assumed.

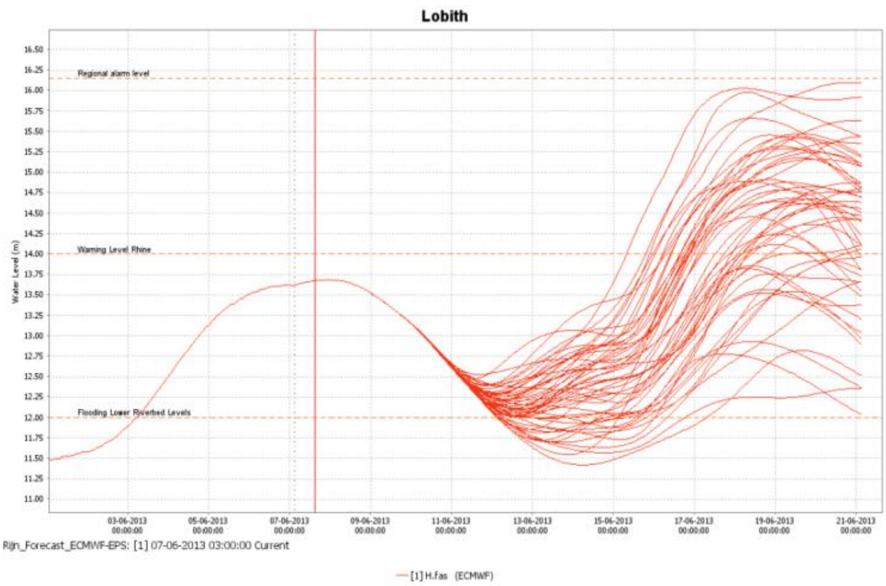

Figure 16: An example ensemble of water level forecasts at location Lobith

3.3 Method description

The flexible evacuation method is based on the input parameters as defined in section 3.2. As said, estimations for loss of life, outflow of preventive evacuees and conditional dike failure probability can be prepared during the cold phase given the evacuation type (vertical or preventive). This data, together with the water level forecasts obtained during the warm phase, is then used to arrive at the evacuation type per zone which minimizes loss of life for the whole system. An overview of the key input parameters required for the flexible evacuation method are shown in Table 3 and an overview of the method is shown in Figure 17.

Table 3: Overview of key input parameters for the flexible evacuation method

Input parameter	Description	Source	Preparation phase
$L_i = F(j,c,t)$	Number of fatalities for zone *i* as function of evacuation type *j*, flood scenario *c* and evacuation time *t*	PBL model (section 2.3.3) and LIWO database (for flood scenarios)	Cold
$E_i = G(j,t)$	Outflow of evacuees from zone *i* to the connecting road as function of evacuation type *j* and evacuation time *t*	Basic traffic models	Cold
$Pf_y = g(h)$	Conditional failure probability for dike section *y* represented by fragility curve *g* as function of water level *h*	Fragility curves (section 2.4.2)	Cold
$h = f(t)$	Forecast of water level *h* as function of time *t*	WMCN (section 3.2.3)	Warm

The outcome of the flexible evacuation method is the evacuation type per zone that minimizes the probability for loss of life for the whole system whilst fulfilling the boundary conditions as discussed in section 3.2.1.

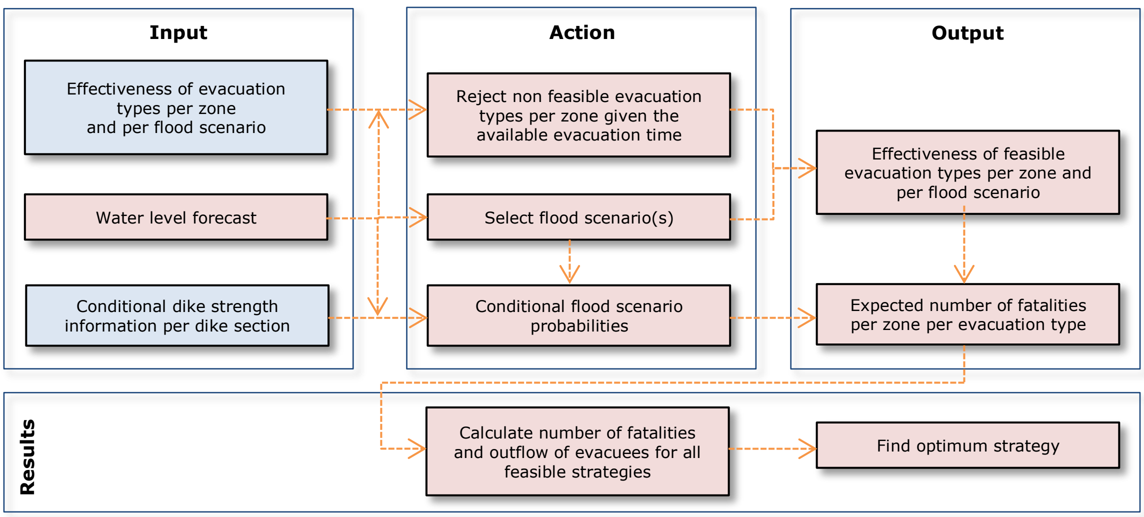

Figure 17: Overview of the method description with the objective to find the optimum evacuation of strategy to minimize the probability for loss of life for a given flood threat. (blue: cold phase, red: warm phase)

3.3.1 Definition of Steps

Several steps are conducted to obtain the desired outcome using the input information. The steps are explained in this section. Subsequently a simplified example study will be conducted in section 3.4.

Firstly, the system area must be defined and the required input parameters must be obtained. The following steps will be conducted in order to obtain the strategy per zone which minimizes the probability of loss of life for the whole system and which fulfils the boundary conditions:

Step 1: Prepare information

Step 2: Select flood scenarios and evacuation time, and determine the consequences

Step 3: Translate water level forecast to flood scenario probabilities

Step 4: Calculate expected loss of life

Step 5: Determine evacuation strategy which minimizes the loss of life risk

Step 1: Prepare information

Firstly, the system (area under treat) needs to be defined and key preparatory data must be collected:

- Number of modular components (zones) and number of citizens within these zones. In this study it is assumed is that each zone responds as a unity, i.e. per zone a single evacuation type is applied.

- Possibilities for preventive evacuation. Evacuation routes and their capacities within each zone must be mapped, as well as the daily capacity and outflow capacity of the connecting roads.

- Possibilities for vertical evacuation. Per zone, investigation of available public shelters and possibilities for sheltering at home taking into account the local maximum water depth.

- Locating potential dike failure locations and mapping uniform (in terms of strength) dike sections.

- Investigation of potential flood scenarios per dike failure location. As discussed in section 2.3.2, a flood scenario is characterized by the parameters: water depth, flow velocity and rise speed of the water.

- Water level threshold (point at which evacuation must be complete).

The above information is considered the most important for defining the threatened area and determining the key input parameters (L_i, E_i, Pf_y and $f(t)$).

Step 2: Select flood scenarios and the evacuation time and determine consequences

Given the water level forecast, during the warm phase the extent of the flood for the various scenarios can be determined. Also, the lead time can be derived as the time between *t=0* (moment of threat recognition) and *t=x* (moment of reaching the water level threshold at which the evacuation must be complete) (as shown in Figure 18). Using an available evacuation time (as part of this lead time) for each zone the loss of life and outflow of preventive evacuees can now be established per evacuation type, dependent on the flood scenario. This information determines the potential effectiveness of strategies. When preventive evacuation is not feasible for a zone within the available evacuation time, e.g. due to road blocking, this strategy is rejected. This is expressed by the boundary condition $N_i \leq C_i$ as mentioned in section 3.2.1. Figure 15 gives a qualitative overview of the extent of the flood when flooding occurs.

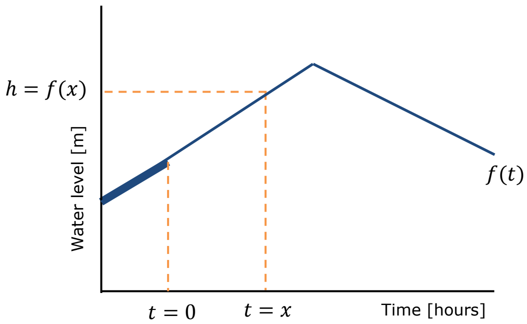

Figure 18: Representation of a water level forecast and its lead time in which t=0 is the moment of threat recognition and t=x the moment of reaching the water level threshold at which the evacuation must be complete

Step 3: Translate water level forecast to flood scenario probabilities

For each dike section the conditional failure probability is determined as function of the water level forecast. For simplicity reasons per dike section only one flood scenario is considered.

In this study the probability of dike failure is linked to the water level threshold value. Hence the lead time is the time between threat recognition and the moment the water level threshold value is reached. Note however, that a dike section can fail before reaching the threshold value in which case the actual time for evacuation is shorter than expected. Especially for slow rising water levels this risk can be significant. In this study this risk is not taken into account but in the recommendations this risk is discussed further.

Step 4: Calculate expected loss of life

In general, expected values are defined as probability times consequences. Using the conditional flood scenario probabilities as determined in step 3, the expected loss of life per zone can be calculated for each evacuation type. As shown in Table 3, L_i depends on evacuation type *j*, flood scenario *c* and evacuation time *t*. For a given available evacuation time *t* and assuming a single flood scenario per dike section *y* (as mentioned under step 3), the expected value for L_i can be determined for each evacuation type *j* using the following expression:

$$\sum_{y=1}^{p} Pf_y(L_i)_y$$

where *p* is the number of dike sections (not to confuse with capitol *Pf* used to express failure probability).

Step 5: Determine evacuation strategy which minimizes the loss of life risk

The expected loss of life value for the whole system is now obtained by summation of the expected loss of life per zone. As for each zone there may be n evacuation types, this may lead to maximum of n^m combinations as described in section 3.2.1. The case leading to the minimum loss of life value for the whole system whilst fulfilling the boundary conditions is the preferred evacuation action for the flood threat considered. The boundary condition is expressed in section 3.2.1. Given the expected flood scenario *c* per zone and the evacuation time *t*, the expected loss of life for zone *i* only depends on the selected evacuation type *j*. The total number of expected fatalities for the optimum strategy for the zones combined can therefore be obtained through the following formula:

$$min\left(\sum_{i=1}^{m} L_i(j)\right)$$

A quick way of finding the preferred combination may be to first assume preventive evacuation for all zones and then, in case of not fulfilling the boundary conditions, successively change the evacuation type options for selected zones (or vice versa). This prioritization may be based on zones where vertical evacuation would lead to relatively low loss of life values or outflow of evacuees would have a large impact.

3.4 Simplified example model

In this section a simplified example is given based on the steps shown in section 3.3.1. Figure 19 shows a system overview for this study. The figure represents an area where people live and work alongside a river. The area is protected from flooding by a dike. The river threshold water level is assumed to be NAP+5m*,* i.e. when the water level reaches this level the evacuation must be complete.

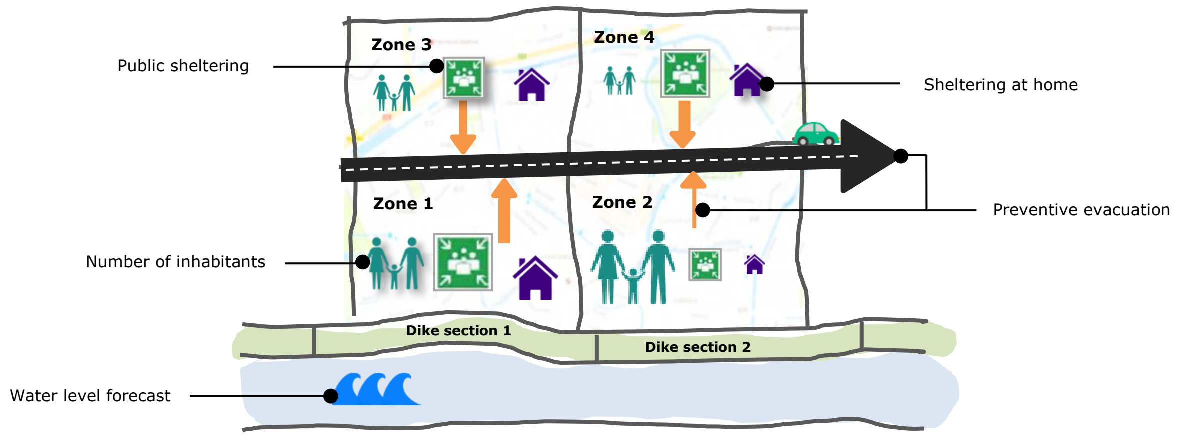

Figure 19: System overview of simplified example with a representation of the possibilities for vertical and preventive evacuation

Step 1: Prepare information

In this example three evacuation types are considered: non-prepared evacuation *(j=1)*, vertical evacuation *(j=2)* assuming both public sheltering and sheltering at home, and preventive evacuation *(j=3)*. The results of non-prepared evacuation mainly serve as a reference for comparison with the other strategies. The dike consists of two uniform dike sections, which in this case equals dike segments. The system is divided in four zones. Table 4 gives a qualitative overview of the most important characteristics based on the system overview shown in Figure 19. Vertical evacuation is assumed to be a combination of public sheltering and sheltering at home.

Table 4: Qualitative overview of important characteristics. (--: strongly below normative, -: below normative, o: normative, +: above normative, ++: strongly above normative)

	Number of citizens	Public shelter availability	Possibilities for shelter at home	Possibilities for preventive evacuation
Zone 1	+	++	+	+
Zone 2	++	--	--	--
Zone 3	o	-	o	o
Zone 4	-	+	o	+

Both *STORAGE* and *OUT* for the connecting road (as described in section 3.2.1) in this example are discussed in step 5.

Step 2: Select flood scenarios and the evacuation time and determine the consequences

Figure 20 shows the water level forecast obtained at t=0. Assuming a threshold value of NAP+5m the resulting lead time *t* is 36 hours. Assuming a notification and decision making time of 12 hours, the available time for evacuation is 24 hours.

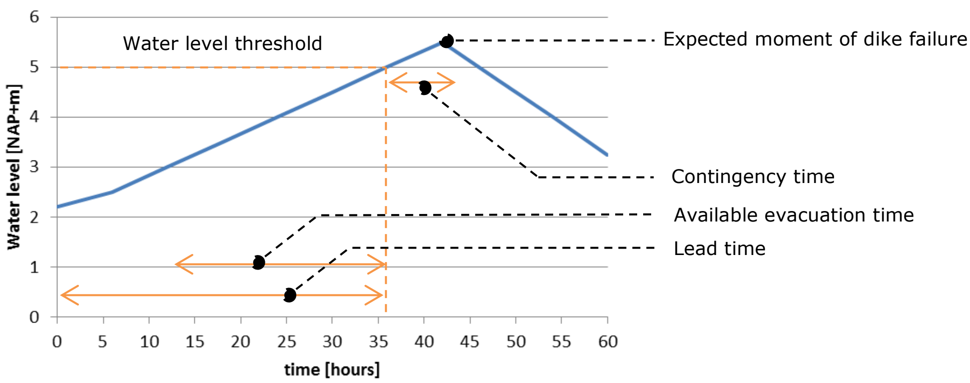

Figure 20: Water level forecast used in the simplified example

The resulting flood scenario per dike section failure is illustrated in Figure 21. Failure of dike section 1 is assumed to cause flooding of zones 1 and 3, and failure of dike section 2 flooding of all zones.

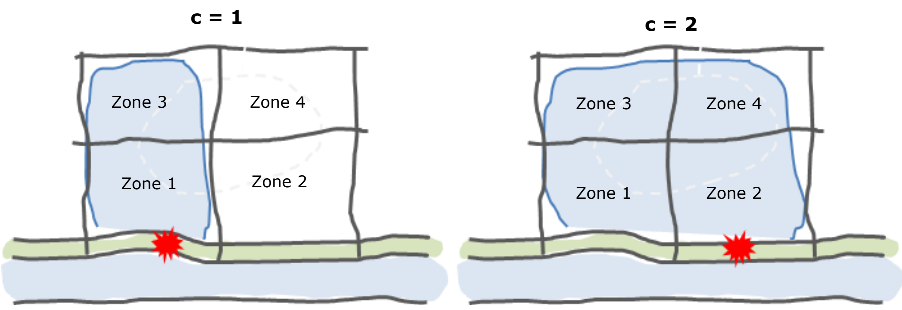

Figure 21: Flood scenarios (c=1 and c=2) taken into account in the simplified example for failure of dike section 1 and 2, respectively

Now, for each zone the loss of life and outflow of evacuees can be established dependent on the evacuation type, the available evacuation time (24 hours) and for the two flood scenario considered. Results are shown in Table 5 and 6 for flood scenarios 1 and 2, respectively.

Table 5: The outflow of evacuees (Ei) and loss of life (Li) for evacuation type (j) per zone (i) for flood scenario 1

c=1	Ei (x 100)				Li			
	i=1	i=2	i=3	i=4	i=1	i=2	i=3	i=4
j=1	0	0	0	0	50	0	35	0
j=2	0	0	0	0	5	0	10	0
j=3	35	x	25	15	0	x	0	0

Table 6: The outflow of evacuees (Ei) and loss of life (Li) for evacuation type (j) per zone (i) for flood scenario 2

c=2	Ei (x 100)				Li			
	i=1	i=2	i=3	i=4	i=1	i=2	i=3	i=4
j=1	0	0	0	0	50	75	35	25
j=2	0	0	0	0	5	30	10	4
j=3	35	x	25	15	0	x	0	0

The following assumptions are made for this simplified example:

- When opting for preventive evacuation, and sufficient time is available, there will be no loss of life. In reality however, there will be a relatively small probability of loss of life due to traffic accidents (as discussed in section 2.3.2).
- Preventive evacuation ($j=3$) is not feasible for zone 2 ($i=2$) as the boundary condition of the number of citizens being smaller than the outflow capacity of zone 2 is not fulfilled ($N_{i=2} \leq C_{i=2}$). Therefore, preventive evacuation is rejected as an option for zone 2.
- If a zone is flooded, the consequences (E_i and L_i) are the same for both flood scenarios.
- If a zone is not flooded there are, obviously, no fatalities. However, as the outflow of preventive evacuees is not flood scenario dependent, there will be preventive evacuees. This is shown for zones 2 and 4 in case of flood scenario 1 (where only zones 1 and 3 are flooded).
- The consequences (E_i and L_i) are in line with Table 3, for example:
  - loss of life for zone 2, when flooded ($c=2$), is relatively high due to poor sheltering possibilities in case of vertical evacuation ($j=2$)
  - loss of life for zone 1 in case of vertical evaluation ($j=2$) is relatively low due to *strongly above normative* possibilities for sheltering
  - zone 4 has relatively few citizens and therefore a relatively low number of fatalities in case of *do nothing* and few evacuees in case of *preventive evacuation*.

Step 3: Translate water level forecast to flood scenario probabilities

Figure 22 shows the fragility curves for dike sections 1 and 2. As shown, it is assumed that for the water level threshold value of NAP+5 m, the conditional failure probabilities for dike sections 1 and 2 are 25% and 20%, respectively. For this simplified example study, failure probabilities are considered independent. It is noted that these failure probabilities are the same as the probabilities for the occurrence of flood scenarios 1 and 2, respectively.

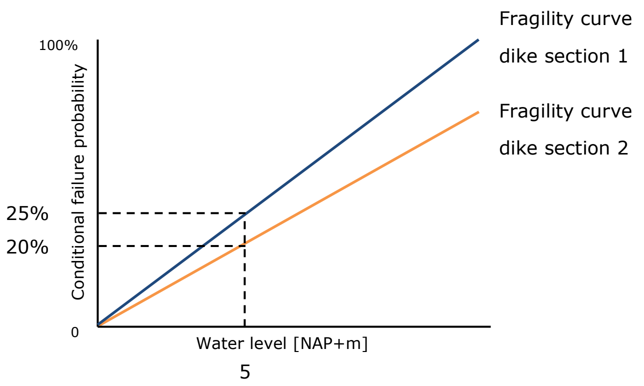

Figure 22: Fragility curves for uniform dike section 1 and 2

Step 4: Calculate expected loss of life

The expected value of loss of life per zone and per evacuation type is now calculated by using the expression discussed in section 3.3.1 step 4. This results in Table 7 below. Note that for E_i there is no expected value as this parameter is not flood scenario dependent.

Table 7: Outflow of evacuees (Ei) and the expected value for loss of life (Li) for flood scenarios probabilities of respectively 25% and 20%

	Ei (x 100)				Expected value for Li			
	i=1	i=2	i=3	i=4	i=1	i=2	i=3	i=4
j=1	0	0	0	0	22.5	15	15.8	5
j=2	0	0	0	0	2.3	6	4.5	1
j=3	35	x	25	15	0	x	0	0

Step 5: Determine evacuation strategy which minimizes the loss of life risk

As part of the boundary condition, discussed in section 3.2.1, the *STORAGE* parameter for this example study is assumed to be zero and *OUT* is considered to be 6500 persons for the given available time of 24 hours.

The expected loss of life for different evacuation strategies is now obtained by summation of the expected loss of life values shown in Table 7 above. It should be noted that in this simplified example non-feasible strategies are rejected as an option, and the number of expected fatalities are not calculated. This is considered a reasonable simplification as the expected loss of life for such strategies will be high (since people are risking to be exposed to flooding while evacuating). In the (more complex) case study for Rotterdam North (chapter 4), the expected loss of life for non-feasible strategies are investigated for comparison reasons.

The results of non-prepared evacuation (evacuation strategy 1 as shown in Table 8) serves as a reference for comparison with the other strategies. As shown, obviously, this strategy leads to the highest total number of fatalities. Strategies 6 to 9 and 14 to 17 do not fulfil the boundary condition that the number of citizens must be smaller than the outflow capacity of zone 2 ($N_{i=2} \leq C_{i=2}$). Therefore, these strategies are rejected as an option. For combination 13, the outflow of evacuees to the connecting road (*IN*) exceeds the maximum outflow capacity (*OUT)* and is therefore also rejected as an option. Combination 12 leads to the minimum total number of fatalities with an expected loss of life of 7 persons. In this simplified example the zones with the highest flood probability, zones 1 and 3, are prioritized for executing preventive evacuation. This matches expectations.

Table 8: Expected number of fatalities for different evacuation strategies for an available evacuation time of 24 hours and assuming conditional flood scenario probabilities of respectively 25% and 20% (NP: non-prepared evacuation, V: vertical evacuation, P: preventive evacuation)

	Evacuation type						Estimated number of fatalities		
Evacuation strategy	Zone 1	Zone 2	Zone 3	Zone 4	IN (x 100)	Maximum outflow capacity exceeded?	Flood scenario 1	Flood scenario 2	Expected (conditional flood scenario probabilities: 25% for scenario 1 and 20% for scenario 2)
1	NP	NP	NP	NP	0	no	85	185	58
2	V	V	V	V	0	no	15	49	14
3	V	V	V	P	15	no	15	45	13
4	V	V	P	V	25	no	5	39	9
5	V	V	P	P	40	no	5	35	8
6	V	P	V	V	-	yes	-	-	-
7	V	P	V	P	-	yes	-	-	-
8	V	P	P	V	-	yes	-	-	-
9	V	P	P	P	-	yes	-	-	-
10	P	V	V	V	35	no	10	44	12
11	P	V	V	P	50	no	10	40	11
12	P	V	P	V	60	no	0	34	7
13	P	V	P	P	75	yes	-	-	-
14	P	P	V	V	-	yes	-	-	-
15	P	P	V	P	-	yes	-	-	-
16	P	P	P	V	-	yes	-	-	-
17	P	P	P	P	-	yes	-	-	-

As a reference, the columns "flood scenario 1" and "flood scenario 2" shows the estimated number of fatalities is case of actual flooding. As can be seen, the optimum evacuation strategy (strategy 12) leads to the smallest estimates for both flood scenarios. It should be noted than in case of no breaching occurs, zero fatalities are expected.

3.5 Three more example studies

In the previous section (3.4) the developed evacuation method was applied using a simplified example. In Appendix A, results of three more examples studies using this method are shown. This section provides an overview of the impact of available time for evacuation (as shown in Figure 47 in Appendix A) and how different flood scenarios affect the outcome of the developed method. In general, the following is concluded:

- *Less time for evacuation*: As shown in Appendix A section A.1, when less time is available for evacuation, fewer strategies are feasible due to a lower outflow capacity. The number of expected fatalities for feasible strategies does not depend on evacuation time. However, because of fewer strategies are feasible it may be that the optimum evacuation strategy (with a higher number of expected fatalities) will be different. Note that non-feasible strategies are excluded in this simplified example studies as the expected number of fatalities for such combinations will be high.

- *More time for evacuation*: As shown in Appendix A.2, when more time is available for evacuation, more evacuation strategies are feasible. As above, the number of expected fatalities for feasible strategies does not depend on evacuation time although the optimum strategy may change (with a lower number of expected fatalities). It is noted that strategies with higher number of preventive evacuees (expressed in terms of *IN*), does not necessarily lead to a lower estimated number of fatalities.

- *Different flood scenarios*: In the example of Appendix A.3, there is no direct link between the number of feasible evacuation strategies and flood scenario. The expected number of fatalities however, strongly depends on flood scenarios. As above, a higher number of preventive evacuees does not necessarily lead to a lower estimated number of fatalities.

Summarized results of the four simplified example studies (section 3.4 and Appendix A) are shown in Table 9 below (note that in this summary only the expected number of fatalities are shown). For each of the four example studies the optimum evacuation strategy is shown. For the three further example studies as discussed in Appendix A, the effectiveness of the optimum strategy (12) of the first simplified example is shown as well.

Table 9: Summarized results of the four simplified example studies assuming flood scenario probabilities of respectively 25% and 20%. (V: vertical evacuation, P: preventive evacuation).

		Evacuation type							
Study	Evacuation strategy (*optimum)	Zone 1	Zone 2	Zone 3	Zone 4	IN (x100)	OUT (x100)	Maximum outflow capacity exceeded?	Expected number of fatalities
First simplified example (section 3.4)	12*	P	V	P	V	60	65	no	7
Less evacuation time	5*	V	V	P	P	40	45	no	8
(Appendix A.1)	12	P	V	P	V	65	45	yes	-
More evacuation time	8*	V	P	P	V	75	85	no	3
(Appendix A.2)	12	P	V	P	V	60	85	no	7
Different flood scenarios	5*	V	V	P	P	40	65	no	15
(Appendix A.3)	12	P	V	P	V	60	65	no	16

Regarding the optimum evacuation strategy for the three further examples and the effectiveness of the optimum combination (12) of the first example, the following is concluded:

- *Less evacuation time*: Given an available evacuation time of 12 hours, the optimum strategy is shown to be combination 5 with a total estimated number of expected fatalities of 8 and 40 (x100) preventive evacuees. Combination 12 is not feasible in this case due to the limited capacity for preventive evacuees (*OUT*). In the first example, combination 5 was already considered to be a good option since the outflow of evacuees is relatively low and the expected number of fatalities is only marginally larger than that of combination 12.

- *More evacuation time*: Given an available evacuation time of 26 hours, the optimum strategy is shown to be combination 8. In this case the two zones with the lowest effectiveness of vertical evacuation (zones 2 and 3) are selected for preventive evacuation. The total estimated number of expected fatalities for this combination is 3 and the outflow of evacuees 75 (x100) persons. Combination 12 is also feasible in this example but leads to more expected fatalities because of the relatively high flood probability and impact of zone 2 when opting for vertical evacuation.

- *Different flood scenarios*: The optimum strategy for different flood scenarios (as illustrated in Figure 36 in Appendix A.3) is shown to be combination 5 with an expected number of fatalities of 15. The expected number of fatalities is higher mainly because of the higher flood probability for zone 2 which zone is characterized by many inhabitants, no possibility for preventive evacuation (given the available time) and poor possibilities for vertical evacuation. Combination 12, which is the optimum strategy in the first example, is also feasible in this example but leads to a higher number of expected fatalities.

3.6 Conclusions

The flexible evacuation method described in this chapter provides insight into the risk for loss of life when applying different evacuation strategies for a given flood threat and available evacuation time. Consequently, the optimum evacuation strategy can be determined (expressed in terms of expected loss of life) based on a mix of vertical and preventive evacuation. Per zone a uniform evacuation type is assumed (either vertical or preventive). The method is shown to be being able to deal with an uncertain and variable flood threat (in terms of available time and flood scenarios). The method takes into account, for each zone, flood probability and characteristics, and possibilities for vertical (both sheltering at home and public sheltering) and preventive evacuation. Accordingly, the method uses a water level forecast and dike strength information.

A simplified (first) example study as discussed in section 3.4, has been carried out to test the potential of the evacuation method. A simple system was considered (as shown in Figure 19), in which zone specific characteristics are taken into account as shown in Table 4. Two different flood scenarios were considered, one resulting in flooding of half of the zones, and the other resulting in flooding of all zones. For both flood scenarios, estimates per zone were determined for loss of life and the outflow of evacuees per evacuation type. By taking into account flood scenario probabilities, using fragility curves, the expected number of fatalities is determined for each zone and per evacuation type. For a given available evacuation time, based on a water level forecast and a threshold value at which evacuation must be complete, all feasible strategies are determined. Subsequently, the strategy resulting in the minimum expected number of fatalities is determined as optimum. For the simplified example, the optimum strategy turned out to be preventive evacuation for the zones where the flood probability is highest and the optimum strategy is the one with the highest number of feasible preventive evacuees. It should be noted that strategies exceeding the maximum outflow capacity (for a given evacuation time), are considered not feasible and are therefore rejected.

In addition to the first example study, three more example studies were carried out with the objective to analyse the impact of available time for evacuation (less and more) and different flood scenarios (section 3.5). From a comparison with the first simplified example study, the following is concluded:

- More or less evacuation time leads to more or fewer feasible strategies, respectively. The number of expected fatalities for feasible strategies does not depend on evacuation time although the optimum strategy may change because more/fewer zones can evacuate preventively.

- The feasible combination with the highest number of preventive evacuees is not necessary optimum although, in general, preventive evacuation leads to a lower number of fatalities. The total number of fatalities of the system depends on the combination of evacuation types for all zones.

- Selection of zones for preventive evacuation is based on zone’s effectiveness when opting for vertical evacuation (assuming both sheltering at home and public sheltering) whilst taken into account the impact on the roads with respect to the maximum outflow capacity.

4 Case Study Rotterdam

4.1 Introduction

In this chapter the generic method as discussed in chapter 3 will be applied for Rotterdam North. An overview of the system area is shown in Figure 23.

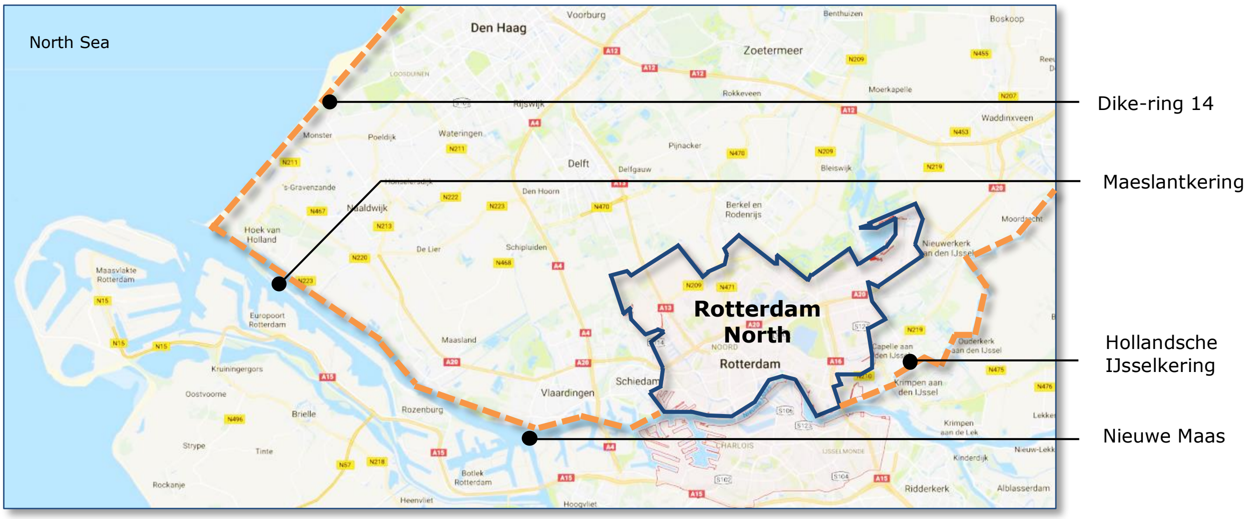

Figure 23: Overview of Rotterdam North

Rotterdam North is located within dike ring 14 along the Nieuwe Maas river. The city of Rotterdam is located in a coastal area which means that high water levels in the Nieuwe Maas are mainly caused by storm surges in combination with high tide at the North Sea (rather than large water discharges upstream). The Maeslantkering protects the river from extreme sea water surges and is closed when the water level at Rotterdam is forecasted to be NAP+3m (or NAP+2.9m at Dordrecht). An extreme flood threat will occur in case of storm surges at sea and the Maeslantkering fails to close. Although the design closure failure probability is 0.1%, research showed that the actual closure failure probability is considered to be 1% per closure event (Rijkswaterstaat, 2015).

Since Rotterdam is located in a coastal area, prediction times for high water levels are short (up to three days) as compared to prediction times for river dominated areas (more to the east in the Netherlands) as shown in Figure 2. Furthermore, storms at sea often coincide with extreme weather conditions in Rotterdam (heavy rainfall in combination with strong winds). This affects the available evacuation time and road capacities. In this study it is assumed that a threat is recognised three days before reaching the water level threshold value. This assumption is considered to be representative for 10% of the cases (as shown in Table 1). In this study four cases are considered with reference to the available evacuation time.

In total 346,800 people (CBS, 2016) are living in Rotterdam North. As can be seen in Figure 23, Rotterdam is surrounded by the cities of Schiedam and Vlaardingen. Although these cities, as well as Rotterdam South, are not considered in this study it is likely that in case of high water levels the probability of flooding in these areas is comparable. This will impact preventive evacuation possibilities for Rotterdam North and must be taken into account. According to a study (Rijkswaterstaat, 2015), limited preventive evacuation fractions of up to 15% can be expected for this densely populated area. Therefore, this study will focus on vertical evacuation as base evacuation strategy and selective preventive evacuation will only be applied provided sufficient time is available.

In this study a simplification is made that all people are considered to be self-reliant, i.e. imprisoned and hospitalised people are excluded. Also, social aspects are not taken into account. In other words, how people will actually react is not considered, only how people should react to minimise loss of life. It should be noted that these social aspects are highly uncertain and may have a large impact on the effectiveness of evacuation. Another simplification of the study is that the social and economic impact of the selected evacuation is not taken into account. Regarding this point, evacuation will have significant consequences (Kolen, 2013). Hence, the selected evacuation strategies will be based solely on minimising the loss of life probability.

In this chapter the five steps of the generic method as discussed in chapter 3 are applied for Rotterdam North (sections 4.2.1 up to 4.2.5), followed by a sensitivity analysis (section 4.3).

4.2 Method Application

In order to obtain the evacuation type per zone which minimizes the expected loss of life for Rotterdam North and prevent the roads from blocking, the following steps will be conducted (as described in section 3.3.1):

1. *Preparatory information* (section 4.2.1): Rotterdam North needs to be defined in terms of modular components (zones) and selection of appropriate evacuation strategies. The following key preparatory data must be collected: possibilities for preventive and vertical evacuation, dike failure locations and probabilities, flood scenarios, and water level threshold value.

2. *Select flood scenarios, evacuation time and consequences* (section 4.2.2)

3. *Translate the water level forecast to flood scenario probabilities* (section 4.2.3)

4. *Calculate expected loss of life values* (section 4.2.4)

5. *Evacuation strategy which minimizes loss of life* (section 4.2.5)

4.2.1 Prepare information

Modular Components

The Rotterdam North case area is divided into 47 zones which represent neighbourhoods according to CBS (Centraal Bureau voor de Statistiek). This division, instead of a division based on e.g. postal codes, is selected as most data is available per CBS neighbourhood. It should be noted that two significant disadvantages of a CBS neighbourhood division are the following:

- Most people do not know the CBS neighbourhood they live in but they do know the postal code. As communication is key for effective evacuation, it will therefore be more challenging to reach all people.

- CBS neighbourhood boundaries can be random and hence boundaries may be in between streets. In the simplified studies as described in chapter 3 the individual zones are separated by physical boundaries such as roads. This means that in the Rotterdam North case study it may happen that one part of a street should evacuate preventively whilst the other part should evacuate vertically to minimise loss of life. This however, is unlikely to happen in practice.

An overview of the CBS neighbourhoods of Rotterdam North is shown in Figure 48 and Table 32 in Appendix B.1. As can be seen, 47 zones are defined with the number of inhabitants ranging from 15 to 25,150 per neighbourhood. As the number of inhabitants in the neighbourhoods *Blijdorpsepolder*, *Kralingse Bos*, *Nieuwe Mathenesse* and *Spaanse Polder* are very low (<115), these neighbourhoods are omitted from the study. Furthermore, *Schiemond* and *Nieuwe Werk* are located "buitendijks" (outside the dike-ring) and are therefore also not taken into account. These neighbourhoods are excluded as their protection is totally different from the protection for neighbourhoods within the dike-ring.

Figure 24 below shows the number of inhabitants for Rotterdam North neighbourhoods based on a 100x100 m^2 population grid. As can be seen, most neighbourhoods are densely populated.

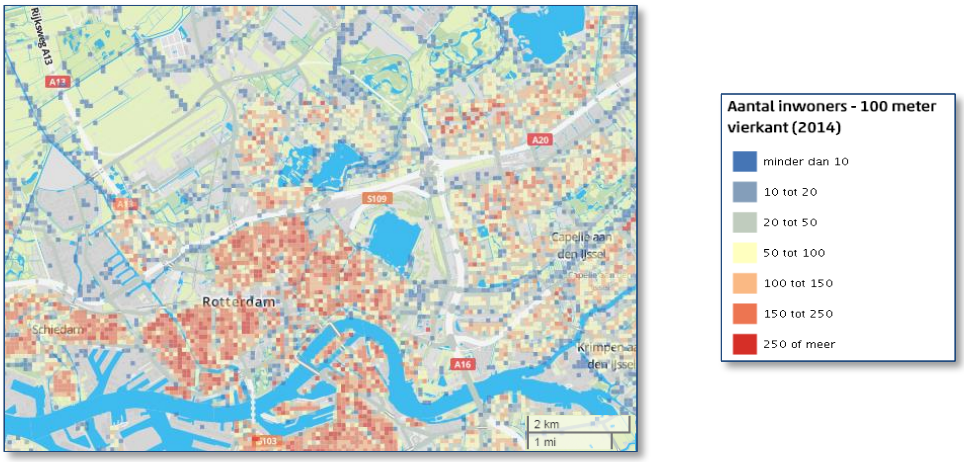

Figure 24: number of inhabitants for Rotterdam North based on a 100x100 m2 grid (CBS,2016)

Appropriate evacuation types

The following three evacuation types are selected for this study:

1. *Non-prepared evacuation*: This resembles the situation that people are not prepared and may be the case when flood occurs unexpectedly and/or when people choose not to prepare. This strategy mainly serves as a reference for comparison with (prepared) *vertical evacuation*.

2. *Vertical evacuation*: Regarding vertical evacuation, both public sheltering and sheltering at home are considered.

   - *Public sheltering*: preferred vertical evacuation option as it, in principle, results in a lower loss of life probability.

   - *Sheltering at home*: In case the public sheltering capacity in a neighbourhood is insufficient, people who cannot make use of public sheltering will shelter at home.

3. *Preventive evacuation*: Although the expected evacuation fraction is considered to be low for Rotterdam North (as shown in Table 1), selective implementation of preventive evacuation for critical neighbourhoods potentially reduces the overall probability for loss of life.

Details of the above evacuation types are found in section 2.3.

Since public sheltering capacities per neighbourhood are low compared with the number of inhabitants, public sheltering a standalone evacuation type per neighbourhood is excluded in this study. However, for comparison reasons the potential impact of all neighbourhoods opting either for 100% public sheltering or sheltering at home is investigated (shown in Figure 34).

Regarding *vertical evacuation*, inhabitants will shelter in a public shelter to the maximum extent possible and the remaining inhabitants will shelter at home (when public sheltering capacity is reached). This is illustrated in Figure 25 below.

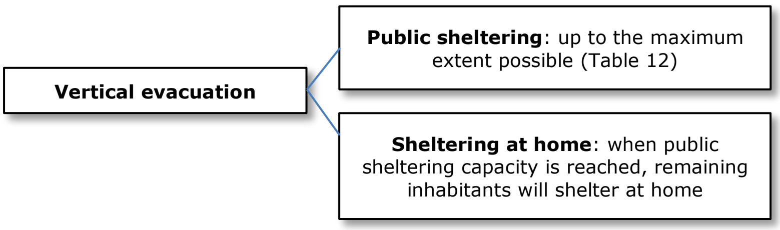

Figure 25: Public sheltering and sheltering at home as part of vertical evacuation for this study

Possibilities for preventive evacuation

In the following, road capacities are analysed for the main roads departing from Rotterdam North and the secondary roads within Rotterdam North. Besides, the corresponding preventive evacuation time is determined per neighbourhood.

The following assumptions are made for road capacities per lane under normal conditions (Kolen and Huizinga, 2017) as shown in Table 10 below.

Table 10: Road conditions under normal conditions

Road	Road capacity under normal conditions [cars/hour]
Main road	2200
Regional road (N-road)	1800
Secondary road (S-road)	1200

In this study it is assumed that under poor conditions such as heavy wind, rainfall and/or stressful situations (such as a flood threat), road capacities are one third of the capacity under normal conditions. All possible evacuation routes from Rotterdam North, with their specific advantages and disadvantages, are shown in Table 33 in Appendix B.2. Four exit points are considered suitable and only these will be taken into account (as shown below in Figure 26). Assuming 2.2 persons per car (Kolen and Huizinga, 2017), the outflow capacity in terms of the number of preventive evacuees per hour for the four suitable exit points is shown in Table 11. As shown, the total outflow capacity of preventive evacuees amounts to 5600 cars per hour, or 12320 evacuees per hour.

Table 11: Outflow capacities for the assumed exit points for Rotterdam North

Exit point	Road capacity under poor conditions [cars/hour]	Outflow capacity [persons/hour]
A13 to Delft	2200	4840
A20 to Gouda	2200	4840
N209 to Bleiswijk	600	1320
N471 to Berkel and Rodenrijs	600	1320
Total	**5600**	**12320**

Figure 26: Exit points taken into account for this study (green). The red exit points are rejected as an option for Rotterdam North

In order to prevent the roads from blocking the maximum total capacity should not be exceeded. When considering the maximum road capacity, it should be taken into account that in case of a flood threat also areas surrounding Rotterdam North will evacuate preventively and (partly) use these exit points. Based on the estimated number of people in surrounding areas under threat (1,050,000 people) and evacuation fractions (Maaskant et al., 2009), the number of preventive evacuees from surrounding areas that will also use these four exit points are estimated. It is assumed that preventive evacuees for surrounding areas will not use secondary roads within Rotterdam North for reaching the exit points.

All roads leading from the neighbourhoods to the exit points are considered to be secondary roads with a capacity (under poor conditions) of 600 cars/hour. Table 34 in Appendix B.2 shows the total number of lanes per neighbourhood leading to the exit points (the number of lanes has been determined using satellite images by Google Maps). Also shown are the total outflow capacities (assuming 2.2 passengers per car) and the minimum required evacuation time for 100% preventive evacuation of inhabitants for each neighbourhood. Key assumptions are:

- It is assumed that the movement of cars is evenly distributed over the evacuation time. This is unlikely under stressful conditions (such as a flood threat) as everybody most likely wants to evacuate as soon as possible. The effect however, of traffic congestions has been incorporated to some extent by taken 1/3 of the normal road capacities.
- All lanes are available and optimally used.

Possibilities for sheltering at home

When dry floors are present, sheltering at home can be considered, possibly in the home of neighbours, family and/or friends in case one's own home is not suitable. Figure 27 shows an estimate of the percentage of all buildings in Rotterdam North with a dry floor that can, in principle, be used for sheltering. As can be seen, in most neighbourhoods 80-100% of the buildings are suitable. This estimate is based on the height of buildings, the local ground level, the surface area of each building, an average floor height of 3 meters and taking into account local maximum water depths. Note that the number of houses suitable for sheltering is a fraction of the total number of buildings.

As can be seen, the dry-floor availability in the neighbourhood Het Lage Land is relatively low (20-40%). This neighbourhood has therefore been investigated to see whether 100% sheltering at home would be a feasible option in case of maximum water depths. Results of this investigation can be found in Appendix B.3, together with a similar study on Provenierswijk (which is a typical neighbourhood in Rotterdam North). It is assumed that a long-term stay (several days and nights) requires a minimum dry surface area of 3,72 m^2 per person (FloodProbe, 2013).

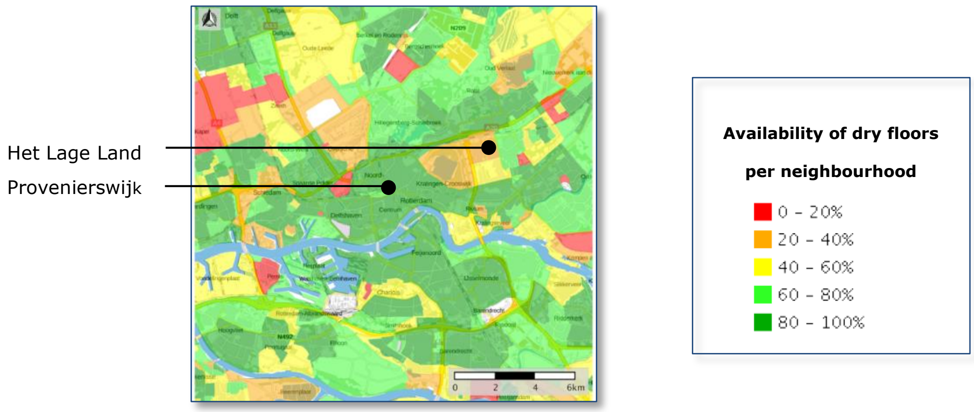

Figure 27: Availability of dry floors per neighbourhood (LIWO)

As shown in Appendix B.3, notwithstanding that *Het Lage Land* is the lowest area in Rotterdam North and has a relatively low percentage of suitable buildings for sheltering, enough dry surface area is available at homes for sheltering 100% of its inhabitants. It is therefore concluded (as shown in Appendix B.3), also taking into account results of Provenierswijk, that for each neighbourhood in Rotterdam North in principle enough sheltering capacity at homes is available for all inhabitants.

Possibilities for public sheltering

Public shelters can be used for sheltering large groups of people, if and when needed. Their primary function is to keep people safe in case of a (flood) threat. Public shelters will also act (secondary function) as collective pickup points for evacuees. Furthermore, support by rescue workers can be provided more quickly and more efficiently. A public shelter can be very basic since people are expected to take care of themselves in times of disaster (and prepare themselves as if they would "go camping"). Regarding dry space requirements, research by FloodProbe (2013) suggests that for a long-term stay (several days and nights) a minimum surface area of 3.72 m^2 per person will be required.

In the Netherlands, currently no public shelters have been identified. In the United States the use of public shelters is well-known and has proven to increase people's safety (in comparison with sheltering at home). Research by Terpsta (2009) has shown that people in the Netherlands are, in principle, willing to evacuate to a public shelter although they prefer sheltering at home, if possible. It can be assumed that public sheltering would be the preferred evacuation strategy if designated shelters are well prepared.

Designating public shelters beforehand (during the cold phase) and proper communication will encourage the use of public sheltering as an adequate evacuation strategy (as discussed in section 2.3.1). Firstly, people must be aware of the risk of flooding and secondly, people must be aware that if sufficient time is lacking, preventive evacuation is often not possible. In that case, focussing on vertical evacuation may be the safer option, in particular the use of public shelters. In the case of a flood threat people need to know, if preventive evacuation is not possible, how and where to evacuate vertically. The previous section has shown already that possibilities for sheltering at home in Rotterdam North are abundantly available. Appendix B.4 shows the estimated public sheltering capacities in Rotterdam North per neighbourhood.

In this study buildings that are considered suitable for serving as public shelter can accommodate large groups of people. Examples are educational buildings, libraries and (local) government buildings. Hospitals and other care institutions are excluded as their priority is to take care of people who are not self-reliant. In this study also private and semi-public offices are excluded although, if needed, in reality such buildings could be used.

The inventory is based on the following approach:

- Eight typical but diverse neighbourhoods in Rotterdam North are selected: *Agniesebuurt*, *Bergpolder*, *Blijdorp*, *Delfshaven*, *Dijkzigt*, *Het Lage Land*, *Provenierswijk* and *Stadsdriehoek*.

- For each of these neighbourhoods a public sheltering inventory is made based on the use of Google satellite images and street view whilst taking into account local maximum water depths. Results are shown in Table 37 in Appendix B.4.

- Using the inventory of potential public sheltering capacity for the eight neighbourhoods, an estimate is made of the potential public sheltering capacity in all remaining neighbourhoods in Rotterdam North. This estimate is based on a comparison of characteristics using Google satellite images and street view and by taking into account local maximum water levels. Results are shown in Table 38 in Appendix B.4 and a summary is shown in Table 12 below.

It can be concluded that limited public sheltering capacity is available in Rotterdam North (some 142.000 persons which represents about 40% of the total number of inhabitants). Besides, as can be seen, large differences can be observed between the various neighbourhoods. For example, in Bergpolder (some 8000 inhabitants) there are no potential public shelters whereas in Agniesebuurt (some 4100 inhabitants) there is potential public sheltering capacity for some 17000 persons. One reason for these large differences is the presence, or not, of (large) educational buildings such as the Rotterdam Hogeschool.

Table 12: Public sheltering capacity per neighbourhood in Rotterdam North (the colour coding is the same as used in Figure 27)

Neighbourhood	Public sheltering capacity per neighbourhood [% of inhabitants]
Agniesebuurt	>100
Bergpolder	0
Blijdorp	10
Bospolder	30
Cool	>100
Cs Kwartier	100
De Esch	50
Delfshaven	30
Dijkzigt	>100
Het Lage Land	20
Hillegersberg Noord	50
Hillegersberg Zuid	10
Kleinpolder	10
Kralingen Oost	>100
Kralingen West	10

Neighbourhood	Public sheltering capacity per neighbourhood [% of its inhabitants]
Landzicht	0
Liskwartier	20
Middelland	30
Molenlaankwartier	40
Nesselande	20
Nieuw Crooswijk	50
Nieuwe Westen	20
Ommoord	10
Oosterflank	20
Oud Crooswijk	20
Oud Mathenesse	20
Oude Noorden	10
Oude Westen	40
Overschie	20
Prinsenland	20

Neighbourhood	Public sheltering capacity per neighbourhood [% of inhabitants]
Provenierswijk	50
Rubroek	30
s'-Gravenland	10
Schiebroek	20
Schieveen	0
Spangen	10
Stadsdriehoek	>100
Struisenburg	50
Terbregge	10
Tussendijken	40
Witte Dorp	0
Zestienhoven	>100
Zevenkamp	10

Dike failure locations, flood scenarios and probabilities

For this section, results of the VNK2 research (Rijkswaterstaat, 2015) on dike-ring 14 are used. This research provides a.o. information on potential failure locations, dike failure probabilities and possible flood scenarios ranging from below normative to extreme (expressed as *tp-1d* and *tp+2d*, respectively).

Figure 28 shows all potential dike failure locations along the Nieuwe Maas for dike-ring 14. The following failure locations are taken into account in this study for Rotterdam North: *Schiedam Sluis Buitenhaven*, *Rotterdam Parksluizen*, *Rotterdam Boerengatsluis* and *Capelle West Nijverheidstraat*. The other failure locations have a minor impact as compared with the potential impact of the above four. It should be noted that, for simplicity reasons, the potential closure failure of the Hollandsche IJsselkering (as indicated in Figure 23) is excluded from this study. In reality, however, a closure failure may result in high water levels to the east of Rotterdam North and consequently may also lead to flooding of the eastern part of Rotterdam North.

Figure 28: Overview of potential failure locations for dike ring 14 along the Nieuwe Maas. After (VNK2)

In order to arrive at the above failure locations, and their corresponding failure probabilities (as shown in Table 39 in Appendix B.5), the following approach was followed in the VNK2 research:

- Dike-ring 14 is subdivided into dike sections, whereby dike sections 1 to 26 are considered relevant for Rotterdam North.

- Per dike section the dominant failure mechanisms are determined and subsequently the failure probability per year. According to the VNK2 study the main failure mechanism for Rotterdam North is overtopping/overflow as the dikes along the city are mostly hard structures where geotechnical mechanisms such as piping can be neglected.

- Apart from dike sections, dike segments have been defined. A dike segment consists of dike sections which, in case of failure, all result in a similar flood scenario. Note that above mentioned potential failure locations are related to failure of different dike segments.

- Per dike segment, flood scenarios have been determined. The flood scenarios, ranging from below normative to extreme, are based on high-water levels (caused by a storm) with a certain probability of occurrence. For instance, a normative flood scenario is based on a high-water level with a probability of 1/10.000 per year (indicated by *tp*), an above normative flood scenario with a probability of 1/100.000 per year (indicated by *tp+1d*) and an extreme flood scenario with a probability of 1/1000.000 year (indicated by *tp+2d*).

As an example, Figure 29 shows the potential flood scenarios (*tp*, *tp+1d* and *tp+2d*) expressed in water depth for failure at *Rotterdam Parksluizen*. Note that these values represent the maximum expected water depths for the whole flooding period. Hence, Figure 29 does not show the development of floods over time. The time element is not taken into account in this study since evacuation is considered to be completed when the water level threshold is reached.

(tp) (tp+1d) (tp+2d)

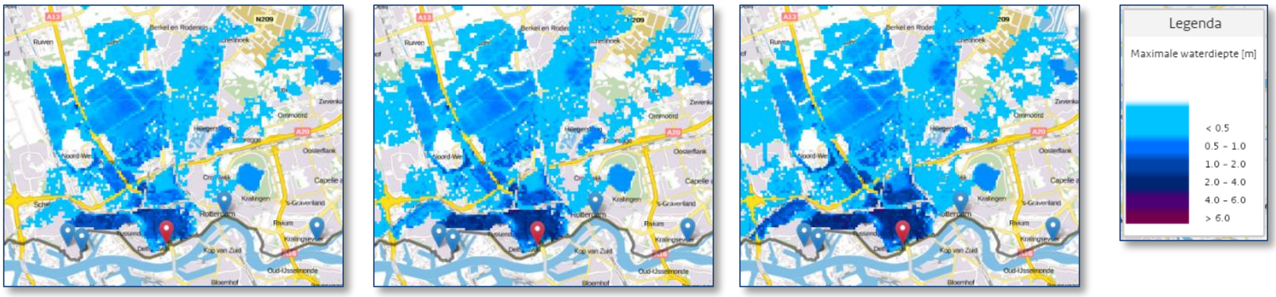

Figure 29: Flood scenarios for failure at Rotterdam Parksluizen ranging from normative (tp) to extreme (tp+2d)

With reference to sections 2.3, the following is noted:

- Consequences of a flood scenario in terms of a number of fatalities can be obtained by using the PBL model. Water depth, flow velocity and rise speed are important input parameters in this model. Table 40 in Appendix B.5 shows a summary of above normative (*tp+1d*) flood scenarios in terms of these parameters.

4.2.2 Select flood scenarios and evacuation time and determine the consequences

Water level forecast

In this study an extreme situation will be considered in which high water levels are expected due to a storm at sea whilst the Maeslantkering fails to close. In case of successful closure of the Maeslantkering, no floods are expected in Rotterdam North except for some areas located "buitendijks". As explained earlier, such areas are not taken into account in this study. The water level development over time as assumed for this study is shown in Table 13 and has a probability of occurrence of 1/100.000 per year (tp+1d) including a failure probability of 1/100 per closure event for the Maeslantkering. The peak water level at Rotterdam in this scenario is NAP+4,1 m (TMR2016).

Currently, no threshold value for evacuation is (yet) incorporated in the disaster protocol of Rotterdam. For this study the water level threshold value is assumed to be NAP+3,70 m, representing the moment at which evacuation must be complete. It is assumed that extreme weather conditions impact during a 24 hours period prior to the water level reaching the threshold value (T-0 hours).

Table 13: Water level development over time at Rotterdam North

Phase	Description	Actual water level	Expected water level at T-0 hours
T-3 days	Threat recognition	Normal tide from NAP-0.30 m to NAP+1.50 m	In case of successful closure Maestlantkering: NAP+2.50 m In case of closure failure Maeslantkering: NAP+3.70 m
T-5 hours	Closure failure Maeslantkering	Around NAP+2 m	NAP+3,70 m
T-0 hours	Water level reaches threshold value	NAP+3.70 m	-
T+5 hours	Water level reaches peak value	NAP+4.10 m	-

In this study it is assumed, that the water level development over time is the same at all dike failure locations.

Evacuation time

In Table 13 the lead time amounts to 3 days, which is the time between the moment of threat recognition (T-3 days) and the moment the evacuation must be complete (T-0 hours). The available evacuation time is part of the total lead time, and depends on the moment of threat recognition and the moment the evacuation should be complete. However, the available evacuation time is reduced by any decision time needed, while extreme weather conditions are assumed to further reduce the available evacuation time. In this study four different available evacuation times (42, 18, 5 or 0 hours) are considered based on evacuation calls given 3, 2, 1.5 or 1 day(s) prior to the moment the water level reaching the threshold value. This is illustrated in Figure 30.

Regarding the available evacuation time, key assumptions are the following:

- Time for decision making is ¼ day (6 hours) (Kolen and Vreugdenhil, 2016)
- Extreme weather conditions impact during a 24-hours period prior to the moment the threshold value is reached (Kolen et al., 2017)
- Time required for vertical evacuation is assumed to be negligible (as discussed in section 2.3.1) and hence, even if there is no evacuation time available, vertical evacuation is still considered feasible

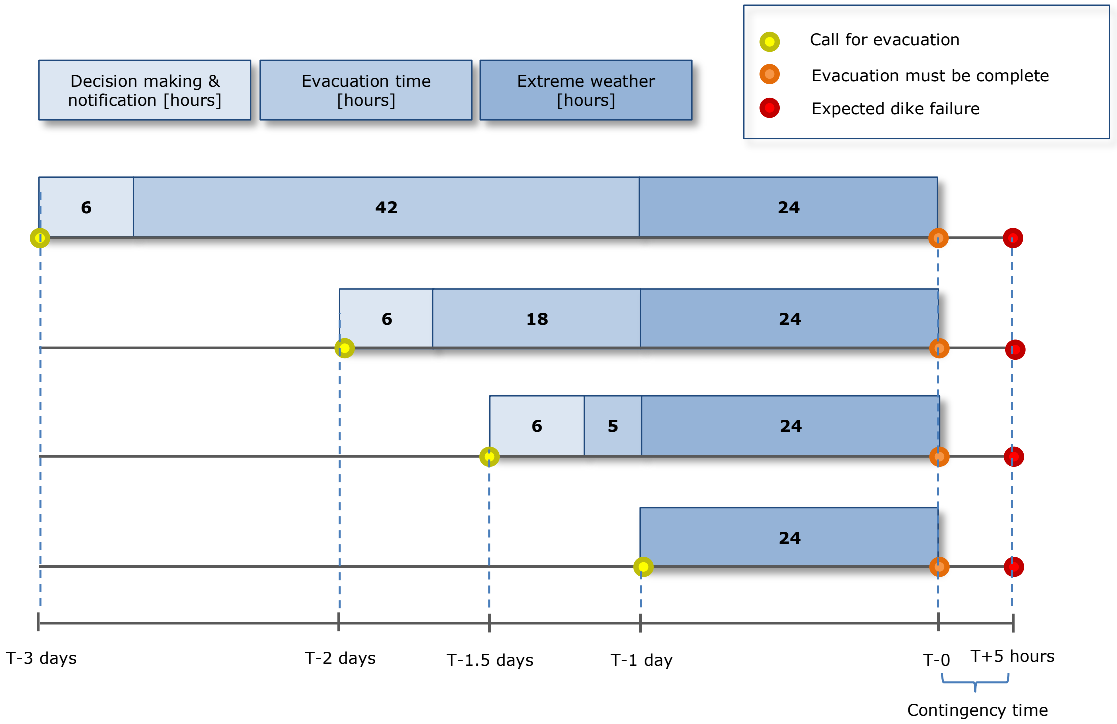

Figure 30: Timeline showing four different available evacuation times cases

Selected flood scenarios

Given the forecasted water levels, flood scenarios are extracted corresponding to the above normative (*tp+1d)* scenario (LIWO). Figure 31 shows these potential flood scenarios expressed in water depth for dike failure at the four locations described in section 4.2.1. As indicated earlier, these values represent maximum expected water depths over the whole flooding period.

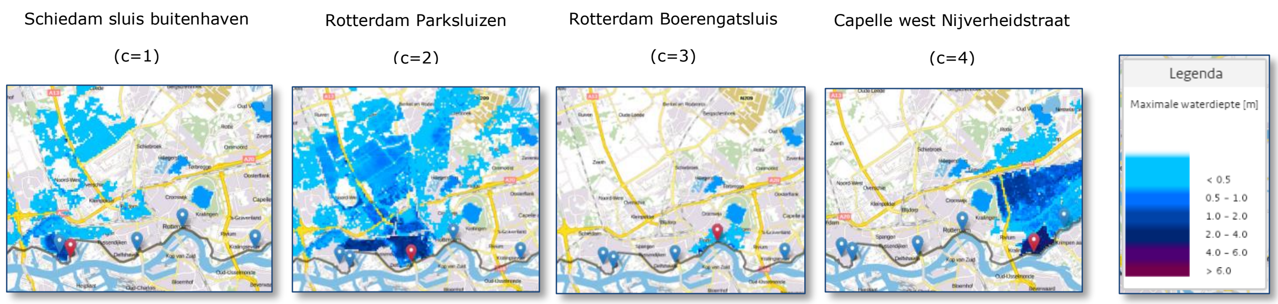

Figure 31: Above normative flood scenarios (tp+1d) for potential failure location at Rotterdam North (LIWO)

Key assumptions are the following:

- In this study one average water depth per neighbourhood and per flood scenario is assumed (average water depths are estimated based on LIWO results).
- Only rapid rising and remaining zones are taken into account (as discussed in section 2.3.2). Rapid rising zones are characterised by a water depth > 2 m and a rising speed > 0.5 m/hr. For remaining zones these values are < 2 m and < 0.5 m/hr, respectively.

- Although loss of life estimates in a *breaching zone* as described in section 2.3.2 are severe (Jonkman, 2007), these zones are relatively small when considering neighbourhoods. Breaching zones are therefore excluded from this research.

A summary of the flood characteristics as described above are shown per neighbourhood and per flood scenario in Table 40 in Appendix B.5.

Loss of life

Given the available evacuation time (42, 18, 5 or 0 hours) and dependent on the flood scenario, for each neighbourhood the loss of life and outflow of evacuees are estimated for each evacuation type (e.g. vertical or preventive evacuation). From this the potential effectiveness of each strategy is determined. As described in chapter 3 per neighbourhood one uniform evacuation type is assumed. Results are shown in Appendix B.6 (Table 42).

Regarding loss of life estimates, the PBL model is used. Key assumptions are the following (based on section 2.3.3):

- Mortality rate for successful preventive evacuation is 0.001%
- Mortality rate for public sheltering is 0.05%
- Mortality rate for sheltering at home is a function of flood scenario characteristics
- Mortality rate for being unprepared is a function of flood scenario characteristics
- Mortality rate for preventive evacuees in case of being exposed to flooding is 5% which is 5 times the average mortality rate of 1% (after: Jonkman, 2007)

Note that for vertical evacuation both public sheltering and sheltering at home is considered (as illustrated in Figure 25) based on the available capacities for Rotterdam North as discussed in section 4.2.1.

4.2.3 Translate water level forecast to flood scenario probabilities

As explained in section 2.4.2, fragility curves can be used to determine conditional dike failure probabilities and thus conditional probabilities of flood scenarios. However, due to the complex situation in coastal influenced areas (including waves, tides, wind and river discharges), no direct relation can be assumed between river discharge and water level (contrary to upstream rivers). Fragility curves for downstream (coastal influenced) areas can be constructed (Rongen, 2017), however, the fragility curves for the Rotterdam North area have not yet been fully established.

For the given flood threat, in order to take account of the effect of flood scenario probabilities, a fragility curve is estimated as shown in Figure 32. This fragility curve is based on a constructed fragility curve for a location close to Rotterdam North which is also overflow/overtopping dominated (Rongen, 2017).

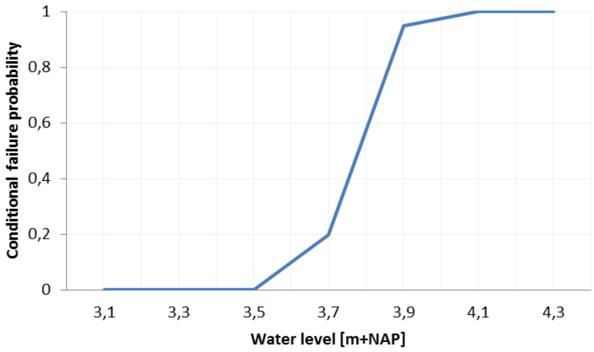

Figure 32: Assumed fragility curve for Boerengatsluis for the given flood threat. The fragility curves for the other three potential dike failure locations are similar

The relative conditional failure probabilities for the four failure locations is estimated based on the failure probabilities per year as obtained from the VNK2 study (Table 14). They are considered to be independent of each other.

Table 14: Failure probabilities per year (VNK2) and the assumed conditional failure probability per failure location for the moment the evacuation must be complete (T-0)

Ring Part/ flood scenario	Failure probability / year (VNK2)	Assumed conditional failure probability at T-0
Schiedam Sluis Buitenhaven	1.00E-03%	17,5%
Rotterdam Parksluizen	1.66E-04%	15%
Rotterdam Boerengatsluis	3.29E-03%	20%
Capelle West Nijverheidstraat	1.15E-04%	12,5%

For this study, only above normative flood scenarios are considered (tp+1d). In reality however, there is always a chance that the actual water level is lower or higher than forecasted, resulting in normative or extreme flood scenarios, respectively. In the recommendations (section 5.2) this subject will be discussed further.

4.2.4 Calculate expected loss of life

Assuming conditional failure probabilities of all four potential failure locations at Rotterdam North as shown in Table 14, the expected loss of life values per neighbourhood and per evacuation type are determined (as shown in Table 44 in Appendix B.6). Table 42 in Appendix B.6, as explained in section 4.2.2, shows the loss of life estimates per selected flood scenario.

As an example, results of the expected loss of life values for the evacuation strategies as discussed in 4.2.1 are shown in Figure 33, assuming unlimited available evacuation time.

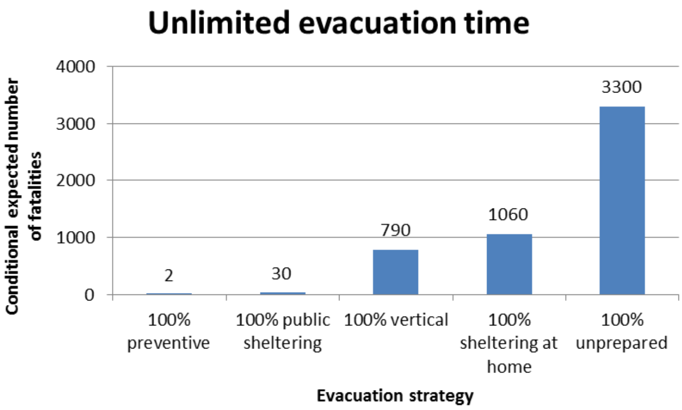

Figure 33: Expected number of fatalities in case all Rotterdam North inhabitants evacuate in the same way, assuming above normative flood scenarios, unlimited amount of available evacuation time and all strategies are feasible. Vertical evacuation is assumed to be a combination of public sheltering and sheltering at home

As can be seen, provided unlimited evacuation time is available, preventive evacuation minimizes loss of life. In practice however, the available evacuation time is often limited (Table 1) which will lead to a significantly higher loss of life value. 100% public sheltering is considered to be a good option but, as discussed in section 4.2.1, the public sheltering capacity in Rotterdam North is limited. Vertical evacuation, assuming both public sheltering (to the maximum extent possible) and sheltering at home, is considered feasible since it requires a relatively short evacuation time and the sheltering at home capacity is abundantly available in Rotterdam North (section 4.2.1). Vertical evacuation will therefore be considered as the base strategy. The optimum evacuation strategy for Rotterdam North, based on a combination of one evacuation type per neighbourhood (vertical or preventive), leads to a maximum loss of life value of 790 (when all inhabitants go for vertical evacuation) and will reduce if selective preventive evacuation is feasible within the available evacuation time. This will be investigated for the four evacuation times (42, 18, 5 and 0 hours as discussed in section 4.2.2) in the next step (section 4.2.5).

4.2.5 Evacuation strategy which minimizes the loss of life risk

In the following the optimum evacuation strategy is determined for the aforementioned (Figure 30) available evacuation times of 42, 18, 5 or 0 hours. As explained earlier, the base strategy is vertical evacuation, assuming both public sheltering (to the maximum extent possible) and sheltering at home. Neighbourhoods will be selected for preventive evacuation provided evacuation time is available to reduce the expected number of fatalities. Selection of neighbourhoods for preventive evacuation is based on the expected mortality rate when opting for vertical evacuation (in Table 15 referred to as prioritization) and the impact preventive evacuation would have on road traffic with respect to the maximum outflow capacity. It should be noted that as an optimization, relatively small neighbourhoods (in terms of the number of inhabitants) may be added provided some outflow capacity is still left (although such neighbourhoods may not rank highly in the prioritization). The results are shown in Appendix B.7 and in this section a summary is given.

Key assumptions related to the maximum road capacity are the following:

- The total outflow capacity at exit points is 12,320 persons per hour (section 4.2.1)
- The outflow of evacuees for each neighbourhood equals the number of its inhabitants in case of preventive evacuation and is zero in case of vertical evacuation

Table 15: Neighbourhood top-10 prioritization based on the expected mortality rate for vertical evacuation (full list shown in Appendix B.8 Table 47)

Prioritization ranking	Neighbourhood	Inhabitants, equals the impact on road capacity when opting for preventive evacuation	Expected mortality rate for vertical evacuation [%]
1	Witte Dorp	600	1.9
2	Oud Mathenesse	7200	1.3
3	Oude Westen	9300	1.1
4	Nieuwe Westen	19300	1.0
5	Het Lage Land	10500	1.0
6	Spangen	10300	0.9
7	Middelland	12000	0.8
8	Oosterflank	10500	0.4
9	Prinsenland	9900	0.1
10	Bergpolder	8000	0.1

Evacuation time of 42 hours

For an evacuation time of 42 hours the maximum outflow capacity for Rotterdam North amounts to 42 (hours) x 12,320 (persons/hour) = 517,500 persons for the total evacuation time. The number of preventive evacuees from surrounding areas amounts to 315,000 persons assuming that 30% of the estimated population of 1,050,000 from surrounding areas that are expected to flood as well (such as Schiedam, Vlaardingen, Rotterdam South, Capelle aan den IJssel, Ridderkerk, Barendrecht, Spijkenisse, Hoek van Holland and Naaldwijk) will also use the exit points of Rotterdam North. This means that the remaining outflow capacity for Rotterdam North amounts to 202,400 persons for the total evacuation time.

Figure 34 shows the conditional expected number of fatalities for the optimum strategy, as well as the base strategy (100% vertical evacuation) and 100% preventive evacuation assuming flood probabilities as shown in Table 14. Figure 35 shows the optimum strategy graphically.

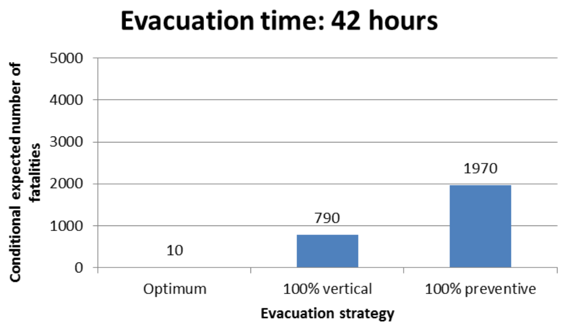

Figure 34: Conditional expected number of fatalities for Rotterdam North given an evacuation time of 42 hours

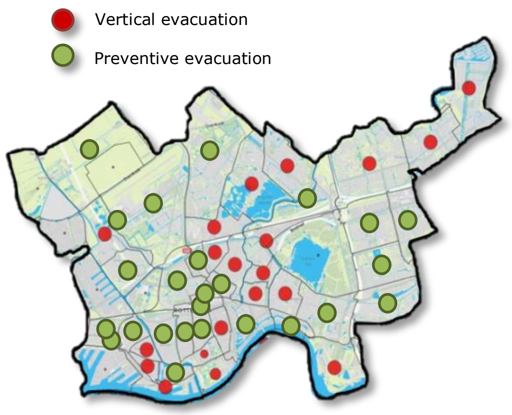

Figure 35: Representation of the optimum strategy for Rotterdam North given an evacuation time of 42 hours

Evacuation time of 18 hours

For an evacuation time of 18 hours the maximum outflow capacity for Rotterdam North amounts to 18 (hours) x 12,320 (persons/hour) = 221,800 persons for the total evacuation time. The number of preventive evacuees from surrounding areas amounts to 105,000 persons assuming that 10% of the estimated population of 1,050,000 from surrounding areas that are expected to flood as well will also use the exit points of Rotterdam North (Maaskant et al, 2009). This means that the remaining outflow capacity for Rotterdam North amounts to some 116,800 persons for the total evacuation time.

Figure 36 shows the conditional expected number of fatalities for the optimum strategy, as well as the base strategy (100% vertical evacuation) and 100% preventive evacuation assuming flood probabilities as shown in Table 14. Figure 37 shows the optimum strategy graphically.

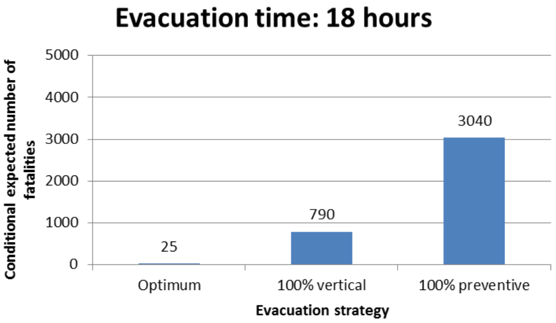

Figure 36: Conditional expected number of fatalities for Rotterdam North for an evacuation time of 18 hours

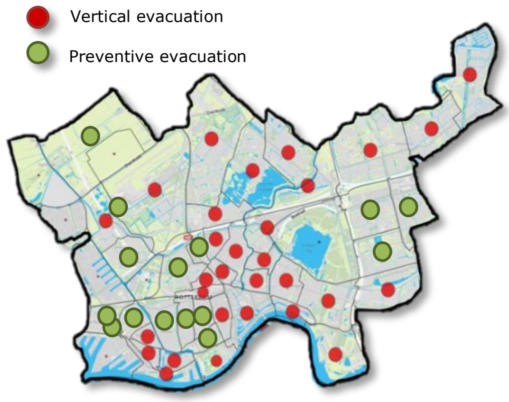

Figure 37: Representation of the optimum strategy for Rotterdam North given an evacuation time of 18 hours

Evacuation time of 5 hours

For an evacuation time of 5 hours the maximum outflow capacity for Rotterdam North amounts to 5 (hours) x 12,320 (persons/hour) = 61,600 persons for the total evacuation time. The number of preventive evacuees from surrounding areas amounts to 31,500 persons assuming that 3% of the estimated population of 1,050,000 from surrounding areas that are expected to flood as well will also use the exit points of Rotterdam North. This means that the remaining outflow capacity for Rotterdam North amounts to some 30,100 persons for the total evacuation time.

Figure 38 shows the conditional expected number of fatalities for the optimum strategy, as well as the base strategy (100% vertical evacuation) and 100% preventive evacuation assuming flood probabilities as shown in Table 14. Figure 39 shows the optimum strategy graphically.

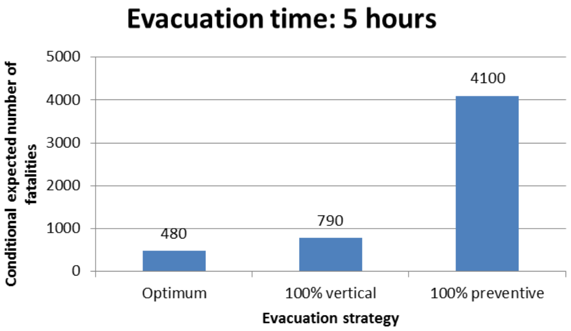

Figure 38: Conditional expected number of fatalities for Rotterdam North for an given evacuation time of 5 hours

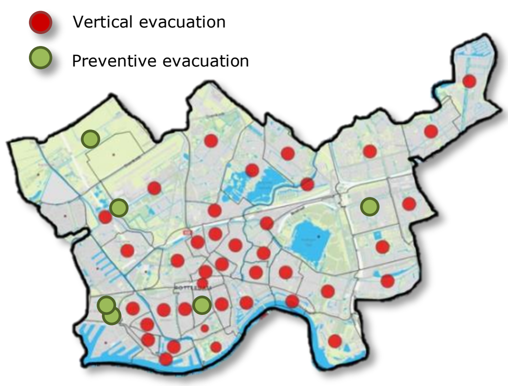

Figure 39: Representation of the optimum strategy for Rotterdam North given an evacuation time of 5 hours

Evacuation time of 0 hours

Given no available evacuation time, the maximum outflow capacity for Rotterdam North is assumed to be zero. Since dike failure is not unexpected in this case and time required for vertical evacuation is assumed to be negligible, vertical evacuation is still considered feasible.

Figure 40 shows the conditional expected number of fatalities for the optimum strategy, as well as the base strategy (100% vertical evacuation) and 100% preventive evacuation assuming flood probabilities as shown in Table 14. Note that the optimum evacuation strategy equals 100% vertical evacuation (base strategy). Figure 41 shows the optimum strategy graphically.

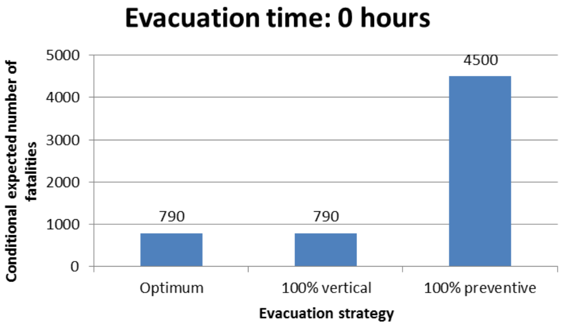

Figure 40: Conditional expected number of fatalities for Rotterdam North for a given evacuation time of 0 hours

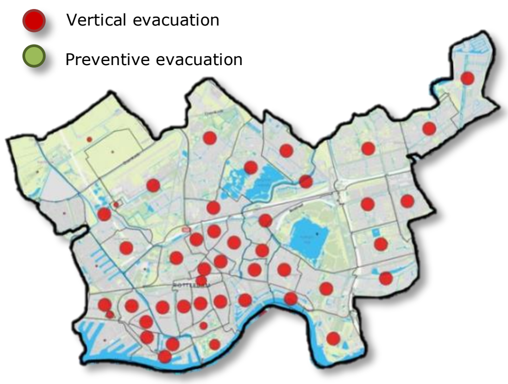

Figure 41: Representation of the optimum strategy for Rotterdam North given an evacuation time of 0 hours

In Table 16 below, a summary is shown for the optimum evacuation strategy given an evacuation time of 42, 18, 5 or 0 hours together with the number of preventive evacuees from Rotterdam North, the number of preventive evacuees from surrounded areas and the total maximum outflow capacity.

Table 16: Summary of the optimum strategy given an evacuation time of 42, 18, 5 or 0 hours

Available evacuation time [hours]	Optimum evacuation strategy	Number of preventive evacuees from Rotterdam North	Number of preventive evacuees from surrounded areas	Total maximum outflow capacity Rotterdam North	Expected loss of life
42	Figure 36	201,500	315,000	517,400	10
18	Figure 38	116,700	105,000	221,800	25
5	Figure 40	29,400	31,500	61,600	480
0	Figure 42	0	-	0	790

4.2.6 Conclusion base case

Regarding the results as shown in section 4.2.5 and summarized in Figure 42, the following is concluded:

- The optimum evacuation strategy as obtained through the flexible evacuation method results in a significant reduction of the expected loss of life as compared with the base strategy (100% vertical evacuation) and 100% preventive evacuation strategy. This reduction is stronger in case of longer available evacuation times.

- For a given available evacuation time the optimum strategy follows from the selection of neighbourhoods for preventive evacuation based on prioritization and the impact on traffic intensity with respect to the maximum road capacity. As an optimisation, relatively small neighbourhoods (in terms of the number of inhabitants) may be added provided some outflow capacity is still left (although such neighbourhoods may not rank highly in the prioritization).

- A shorter available evacuation time, for example because of postponing a call for evacuation or due to a long decision making process, leads to a higher expected number of fatalities for the optimum strategy. When no evacuation time is available, 100% vertical evacuation (base strategy) is the optimum strategy.

- The effectiveness (in terms of expected loss of life) of the base strategy is independent of the available evacuation time as the assumed time required for vertical evacuation is negligible. Opting for 100% preventive evacuation leads to a relatively high number of expected fatalities and increases significantly for shorter available evacuation times.

- Prioritization of neighbourhoods for preventive evacuation, based on the expected mortality rate for vertical evacuation, is not affected by the available evacuation time. The selection however, of the number of neighbourhoods for preventive evacuation for the optimum strategy reduces when less evacuation time is available (and vice versa). The steepness of the curve representing the expected loss of life for the optimum strategy sharply increases for available evacuation times less than 20 hours. This is caused by the most critical neighbourhoods being able to evacuate preventively for evacuation times larger than 20 hours.

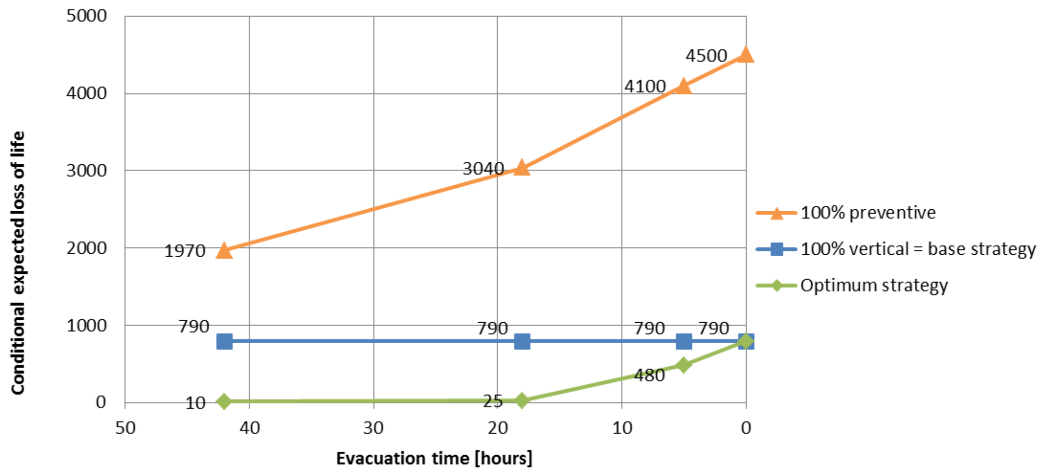

Figure 42: Expected number of fatalities for Rotterdam North for the optimum strategy, the base strategy (100% vertical evacuation) and for 100% preventive evacuation

4.3 Sensitivity analysis

In the previous section (4.2) the flexible evacuation method was applied for Rotterdam North. These results were obtained by model assumptions. In section 4.3.1 a closer look is taken at the sensitivity of five parameters. In section 4.3.2 three "what-if" scenarios are worked out to see how the outcome of the method might be affected by changes in specific variables.

4.3.1 Parameters sensitivity

This section takes a closer look at five parameters, i.e. *road capacity*, *water depth, public sheltering capacity*, *flood probability* and *available evacuation time*. An overview is provided of the impact of these parameters on the outcome of the method. It should be noted that this sensitivity analysis is conducted for a call for evacuation at T-2 days (in which the evacuation time is 18 hours).

Regarding the three parameters a best-case and worst-case is investigated as shown in Table 17 below. The best and worst cases for water depth, when flooded, are based on the average water depth differences between normative (tp), above normative (tp+1d) and extreme (tp+2d) scenarios (LIWO).

Table 17: Best-case and worst case parameters for the road capacity, water depth, public sheltering capacity and flood probability

Parameter	Best-case	Base case (section 4.2)	Worst-case
Road capacity	Base case +20%	Normal capacity/3 (Table 10)	Base case -20%
Water depth	Base case -30%	(Table 41 Appendix B.5)	Base case +30%
Public sheltering capacity	Base case +20%	(Table 38 Appendix B.4)	Base case -20%
Flood probability	Base case -10%	(Table 14)	Base case +10%
Available evacuation time	Base case -10%	18 hours	Base case +10%

In general, the following is concluded:

- *Road capacity*: A higher maximum road capacity (best-case) leads to a higher total outflow capacity for preventive evacuees. In general, the expected loss of life is lower for preventive evacuees and hence the expected number of fatalities is lower in the best case. The expected number of fatalities will be higher in the worst case because fewer inhabitants can indeed successfully evacuate preventively. It should furthermore be noted that a change in road capacities does not lead to a different prioritization of neighborhoods since flood characteristics and vertical evacuation possibilities do not change.

- *Water depth*: Water depth is an important flood characteristic and impacts on the expected mortality rate per neighborhood. When opting for vertical evacuation, a higher water depth (worst-case) leads to a higher mortality rate and a lower water depth (best-case) to a lower mortality rate. The prioritization of neighbourhoods for preventive evacuation is therefore likely to change when the water depth changes. However, as in this study a change in water depth is evenly applied over all neighbourhoods, the prioritization of neighbourhoods is rather insensitive to water depth. Possibilities for preventive evacuation are not dependent on flood characteristics as evacuation is assumed to be complete before the onset of the actual flood.

- *Public sheltering capacity*: The public sheltering capacity impacts on the expected mortality rate of neighbourhoods. As can be seen in Figure 32, the number of fatalities in case of public sheltering is significantly lower than in case of sheltering at home or vertical evacuation consisting of mix of public sheltering and sheltering at home. Therefore, by increasing the public sheltering capacity (best case) the number of fatalities decreases and by reducing the capacity (worst case) this number increases. As is the case for a change in water depth, a change in the public sheltering capacity will only have a limited impact on the prioritization for preventive evacuation. The reason is the change in public sheltering capacity is evenly applied over all neighbourhoods. Furthermore, the possibilities for preventive evacuation are not affected by a change in public sheltering capacity.

- *Flood probability*: The flood probability, by increasing or decreasing the conditional dike failure probabilities at Rotterdam North impacts on the expected mortality rate per neighbourhood. Increasing flood probability (worst-case) increases the expected number of fatalities and decreasing the flood probability (best-case) decreases the expected number of fatalities, as shown in Figure ?. As is the case for a change in water depth and public sheltering capacity, a change in the flood probability will only have a limited impact on the prioritization for preventive evacuation (as shown in Table 47 in Appendix B.8). The reason is the change in flood probability is applied over all potential dike failure locations.

- *Available evacuation time*: As already concluded in section 4.2.6, increasing or decreasing the available evacuation time impacts on the expected number of fatalities for the optimum strategy. As is the case for a change in road capacity, a change in available evacuation time does not lead to a different prioritization of neighborhoods since flood characteristics and vertical evacuation possibilities do not change.

Summarized results of the best-case and worst-case sensitivities (Appendix B.9) are shown in Table 18 below. For each of these sensitivities the optimum evacuation strategy is shown together with the effectiveness of the optimum evacuation strategy of the base case (section 4.2.5) in combination with the specific best/worst case parameters. Regarding available evacuation time, note that only the case is investigated given an evacuation time of 18 hours.

Table 18: Summary of the results for the optimum evacuation strategy for the sensitivity studies

Study	Base case strategy/ optimum strategy	Total outflow capacity minus preventive evacuees from surrounded areas	Preventive evacuees from Rotterdam North	Maximum outflow capacity exceeded?	Expected loss of life
Base case (section 4.2.5)	Table 45 Appendix B.7	116,800	116,700	no	25
Best-case road capacity	Base case	161,000	116,700	no	25
	Optimum (Table 48 Appendix B.9)	161,000	160,800	no	15
Worst-case road capacity	Base case	85,000	116,700	yes	390
	Optimum (Table 48 Appendix B.9)	85,000	85,000	no	50
Best-case water depth	Base case	116,800	116,700	no	20
	Optimum (Table 49 Appendix B.9)	116,800	116,700	no	20
Worst-case water depth	Base case	116,800	116,700	no	30
	Optimum equals base case	116,800	116,700	no	30
Best-case public sheltering capacity	Base case	116,800	116,700	no	24
	Optimum equals base case	116,800	116,700	no	24
Worst-case public sheltering capacity	Base case	116,800	116,700	no	26
	Optimum equals base case	116,800	116,700	no	26

Best-case flood probability	Base case	116,800	116,700	no	10
	Optimum equals base case	116,800	116,700	no	10
Worst-case flood probability	Base case	116,800	116,700	no	40
	Optimum equals base case	116,800	116,700	no	40
Best-case Available evacuation time	Base case	138,900	116,700	no	25
	Optimum (Table 52 Appendix B.9)	138,900	138,700	no	20
Worst-case Available evacuation time	Base case	94,500	116,700	yes	280
	Optimum (Table 52 Appendix B.9)	94,500	94,300	no	35

Regarding the optimum strategies in the sensitivity studies and the effectiveness of the optimum base-case strategy using the best and worst case parameters, the following is concluded:

- *Road capacity*
  - *Best-case*: The optimum strategy resembles the base case strategy but, due to the higher overall outflow capacity, includes more selected neighbourhoods for preventive evacuation. The expected number of fatalities is reduced significantly (15).
  - *Worst-case*: Due to the lower overall outflow capacity, the optimum strategy includes less selected neighbourhoods for preventive evacuation. The expected number of fatalities is higher (50). The optimum evacuation strategy from the base case results in a "wrong call" as the maximum outflow capacity is exceeded and leads to a significantly higher expected number of fatalities (390). Another reason for the different optimum strategy is that relatively small neighbourhoods (in terms of inhabitants) have been added for optimization purposes.
- *Water depth*:
  - *Best-case*: The optimum strategy does not differ significantly from the base case in terms of neighbourhoods selected for preventive evacuation. The reason is that the prioritization is almost similar to that of the base case and because of the inclusion of only small neighbourhoods for optimization purposes. The expected number of fatalities is the same (when rounded) as the optimum strategy of the base case (20).
  - *Worst-case*: The optimum strategy is the same as the optimum strategy for the base case. The expected number of fatalities (30), however is (as expected) higher since the flood characteristics are worse.
- *Public sheltering capacity*:
  - *Best*-case: The optimum strategy is the same as the optimum strategy for the base case. The expected number of fatalities (24), however is (as expected) lower since the possibilities for vertical evacuation have improved. Note that the prioritization is also the same as for the base case.
  - *Worst*-case: The optimum strategy is the same as the optimum strategy for the base case. The expected number of fatalities (26), however is (as expected) higher since the possibilities for vertical evacuation have reduced. Note the prioritization is slightly different from the one for the base case but this does not lead to a different optimum strategy.

- *Flood probability*:

  - Best-case: The optimum strategy is the same as the optimum strategy for the base case. The expected number of fatalities (10), however is (as expected) lower since the flood probabilities are reduced.

  - Worst-case: The optimum strategy is the same as the optimum strategy for the worst-case. The expected number of fatalities (40), however is (as expected) higher since the flood probabilities are increased.

- *Available evacuation time*:

  - *Best-case*: The optimum strategy resembles the base case strategy but, due to the higher overall outflow capacity, includes more selected neighbourhoods for preventive evacuation. The expected number of fatalities is reduced to 20.

  - *Worst-case*: Due to the lower overall outflow capacity, the optimum strategy includes less selected neighbourhoods for preventive evacuation. The expected number of fatalities is higher (35). The optimum evacuation strategy from the base case results in a "wrong call" as the maximum outflow capacity is exceeded, leading to a significantly higher expected number of fatalities (280).

The expected loss of life estimates for the optimum evacuation strategy per sensitivity parameter is graphically shown in Figure 43. As can be seen, flood probability, available evacuation time and the road capacity are the most sensitive parameters and water depth and public sheltering capacity are significantly less sensitive to changes. The prioritization of neighbourhoods for preventive evacuation, as shown in Table 47 in Appendix B.8, was found to be rather insensitive to parameter changes when evenly applied over all zones.

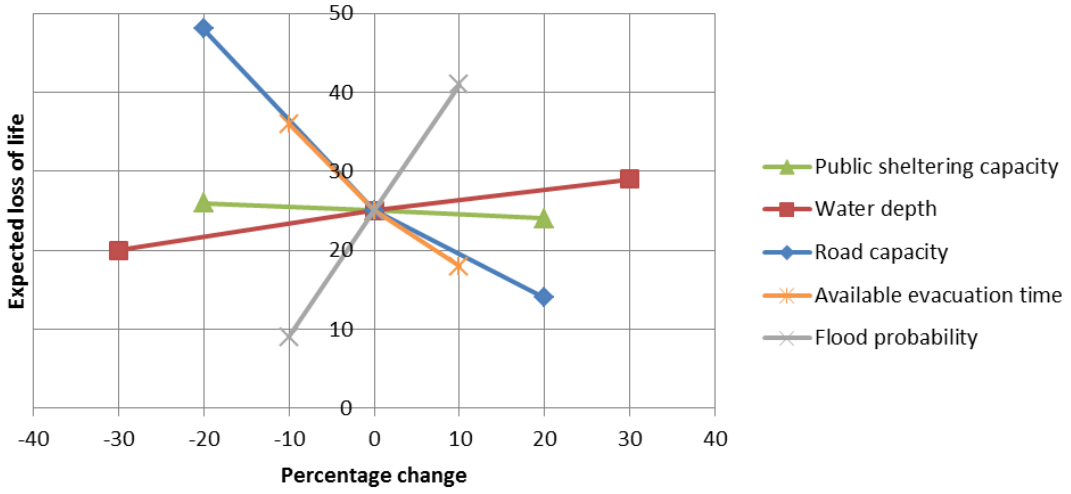

Figure 43: A graphical representation of expected loss of life estimates for the optimum evacuation strategy per sensitivity parameter

4.3.2 What-if scenarios

In this section a number of scenarios is worked out to see how the outcome of the flexible evacuation method will be affected by changes in specific variables (or boundary conditions). The following scenarios are worked out in more detail:

1. What if 100% public sheltering is possible for the top-four critical neighbourhoods?

2. What if the conditional failure probability for one potential failure location is extremely high?

3. What if four random neighbourhoods already started evacuating preventively, independent of the base strategy and decisions by the authority?

Summarized results of what-if scenarios (Appendix B.9) are shown in Table 19 below. For each of these scenarios the optimum evacuation strategy is shown together with the effectiveness of the optimum evacuation strategy of the base case (section 4.2.5). Regarding the available evacuation time, only the case given an evacuation time of 18 hours is investigated.

Table 19: Summary of results for the optimum evacuation strategy for the what-if scenarios compared with the what-if scenarios but using the base case strategy (section 4.2.5)

		Optimum strategy/base case strategy	Total outflow capacity minus preventive evacuees from surrounded areas	Preventive evacuees from Rotterdam North	Maximum outflow capacity exceeded?	Expected loss of life
	Base case (section 4.2.5)	Table 45 Appendix B.7	116765	116705	no	25
1	100% public sheltering is possible for the top-four critical neighbourhoods	Optimum (Table 53 Appendix B.9)	116765	116755	no	18
		Base case strategy	116765	116705	no	25
2	Failure probability for one potential failure location is extremely high	Optimum equals base case strategy	116765	116705	no	28
		Base case strategy	116765	116705	no	28
3	4 neighbourhoods already started evacuating preventively, independent of the base strategy and decisions by the authority	Optimum (Table 53 Appendix B.9)	116765	116520	no	35
		Base case strategy	116765	137885	yes	290

The following is concluded per what-if scenario:

- *What if 100% public sheltering is possible for the top-four critical neighbourhoods?* For this scenario, public sheltering is possible for 100% of the inhabitants of the top-four critical neighbourhoods (Witte Dorp, Oud Mathenesse, Oude Westen and Nieuwe Westen) as shown in Table 19. The optimum strategy for this scenario resembles the optimum strategy for the base case but, the top-four critical neighbourhoods will evacuate vertically (in this case 100% public sheltering) and other neighbourhoods are selected for preventive evacuation (based on the "new" prioritization). As shown in Figure 44, the expected number of fatalities (18) is lower for this scenario. Besides, the expected loss of life executing the base strategy (100% vertical evacuation) reduces significantly to 390 (as compared to a 790 for the base case as shown in Figure 44).

- *What if the conditional failure probability for one potential failure location is extremely high?* For this scenario the conditional failure probability of the potential dike failure location Schiedam Sluis Buitenhaven, as shown in Figure ?, is assumed to be 85% instead of 17,5%. This could happen, for example, due to a vessel collision with the water defence structure. The prioritization of neighbourhoods for preventive evacuation is likely to change when the flood probability changes. However, as flooding due to failure at Schiedam Sluis Buitenhaven only affects a limited number of neighbourhoods, the prioritization is rather insensitive to this particular change in failure probability. Therefore, the optimum strategy is in this particular case the same as in the base case. As shown in Figure 44, the expected number of fatalities (28) though is slightly higher.

- *What if four random neighbourhoods already started evacuating preventively, independent of the base strategy and decisions by the authority?* For this scenario the (randomly picked) neighbourhoods Het Lage Land, Cool, Hillegersberg-Noord and Hillegersberg-Zuid are assumed to evacuate preventively independent of the base strategy and decisions by the authority. The prioritization of neighbourhoods for preventive evacuation is not affected but of the remaining neighbourhoods fewer can evacuate preventively due to road capacity limitations. This leads to a higher expected number of fatalities (35) for the optimum strategy for this scenario. For this particular case, when following the evacuation strategy from the base case, the maximum outflow capacity would be exceeded. This would result in a significantly higher expected number of fatalities (290 as shown in Table 19).

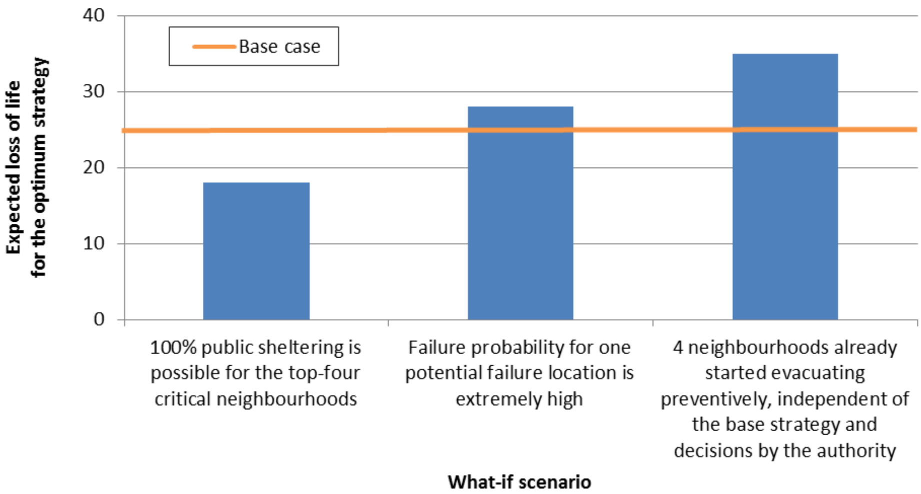

Figure 44: Expected number of fatalities for the optimum strategy for the what-if scenarios compared with the optimum strategy for the base case

5 Conclusion and recommendation

5.1 Conclusion

The main research question of this master of science thesis was:

In case of a flood threat and given a call for evacuation, what is the optimum evacuation strategy by a combination of vertical and preventive evacuation, in order to minimize the risk for loss of life?

During this thesis a flexible evacuation method was developed and applied to a case study on Rotterdam North. This method determines the optimum evacuation strategy, in terms of the expected loss of life, for a given flood threat and an available time for evacuation. The optimum strategy results in a significant reduction of the expected loss of life as compared with 100% vertical or 100% preventive evacuation. This reduction increases when the available evacuation time increases.

Starting from the base strategy (vertical evacuation) and given an available evacuation time, the optimum strategy as a mix of vertical and preventive evacuation, follows from the selection of zones for preventive evacuation. The prioritization of these zones is based on the expected mortality rate when opting for the base strategy (assuming both sheltering at home and public sheltering). Zones ranking highly in the prioritization, also referred to as critical zones, are characterised by a relatively high conditional flood probability, severe flood characteristics and/or poor possibilities for vertical evacuation (e.g. due to the absence of dry floors and/or buildings suitable for public sheltering). Preparatory work for the prioritization can already be done during the cold phase (prior to an actual flood threat).

The flexible evacuation method was applied to a case study on Rotterdam North. This thesis confirms findings of previous publications that for the region of Rotterdam, focussing on vertical evacuation, and using preventive evacuation as an additional measure when time is available, is most effective for reducing the expected loss of life for a given flood threat.

In the case of a flood threat and given the available time for evacuation, the expected loss of life corresponding to the optimum evacuation strategy is most sensitive to flood probability, available evacuation time and road capacity. Flood characteristics and public sheltering capacity are found to be less important. In particular, the available evacuation time is found to be crucial and hence, decision makers should act quickly and preparatory work should already be carried out as much as possible in the cold phase. The prioritization of zones for preventive evacuation was found to be rather insensitive especially to parameter changes when evenly applied over all zones. However, a change in available evacuation time or road capacity does impact on the optimum strategy as the maximum outflow capacity of the threatened area is affected.

In general, shorter available evacuation times cause the expected loss of life to increase (except for 100% vertical evacuation) since fewer people (located in critical zones) can evacuate preventively. When preparatory data is collected during the cold phase and optimized during the warm phase, the flexible evacuation method can identify the optimum strategy in a very short period of time. This method can therefore significantly improve the current approach where all data gathering, consultations, meetings, etc. are carried out during the warm phase (actual flood threat).

When the available road capacity is smaller or the evacuation time shorter than assumed, the evacuation strategy obtained through the flexible evacuation method may result in a significant increase of expected loss of life since people may be exposed to the flood whilst evacuating (when people are extra vulnerable).

By investigating what-if scenarios, it is shown that the flexible evacuation method can cope with changes in specific variables (or boundary conditions). If, for instance, during the warm phase one failure location appears to be (extremely) weak, or some zones already started evacuating preventively, the model can quickly adapt to this new boundary conditions.

Finally, improving opportunities for public sheltering in critical zones reduces the expected loss of life (both for the optimum and base strategy), especially so when 100% public sheltering in critical zones is possible. These improvements can be realized during the cold phase.

5.2 Recommendations

This section provides recommendations for the improvement and implementation of the developed flexible evacuation method and recommendations related to the optimization of case study results for Rotterdam North.

Recommendations for improvement of the flexible evacuation method

In this study, it is assumed that the movement of cars is evenly distributed over the evacuation time. In practice, this is unlikely under stressful conditions (such as a flood threat) as most people probably want to evacuate as soon as possible. Therefore, the road intensity may be (too) high early in the evacuation period. To a certain extent this is taken into account by assuming 1/3 of the normal road capacities during a flood threat. It is recommended however, to further investigate this effect especially so as the sensitivity analysis showed the road capacity to be a key parameter.

It is recommended to implement the conditional failure probability of potential failure locations to take into account the possibility that dike failure occurs before the threshold value is reached. This possibility, although being lower for lower water levels, cannot be ignored. Especially for slowly rising water levels, and/or piping dominated failure mechanisms this risk can be significant. Further research is recommended to implement this uncertainty in the flexible evacuation method.

As concluded, when the actual available evacuation time is less than expected, the evacuation strategy based on the forecasted available evacuation time will result in a significant increase in expected loss of life as people are risking to be exposed to the flood while evacuating. It is therefore recommended to implement the uncertainty in available evacuation time by incorporating probabilities and consequences. Note that consequences of changes in available evacuation time can already be established through the flexible evacuation method, i.e. only probabilities should be added. Besides, it is recommended to investigate whether additional contingency time should be built into the method.

In this study one flood scenario is selected for each failure location based on a single forecasted water level. It is recommended to implement the uncertainty in the extent of flood scenarios (ranging from below normative to extreme) by incorporating the uncertainty in the water level forecasts. In order to do so, probabilities and consequences of different water levels should be incorporated.

In this study the selection of the optimum evacuation strategy is solely based on minimizing loss of life whilst excluding other potential factors. In reality however, authorities will take account of the economic and societal impact of an evacuation strategy. It is recommended to investigate how this can be incorporated in the developed method.

It is furthermore recommended to take a closer look at the interdependency of dike failures in case of high water levels. In this study failure probabilities of multiple dike sections were considered independent. In reality however, this may not be the case since one dike failure may potentially reduce the hydraulic load on surrounding sections.

Recommendations for implementation of the method

As shown, the available evacuation time is a sensitive parameter and impacts heavily on the expected loss of life. Therefore, when using for the flexible evacuation method, it is recommended to carry out preparatory work as much as possible during the cold phase (when there is no actual flood threat). In this way, the method can be quickly optimized during the warm phase (when there is an actual flood threat) and no valuable time is lost. Preparatory work that can be carried out during the cold phase includes zone prioritization for preventive evacuation and establishing potential evacuation routes. The prioritization is based on potential flood scenarios, dike strength information and possibilities for vertical evacuation (both public sheltering and sheltering at home). Most of these information is well accessible, for instance by using LIWO database.

It is recommended to make people aware of the base strategy (vertical evacuation) and inform them how to act in case of a flood threat. Together with fast decisions by the authority this may lower the chance that people will decide for themselves to evacuate preventively (which could put people at risk and decrease the effectiveness of the optimum strategy).

There is currently no emergency protocol for the Netherlands in which a water-level threshold value is specified for triggering specific evacuation actions in case of a flood threat. Also there are no designated public shelters (yet). It is recommended to update the emergency protocol so as to include the above.

Recommendations on optimizing Rotterdam North case study results

For the case study conditional failure probabilities are assumed based on fragility curves obtained for a location close to Rotterdam North and failure probabilities (per year) extracted from the VNK2 study. It is recommended to establish fragility curves for the actual Rotterdam North area although it should be noted that due to the complex situation in coastal areas, it may be difficult to obtain conditional failure probabilities from a single fragility curve. It is furthermore recommended to investigate the potential of other methods for determining conditional dike failure probabilities so as to increase the accuracy of flood probabilities.

For the case study, zones were defined as CBS neighbourhoods. This definition, instead of a division according to e.g. postal codes, is selected as most data is available per CBS neighbourhood. There are two significant disadvantages of a CBS neighbourhood definition. First, most people do not know their CBS neighbourhood which challenges communication between the authorities and the public and second, boundaries between neighbourhoods may be 'random'. The latter could, when using the current method, result in preventive evacuation for one part of a street and vertical evacuation for the other. This is unlikely to happen in practice as people may copy the behaviour of their neighbours. It is therefore recommended to do further research on the optimal division of zones (for instance postal code areas).

In this study a simplification is made by assuming that all people are self-reliant, i.e. imprisoned and hospitalised people are not taken into account. It is recommended to include non-self-reliant people in the evacuation method. In general, these people will be more vulnerable which should be taken into account when prioritizing preventive evacuation and/or public sheltering.

For a limited number of neighbourhoods an inventory was made of public sheltering capacities. For the remaining neighbourhoods the public sheltering capacity was estimated by comparison of neighbourhood specific characteristics using Google Maps and Streetview. Firstly, the accuracy of the inventory based on Google Maps should be confirmed by further checking on site. Secondly, it has not been investigated whether building authorities would indeed accept the selected building(s) for sheltering. Thirdly, it is recommended to investigate whether public sheltering in another area could be effective in which case public sheltering could be prioritized (as a single evacuation type). As concluded, when public sheltering is possible for inhabitants in critical neighbourhoods, both the expected loss of life for the base strategy and the optimum strategy is reduced. Therefore, it is recommended to investigate possibilities for implementing designated public shelters in critical zones.

In this study flood characteristics are averaged over the corresponding neighbourhoods. Therefore, the effect of rapid rising zones may be averaged out over remaining zones which would result in a significantly lower expected mortality rate. In order to increase the accuracy and reliability of the case study results, it is recommended to further investigate the effect of local flood characteristics.

Final recommendation

The title of the PhD thesis by Kolen, *"Certainty of uncertainty in evacuation for threat driven response"*, perfectly describes uncertainties surrounding the evacuation in response to a flood threat. It is therefore recommended to test the evacuation procedures in the Netherlands in a real-life situation during which decision processes by authorities and citizens are investigated as well as the feasibility and effectiveness of evacuation strategies. Findings can be used for validation and calibration of the flexible evacuation method.

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Appendices

Appendix A - Three more example studies

In follow-up of the first example study that was discussed, step by step, in section 3.4, in this appendix results of three further examples studies are shown. These further studies are variants of the first example study: (1) *less time for evacuation*, (2) *more time for evacuation* and (3) *different flood scenarios*. For these further studies the following data is assumed the same as for the first example study:

- System as shown in Figure 10 and zone characteristics as presented in Table 3
- Conditional failure probabilities for dike sections 1 and 2 as given in Figure 13

A representation of the available time for the simplified example studies are shown in Figure 45.

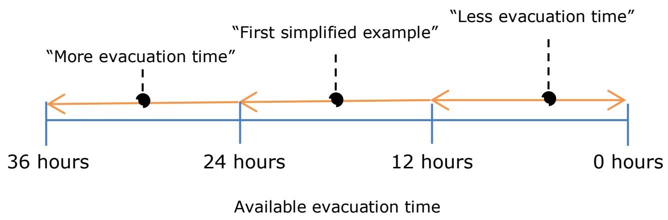

Figure 45: Representation of the available evacuation time for the simplified example studies

A.1 Less time for evacuation

In this example the same flood scenarios are used as in the simplified example of section 3.4 (Figure 12). Flood scenario 1 ($c = 1$) leads to flooding of zone 1 and 3 and flood scenario 2 ($c = 2$) leads to flooding of all four zones.

Less time available for evacuation can be the case when either one or all of the following applies:

- Different water level forecast with a faster rise to the threshold water level (as shown in Figure 46).
- More time required for threat notification and/or decision making (Figure 36)
- Extreme weather conditions during the lead time, resulting in a shorter evacuation time as people cannot evacuate safely

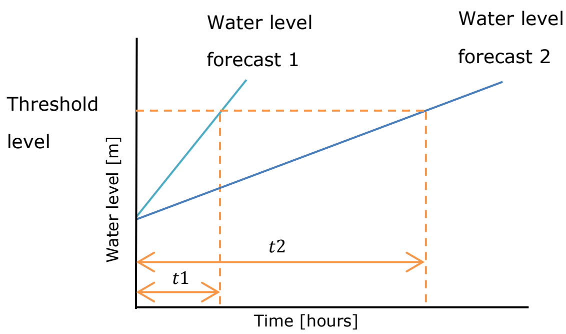

Figure 46: Representation of the relation between water level propagation and the lead (evacuation) time

The outflow of evacuees and the estimated number of fatalities per zone and per evacuation type is shown in Table 20 and 21, for flood scenario 1 and 2, respectively.

Table 20: The outflow of evacuees (Ei) and loss of life (Li) for evacuation type (j) per zone (i) for flood scenario 1 (assuming 12 hours for evacuation)

c = 1	**Ei (x 100)**				**Li**			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
j = 1	0	0	0	0	50	0	35	0
j = 2	0	0	0	0	5	0	10	0
j = 3	x	x	25	15	x	x	0	0

Table 21: The outflow of evacuees (Ei) and loss of life (Li) for evacuation type (j) per zone (i) for flood scenario 2 (assuming 12 hours for evacuation)

c=2	**Ei (x 100)**				**Li**			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
j = 1	0	0	0	0	50	75	35	25
j = 2	0	0	0	0	5	30	10	4
j = 3	x	x	25	15	x	x	0	0

Regarding the effectiveness of evacuation types, the following assumptions are made:

- In contrast with the first example, zone 1 is not able to fulfil the boundary condition $N_i \leq C_i$ because of less evacuation time. Therefore, the preventive evacuation (*j=3*) is rejected as an option for this zone. Preventive evacuation is also not an option for zone 2, as was the case in the first example.

- Less time for evacuation does not lead to a larger number of fatalities for vertical evacuation (*j=2*). This is a reasonable assumption since vertical evacuation requires a relatively short evacuation time and should be feasible within the time frame assumed for this case.

- Number of preventive evacuees (E_i) for zones 3 and 4, when opting for preventive evacuation is the same as in the first example and is not reduced. The reason is that for these strategies all people located in these zones are able to evacuate within the assumed evacuation time.

Taking into account the same flood probabilities as in the first example (25% for flood scenario 1 and 20% for flood scenario 2) the results of the expected number of fatalities (*Li)* are shown in Table 22.

Table 22: Outflow of evacuees (Ei) and the expected value for loss of life (Li) for flood scenarios probabilities of respectively 25% and 20% (assuming 12 hours for evacuation)

	Ei (x 100)				**Expected value for Li**			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
j = 1	0	0	0	0	23	15	16	5
j = 2	0	0	0	0	2	6	5	1
j = 3	x	x	25	15	x	x	0	0

Using these expected loss of life estimates, all evacuation strategies combinations are determined. As the time for evacuation is reduced, the *OUT* parameter is reduced in this example to 45 (x 100) persons. This OUT parameter is critical for the boundary condition as discussed in section 3.2.1 and determines whether or not a combination is feasible. Results are shown in Table 23 below.

The strategy minimizing the expected loss of life for the whole system is shown to be vertical evacuation for zones 1 and 2 and preventive evacuation for zones 3 and 4 (strategy 5). The total estimated number of expected fatalities for this strategy is 8. The optimum strategy in the first example (strategy 12) is not feasible in this case due to the limited capacity for preventive evacuees. In general, it is noted that fewer strategies are feasible within this time frame which is in line with expectations.

Table 23: Total number of expected fatalities for the simplified example with less time for evacuation and assuming flood scenario probabilities of respectively 25% and 20% (assuming 12 hours for evacuation)

	Evacuation type						Estimated number of fatalities		
Evacuation strategy	Zone 1	Zone 2	Zone 3	Zone 4	IN (x 100)	Maximum outflow capacity exceeded?	Flood scenario 1	Flood scenario 2	Expected (conditional flood scenario probabilities: 25% for scenario 1 and 20% for scenario 2)
1	NP	NP	NP	NP	0	no	85	185	58
2	V	V	V	V	0	no	15	49	14
3	V	V	V	P	15	no	15	45	13
4	V	V	P	V	25	no	5	39	9
5	V	V	P	P	40	no	5	35	8
6	V	P	V	V	50	yes	-	-	-
7	V	P	V	P	65	yes	-	-	-
8	V	P	P	V	75	yes	-	-	-
9	V	P	P	P	90	yes	-	-	-
10	P	V	V	V	35	yes	-	-	-
11	P	V	V	P	50	yes	-	-	-
12	P	V	P	V	60	yes	-	-	-
13	P	V	P	P	75	yes	-	-	-
14	P	P	V	V	85	yes	-	-	-
15	P	P	V	P	100	yes	-	-	-
16	P	P	P	V	110	yes	-	-	-
17	P	P	P	P	125	yes	-	-	-

A.2 More evacuation time

In this example the same flood scenarios are used as in the first example of section 3.4 (Figure 12). Flood scenario 1 (*c = 1*) leads to flooding of zone 1 and 3 and flood scenario 2 (*c = 2*) leads to flooding of all four zones. Note that, regarding factors influencing evacuation time, the same remarks apply as for the previous example with less evacuation time.

The outflow of evacuees and the estimated number of fatalities per zone and per evacuation type is shown in table 24 and 25, for flood scenario 1 and 2, respectively.

Table 24:The outflow of evacuees (Ei) and loss of life (Li) for evacuation type (j) per zone (i) for flood scenario 1 (assuming 36 hours for evacuation)

c = 1	Ei (x 100)				Li			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
j = 1	0	0	0	0	50	0	35	0
j = 2	0	0	0	0	5	0	10	0
j = 3	35	50	25	15	0	0	0	0

Table 25: The outflow of evacuees (Ei) and loss of life (Li) for evacuation type (j) per zone (i) for flood scenario 2 (assuming 36 hours for evacuation)

c = 2	Ei (x 100)				Li			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
j = 1	0	0	0	0	50	75	35	25
j = 2	0	0	0	0	5	30	10	4
j = 3	35	50	25	15	0	0	0	0

As can be seen, with more available time for evacuation, all zones fulfil the boundary condition ($N_i \leq C_i$) and hence preventive evacuation is possible for all zones individually. Taking into account the same flood probabilities as using in the first example (25% for flood scenario 1 and 20% for flood scenario 2) the results of the expected number of fatalities (*Li)* are shown in Table 26.

Table 26: Outflow of evacuees (Ei) and the expected value for loss of life (Li) for flood scenarios probabilities of respectively 25% and 20% (assuming 36 hours for evacuation)

	Ei (x 100)				Expected value for Li			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
j = 1	0	0	0	0	23	15	16	5
j = 2	0	0	0	0	2	6	5	1
j = 3	35	50	25	15	0	0	0	0

Using these expected loss of life estimates, all evacuation strategies are determined. Since the evacuation time is increased, the *OUT* parameter is assumed to be 85 (x 100) persons. Results are shown in Table 27 below.

Table 27: Total number of expected fatalities for the simplified example with more time for evacuation and assuming flood scenario probabilities of respectively 25% and 20% (assuming 36 hours for evacuation)

Evacuation type							Estimated number of fatalities		
Evacuation strategy	Zone 1	Zone 2	Zone 3	Zone 4	IN (x 100)	Maximum outflow capacity exceeded?	Flood scenario 1	Flood scenario 2	Expected (conditional flood scenario probabilities: 25% for scenario 1 and 20% for scenario 2)
1	NP	NP	NP	NP	0	no	85	185	58
2	V	V	V	V	0	no	15	49	14
3	V	V	V	P	15	no	15	45	13
4	V	V	P	V	25	no	5	39	9
5	V	V	P	P	40	no	5	35	8
6	V	P	V	V	50	no	15	19	8
7	V	P	V	P	65	no	15	15	7
8	V	P	P	V	75	no	5	9	3
9	V	P	P	P	90	yes	-	-	-
10	P	V	V	V	35	no	10	44	12
11	P	V	V	P	50	no	10	40	11
12	P	V	P	V	60	no	0	34	7
13	P	V	P	P	75	no	0	30	6
14	P	P	V	V	85	no	10	14	6
15	P	P	V	P	100	yes	-	-	-
16	P	P	P	V	110	yes	-	-	-
17	P	P	P	P	125	yes	-	-	-

The strategy minimizing the expected loss of life for the whole system is shown to be vertical evacuation for zones 1 and 4 and preventive evacuation for zones 2 and 3 (strategy 8). The total estimated number of expected fatalities for this strategy is 3 and the outflow of evacuees 75 (x100) persons.

Combination 12, which is the optimum strategy in the first example, is also feasible for this case but leads to a higher number of expected fatalities. It is noted that for strategy 14, vertical evacuation for zones 3 and 4, and preventive evacuation for the relatively highly populated zones 1 and 2, the number of preventive evacuees is higher but the expected number of fatalities is higher as well.

A.3 Different flood scenarios

In this example the flood scenarios are different from those used in the first example of section 3.4. Flood scenario 1 ($c = 1$) leads to flooding of all zones and flood scenario 2 ($c = 2$) leads to flooding of zones 2 and 4 (as shown in Figure 47). The zone characteristics, as well as the evacuation time, are the same as for the first example.

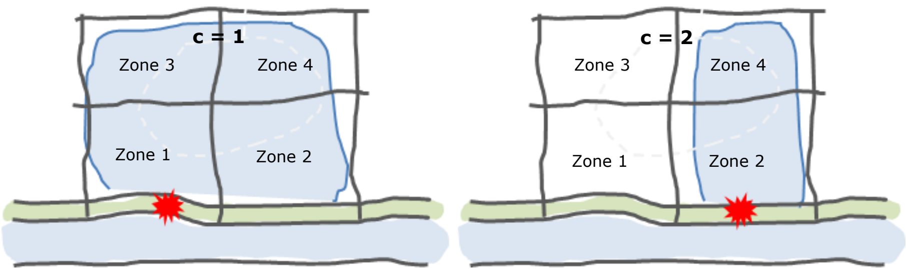

Figure 47: Flood scenarios for the simplified example with different flood scenarios

The outflow of evacuees and the estimated number of fatalities per zone and per evacuation type is shown in tables 28 and 29, for flood scenario 1 and 2, respectively.

Table 28: The outflow of evacuees (Ei) and loss of life (Li) for evacuation type (j) per zone (i) for flood scenario 1 (assuming different flood scenarios as in the first example)

c = 1	**Ei (x 100)**				**Li**			
	i=1	i=2	i=3	i=4	i=1	i=2	i=3	i=4
j = 1	0	0	0	0	50	75	35	25
j = 2	0	0	0	0	5	30	10	4
j = 3	35	x	25	15	0	x	0	0

Table 29: The outflow of evacuees (Ei) and loss of life (Li) for evacuation type (j) per zone (i) for flood scenario 2 (assuming different flood scenarios as in the first example)

c = 2	**Ei (x 100)**				**Li**			
	i=1	i=2	i=3	i=4	i=1	i=2	i=3	i=4
j = 1	0	0	0	0	0	75	0	25
j = 2	0	0	0	0	0	30	0	4
j = 3	35	x	25	15	0	x	0	0

In this example, the flood probabilities for flood scenario 1 ($c=1$) and flood scenario 2 ($c=2$) are assumed to be 25% and 20%, respectively. This results in in the expected number of fatalities (*Li*) as shown in Table 30.

Table 30: Outflow of evacuees (Ei) and the expected value for loss of life (Li) for flood scenarios probabilities of respectively 25% and 20% (assuming different flood scenarios as in the first example)

	Ei (x 100)				**Expected value for Li**			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
j = 1	0	0	0	0	10	34	7	11
j = 2	0	0	0	0	1	14	2	2
j = 3	35	x	25	15	0	x	0	0

Using these expected loss of life estimates, all strategies are determined. Note that the parameter *OUT* in this case is the same as in the first example, i.e. 65 (x 100) persons. Results are shown in Table 31.

Table 31: Total number of expected fatalities for the simplified example with different flood scenarios and assuming flood scenario probabilities of respectively 25% and 20%

		Evacuation type					**Estimated number of fatalities**		
Evacuation strategy	Zone 1	Zone 2	Zone 3	Zone 4	IN (x 100)	Maximum outflow capacity exceeded?	Flood scenario 1	Flood scenario 2	Expected (conditional flood scenario probabilities: 25% for scenario 1 and 20% for scenario 2)
1	NP	NP	NP	NP	0	no	185	100	66
2	V	V	V	V	0	no	49	34	19
3	V	V	V	P	15	no	45	30	17
4	V	V	P	V	25	no	39	34	17
5	V	V	P	P	40	no	35	30	15
6	V	P	V	V	50	yes	-	-	-
7	V	P	V	P	65	yes	-	-	-
8	V	P	P	V	75	yes	-	-	-
9	V	P	P	P	90	yes	-	-	-
10	P	V	V	V	35	no	44	34	18
11	P	V	V	P	50	no	40	30	16
12	P	V	P	V	60	no	34	34	15
13	P	V	P	P	75	yes	-	-	-
14	P	P	V	V	85	yes	-	-	-
15	P	P	V	P	100	yes	-	-	-
16	P	P	P	V	110	yes	-	-	-
17	P	P	P	P	125	yes	-	-	-

The evacuation strategy minimizing the expected loss of life for the whole system is shown to be vertical evacuation for zones 1 and 2, and preventive evacuation for zones 3 and 4 (strategy 5). The total estimated number of expected fatalities for this combination is 15 (when rounded) and the outflow of evacuees 40 (x100) persons. The number of expected fatalities is higher than the number for strategy 5 in the first example. This is caused mainly by the higher flood probability for zone 2 which zone is characterized by many inhabitants, no possibility for preventive evacuation (given the evacuation time) and poor possibilities for vertical evacuation.

When rounded, the expected number of fatalities for strategy 5 and 12 (optimum strategy in the first example study) are the same. Strategy 5 is preferred since the number of preventive evacuees is lower (reducing the risk that roads will get blocked). It is noted that for strategies 11 and 12 the number of preventive evacuees is higher but the expected number of fatalities is higher as well.

Appendix B – Case study Rotterdam North

B.1 Neighbourhood in Rotterdam North

Figure 48 shows the Rotterdam North case area, divided into 47 zones which represent neighbourhoods according to CBS (Centraal Bureau voor de Statistiek). Table 34 the corresponding number of inhabitants.

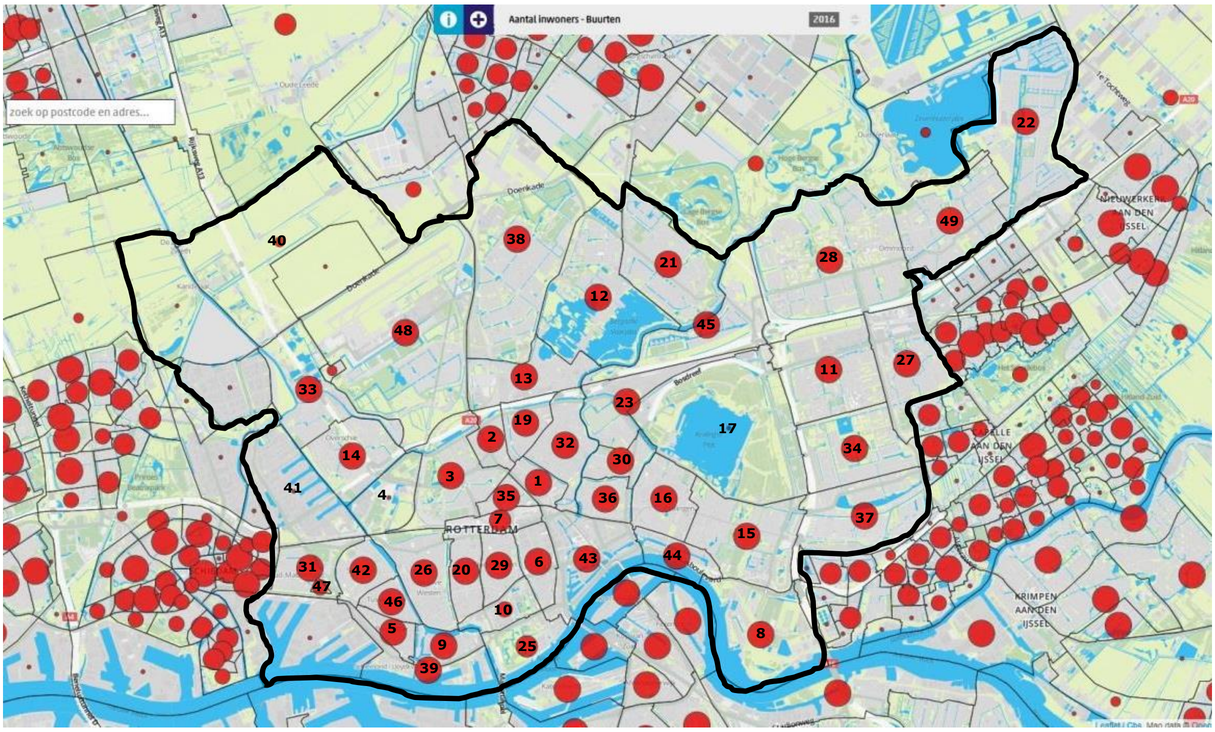

Figure 48: Overview of neighbourhoods in Rotterdam North. After: (CBS, 2016)

Table 32: Number of inhabitants for each neighbourhoods in Rotterdam North (crossed out neighbourhoods are neglected in this study because of a low number of inhabitants or due to the fact that neighbourhoods are located outside of a dike protection) Zone numbers relate to numbers in Figure 37

Zone	Neighbourhood	Number of inhabitants	Zone	Neighbourhood	Number of inhabitants
1	Agniesebuurt	4115	26	Nieuwe Westen	19260
2	Bergpolder	7985	27	Oosterflank	10500
3	Blijdorp	10160	28	Ommoord	25150
4	~~Blijdorpsepolder~~	~~115~~	29	Oude Westen	9350
5	Bospolder	7135	30	Oud Crooswijk	8080
6	Cool	5395	31	Oud Mathenesse	7155
7	Cs Kwartier	1060	32	Oude Noorden	16995
8	De Esch	4420	33	Overschie	6710
9	Delfshaven	6835	34	Prinsenland	9950
10	Dijkzigt	710	35	Provenierswijk	4685
11	Het Lage Land	10550	36	Rubroek	8310
12	Hillegersberg Noord	7820	37	`s Gravenland	8205
13	Hillegersberg Zuid	7965	38	Schiebroek	16305
14	Kleinpolder	7525	39	~~Schiemond~~	~~5150~~
15	Kralingen Oost	7995	40	Schieveen	335
16	Kralingen West	15785	41	~~Spaanse Polder~~	~~95~~
17	~~Kralingse Bos~~	~~110~~	42	Spangen	10285
18	Landzicht	380	43	Stadsdriehoek	14825
19	Liskwartier	7620	44	Struisenburg	5505
20	Middelland	11985	45	Terbregge	3525
21	Molenlaankwartier	7955	46	Tussendijken	7045
22	Nesselande	12425	47	Witte Dorp	575
23	Nieuw Crooswijk	2950	48	Zestienhoven	2090
24	~~Nieuw Mathenesse~~	~~15~~	49	Zevenkamp	16125
25	~~Nieuwe Werk~~	~~1575~~	**Total**		**359735**

B.2 Preventive evacuation times per neighbourhood

Table 33: All possible exit points for Rotterdam North (highlighted green are considered in this study)

Exit points	Number of lanes	Road capacities under poor conditions (cars/ hour)	Advantages/ disadvantages
A16 to Dordrecht	4	4400	Due to expected floods to the south-west of Rotterdam in the case of expected high water levels at the Maas, this option is rejected
A13 to Delft	3	3300	Evacuation in the direction of the North is considered an option
A4 to Delft	3	3300	Due to expected floods to the west of Rotterdam in case of high water levels at the Maas many evacuees from the west of Rotterdam are expected to take this route
A20 to Schiedam	3	3300	Due to expected floods to the west of Rotterdam in the case of expected high water levels at the Maas, this option is rejected
A20 to Gouda	3	3300	Evacuation in the direction of the North East is considered to be an option
N209 to Bleiswijk	1	900	This is considered an option
N471 to Berkel and Rodenrijs	1	900	This is considered an option
S123 Willemsbrug to Noordereiland	2	1200	On a normal day this road is already often blocked due to traffic congestions. Also, in case of high water levels in the Maas floods can be expected to the south of Rotterdam. This option is therefore rejected.
S103 Maastunnel to Rotterdam South	2	1200	The same as S123
S106 Erasmusbrug to Rotterdam South	2	1200	The same as S123

Table 34: Possibilities for preventive evacuation for each neighbourhood in Rotterdam North

Neighbourhood (CBS)	Number of inhabitants	Number of lanes	Total road capacity under poor conditions (cars/hour)	Total outflow capacity per neighbourhood under poor conditions (persons/hour)	Min. required evacuation time for 100% leaving the neighbourhood (hours)
Agniesebuurt	4115	4	1600	3520	1,2
Bergpolder	7985	4	1600	3520	2,3
Blijdorp	10160	4	1600	3520	2,9
Bospolder	7135	3	1200	2640	2,7
Cool	5395	4	1600	3520	1,5
Cs Kwartier	1060	2	800	1760	0,6
De Esch	4420	3	1200	2640	1,7
Delfshaven	6835	4	1600	3520	1,9
Dijkzigt	710	2	800	1760	0,4
Het lage land	10550	3	1200	2640	4,0
Hillegersberg Noord	7820	2	800	1760	4,4
Hillegersberg Zuid	7965	2	800	1760	4,5
Kleinpolder	7525	2	800	1760	4,3
Kralingen Oost	7995	4	1600	3520	2,3
Kralingen West	15785	4	1600	3520	4,5
Landzicht	380	2	800	1760	0,2
Liskwartier	7620	4	1600	3520	2,2
Middelland	11985	3	1200	2640	4,5
Molenlaankwartier	7955	3	1200	2640	3,0
Nesselande	12425	4	1600	3520	3,5
Nieuw Crooswijk	2950	4	1600	3520	0,8
Nieuwe Westen	19260	3	1200	2640	7,3
Ommoord	25150	3	1200	2640	9,5
Oosterflank	10500	3	1200	2640	4,0
Oud Crooswijk	8080	4	1600	3520	2,3
Oud Mathenesse	7155	3	1200	2640	2,7
Oude Noorden	16995	4	1600	3520	4,8
Oude Westen	9350	3	1200	2640	3,5
Overschie	6710	2	800	1760	3,8
Prinsenland	9950	2	800	1760	5,7
Provenierswijk	4685	4	1600	3520	1,3
Rubroek	8310	4	1600	3520	2,4
s gravenland	8205	4	1600	3520	2,3
Schiebroek	16305	2	800	1760	9,3
Schieveen	335	1	400	880	0,4
Spangen	10285	4	1600	3520	2,9
Stadsdriehoek	14825	4	1600	3520	4,2
Struisenburg	5505	4	1600	3520	1,6
Terbregge	3525	1	400	880	4,0
Tussendijken	7045	4	1600	3520	2,0
Witte Dorp	575	2	800	1760	0,3
Zestienhoven	2090	1	400	880	2,4
Zevenkamp	16125	4	1600	3520	4,6

Table 33: Travel time to exit points for all neighbourhoods in Rotterdam North according to Google Maps

		Travel time to exit points according Google Maps [minutes] [normal circumstances]				
		A13 in direction Delft	**A20** in direction Gouda	**N209** in direction Bleiswijk	**N471** in direction Berkel and Rodenrijs	**Average** travel time over all exits
Neighbourhood	Centroid coordinates	51.952841, 4.414230	51.959366, 4.572694	51.972802, 4.482780	51.970028, 4.454055	
Agniesebuurt	51.929722, 4.475966	10	11	12	11	11
Bergpolder	51.934934, 4.464609	5	7	7	6	7
Blijdorp	51.929963, 4.457658	6	9	10	9	9
Blijdorpsepolder	51.927474, 4.441990	7	11	12	12	11
Bospolder	51.908925, 4.442473	11	16	17	15	15
Cool	51.919584, 4.476353	13	15	16	15	15
Cs Kwartier	51.923677, 4.468305	8	13	14	12	12
De Esch	51.908513, 4.527142	17	8	17	18	15
Delfshaven	51.907180, 4.452861	12	16	17	16	16
Dijkzigt	51.911483, 4.469517	12	17	17	16	16
Het Lage Land	51.945260, 4.543433	15	8	13	15	13
Hillegersberg Noord	51.954011, 4.489136	12	12	7	9	10
Hillegersberg Zuid	51.943967, 4.475153	9	10	8	8	9
Kleinpolder	51.932884, 4.433304	6	13	13	11	11
Kralingen Oost	51.921156, 4.524849	14	7	14	16	13
Kralingen West	51.926572, 4.503957	13	13	16	15	15
Kralingse Bos	51.934449, 4.519361	14	10	16	16	14
Landzicht	51.945075, 4.429147	3	12	8	8	8
Liskwartier	51.937082, 4.472980	8	9	10	9	9
Middelland	51.916296, 4.459295	8	14	14	12	12
Molenlaankwartier	51.959562, 4.504707	9	12	3	6	8
Nesselande	51.979832, 4.582593	20	7* (different coordinate used for exit point)	21	21	16
Nieuw Crooswijk	51.940895, 4.493713	7	10	10	9	9
Nieuw Mathenesse	51.908430, 4.426322	-	-	-	-	0
Nieuwe Werk	51.906955, 4.473224	16	18	21	20	19
Nieuwe Westen	51.916179, 4.449245	9	14	14	13	13
Ommoord	51.959563,	16	8	11	13	12

	4.542502					
Oud Crooswijk	51.931726, 4.494892	10	12	13	11	12
Oud Mathenesse	51.917331, 4.423346	6	10	12	10	10
Oude Noorden	51.934162, 4.480951	10	12	13	12	12
Overschie	51.933891, 4.429848	5	11	11	10	10
Prinsenland	51.933968, 4.548481	15	8	14	15	13
Provenierswijk	51.927435, 4.468634	7	12	13	12	11
Rubroek	51.926790, 4.491405	13	15	16	15	15
's Gravenland	51.925677, 4.551492	12	6	14	13	12
Schiebroek	51.961394, 4.470461	11	13	7	8	10
Schiemond	51.902501, 4.454328	12	16	18	17	16
Schieveen	51.957466, 4.425127	1	10	5	4	5
Spaanse Polder	51.927449, 4.420420	6	14	12	11	11
Spangen	51.917011, 4.436435	7	12	13	11	11
Stadsdriehoek	51.917804, 4.487411	16	12	19	17	16
Struisenburg	51.919307, 4.508574	16	10	18	18	16
Terbregge	51.950315, 4.515839	12	11	8	10	11
Tussendijken	51.913006, 4.441841	10	15	16	14	14
Witte Dorp	51.914736, 4.426512	8	12	13	12	12
Zestienhoven	51.949103, 4.446197	6	10	7	5	7
Zevenkamp	51.964471, 4.570927	16	8	18	18	15

B.3 Shelter at home capacities in Rotterdam North

Provenierswijk

For this investigation the neighbourhood Provenierswijk is divided into 22 sections (Figure 49). For each section the average number of floors in houses is estimated using Google Street View. Assumption is that the first two floors are not suitable for sheltering when taking into account potential water depths. This is considered a conservative assumption. Thereafter the surface area of the houses is estimated using a measurement tool in Google Maps. It is then assumed that some 70% of the surface area is suitable for sheltering. As shown in Table 35, the total shelter capacity at homes is estimated at 33451 persons which is much higher than the number of inhabitants in Provenierswijk (4685).

Figure 49: Sections within the neighbourhood: Provenierswijk

Table 35: Sheltering at home capacities for Provenierswijk

Neighbourhood section (Figure 39)	Surface area buildings [m2]	Average number of floors	Shelter at home capacity [persons]
1	7390	5	4172
2	2460	4	926
3	0	0	0
4	4820	4	1814
5	4930	3.5	1392
6	2860	3	538
7	3210	4	1208
8	3220	3	606
9	4760	4	1791
10	4470	3.5	1262
11	3420	3.5	965
12	3920	4	1475
13	2260	3.5	820
14	2870	4	1389
15	7750	4	3750
16	0	0	0
17	0	0	0
18	930	6	900
19	2775	4	1343
20	1690	3.5	613
21	2350	4	1137
22	3770	5	2736
Total			**33451**

Het Lage Land

For this investigation the neighbourhood Het Lage Land is divided into 19 sections (Figure 50). Taking into account the maximum local water depth (> 6m), the first three floors are rejected as an option for sheltering. Then, using a similar method as used for Provenierswijk, results are shown in Table 35. It should be noted that different from Provenierswijk, housed are much less uniform. For this reason, the dry space surface area could not be estimated by averaging the number of floors and surface area but was calculated by summation of estimated dry space surface space for each apartment building and house.

As shown in Table 36, the total shelter capacity at homes is estimated at 37914 persons which also abundantly exceeds the number of inhabitants in Het Lage Land (10550).

Figure 50: Sections within the neighbourhood: Het Lage Land

Table 36: Sheltering at home capacities for Het Lage Land

Neighbourhood section (Figure 40)	Dry surface area [m2] at houses	Shelter at home capacity [persons]
1	0	0
2	0	0
3	15620	2939
4	8415	1583
5	8250	1552
6	24320	4576
7	10520	1980
8	25085	4720
9	2175	409
10	13580	2555
11	13395	2521
12	29080	5472
13	5745	1081
14	1800	339
15	18150	3415
16	18150	3415
17	0	0
18	7200	1355
19	0	0
Total		**37914**

B.4 Public sheltering capacities in Rotterdam North

Table 37 shows an inventory of potential public sheltering possibilities in eight typical neighbourhoods in Rotterdam North, i.e. Agniesebuurt, Bergpolder, Blijdorp, Delfshaven, Dijkzigt, Het Lage Land, Provenierswijk and Stadsdriehoek. In this study buildings that are considered as potential public shelters can accommodate large groups of people, such as educational buildings, libraries and (local) government buildings and should be well accessible. Hospitals and other care institutions are excluded as their priority is to take care of people who are not self-reliant. In this study also private and semi-public offices are excluded although, if needed, in reality such buildings could be used.

The inventory is based on the use of Google maps whilst taking into account the above requirements and local maximum water depths. As can be seen, large differences can be observed between the various neighbourhoods. For example, in Bergpolder with 7985 inhabitants there are no potential public shelters whereas in Agniesebuurt with 4115 inhabitants there is potential public sheltering capacity for 17091 persons. One reason for these large differences is the presence, or not, of (large) educational buildings such as the Rotterdam Hogeschool.

Table 37: Estimated public sheltering capacities for eight typical neighbourhoods in Rotterdam North

Neighbourhood	Potential public shelter	Address	Dry surface area [m^2]	Potential shelter capacity [persons]	Total potential public shelter capacity [persons]
Agniesebuurt	Educational building complex	Heer Bokelweg 255	42816	10704	17091
	Office building	Heer Bokelweg 159	12500	3125	
	Office building	Teilingerstraat 176	13050	3262	
Bergpolder	-	-	-	-	0
Blijdorp	Educational building	Bentincklaan 280	3490	872	1274
	Educational building	Baljuwstraat 2	1610	402	
Delfshaven	Office building	Heiman Dullaertplein 3	5110	1277	2118
	Societal building	Dunantstraat 44	1092	273	
	Educational building	Pieter de Hoochstraat 29	848	212	
	Societal building	Westzeedijk 493	756	189	
	Eductional building	Westzeedijk 497	670	167	
Dijkzigt	City Office building	Hartmansstraat 15	1100	275	11415
	Educational building	Wytemaweg 25	2517	629	
	Educational building complex	Museumpark 40	17912	4478	
	Educational building complex	Rochussenstraat 198	14640	3660	
	Educational building	G.J. de Jonghweg 4-6	9492	2373	
Het Lage Land	Police academy	Koperstraat 19	1508	377	1652
	Educational building	Prins alexanderlaan 55	2820	705	
	Educational building	Prins Alexanderlaan 41	2280	570	
Provenierswijk	Educational building	Walenburgerweg 128-130	3392	848	2209
	Educational building complex	Stationsingel 80	1606	402	
	Educational building	Zuster Hennekeplein 80	3835	959	
Stadsdriehoek	City hall	Coolsingel 40	6600	1650	17890
	Office building	Doelwater 5	15104	3776	
	Educational building	Blaak 10	4320	1080	
	Office Building	Korte Hoogstraat 31	1820	455	
	Educational building	Wijnhaven 103-107	4590	1147	
	Educational building	Wijnhaven 99	2700	675	
	Educational building	Wijnhaven 61	9120	2280	
	Office building	Blaak 40	4130	1032	
	Central library	Hoogstraat 110	9500	2375	
	Office building	Boompjes 200	12480	3120	
	Educational building	Nieuwemarkt 1	1200	300	

Based on the inventory of potential public sheltering capacity for the eight neighbourhoods as shown in Table 38, an estimate is made for the potential public sheltering capacity in all remaining neighbourhoods in Rotterdam North. This estimate is based on a comparison of characteristics using Google satellite images and street view.

Table 38: estimated public sheltering capacities for all remaining neighbourhoods in Rotterdam North based on a comparison of characteristics using Google Maps and Street View

Neighbourhood	Number of inhabitants	Description/ comparison	Estimated potential shelter capacity [person]
Agniesebuurt	4115	-	17091
Bergpolder	7985	-	0
Blijdorp	10160	-	1274
Bospolder	7135	Comparable with Delfshaven (surface area and location)	2100
Cool	5395	Comparable with Stadsdriehoek (but slightly smaller)	14000
Cs Kwartier	1060	No direct comparison with other neighbourhoods but sheltering capacity is estimated to be low as there are mainly private company offices	1000
De Esch	4420	No direct comparison with other neighbourhoods but presence of military base may offer sheltering capacity	2500
Delfshaven	6835	-	2118
Dijkzigt	710	-	11415
Het Lage Land	10550	-	1652
Hillegersberg Noord	7820	No direct comparison with other neighbourhoods. Urban area with moderate public sheltering capacity.	4000
Hillegersberg Zuid	7965	Comparable with Blijdorp (surface area and facilities)	1100
Kleinpolder	7525	Mainly private homes. Estimated public sheltering capacity to be very low	500
Kralingen Oost	7995	Comparable with Dijkzigt. Presence of Erasmus University. Estimated public sheltering capacity estimated to be high	15000
Kralingen West	15785	Comparable with Blijdorp but slightly larger surface area	1500
Landzicht	380	Very small with private homes only	0
Liskwartier	7620	Comparable with Blijdorp	1200
Middelland	11985	No direct comparison with other neighbourhoods. Large area with private homes and some educational buildings	3500
Molenlaankwartier	7955	No direct comparison with other neighbourhoods. Large area with private homes and some educational buildings	3500
Nesselande	12425	No direct comparison with other neighbourhoods. Low to moderate public sheltering capacity.	2000
Nieuw Crooswijk	2950	No direct comparison with other neighbourhoods. Estimated to have low public sheltering capacity.	1500
Nieuwe Westen	19260	No direct comparison with other neighbourhoods. Large area with private homes and some educational buildings, similar to Midelland	3500
Ommoord	25150	Comparable with Het Lage Land	1700
Oud Crooswijk	8080	Comparable with Blijdorp	1200
Oud Mathenesse	7155	No direct comparison with other neighbourhoods. Estimated to have low public sheltering capacity.	1500
Oude Noorden	16995	Comparable with Blijdorp but larger surface area	1500
Overschie	6710	No direct comparison with other neighbourhoods. Estimated to have low public sheltering capacity.	1500
Prinsenland	9950	Comparable with Het Lage Land	1600
Provenierswijk	4685	-	2209
Rubroek	8310	Low to moderate public sheltering capacity	2500
's Gravenland	8205	No direct comparison with other neighbourhoods. Estimated to have very low public sheltering capacity.	500
Schiebroek	16305	No direct comparison with other neighbourhoods. Moderate estimated public sheltering capacity.	3500
Schieveen	335	No public sheltering capacity	0
Spangen	10285	Comparable with Blijdorp as far as public sheltering capacity is concerned	1200
Stadsdriehoek	14825	-	17890
Struisenburg	5505	No direct comparison with other neighbourhoods. Moderate estimated public sheltering capacity.	3000
Terbregge	3525	No direct comparison with other neighbourhoods. Very small estimated public sheltering capacity.	500
Tussendijken	7045	No direct comparison with other neighbourhoods. Moderate estimated public sheltering capacity.	2500
Witte Dorp	575	No public sheltering capacity	0
Zestienhoven	2090	No direct comparison with other neighbourhoods. Moderate estimated public sheltering capacity.	2500
Zevenkamp	16125	Comparable with Het Lage Land	1600
Total			**137349**

B.5 Failure locations and flood scenarios

Table 39: Failure probabilities per year for dike section 1-26 of dike ring 14 (VNK2)

Dike section		**Dike segment**		
Number	Failure probability per year	Number	Name	Failure probability per year
1	4,36E-09	**1**	Capelle West Nijverheidstraat	1.15E-06
2	3,17E-07			
3	7,34E-07			
4	9,83E-08			
5	1,88E-08	**2**	Rotterdam Boerengatsluis	3.29E-05
6	1,45E-07			
7	1,80E-06			
8	1,81E-07			
9	4,22E-08			
10	9,61E-08			
11	9,31E-07			
12	7,97E-07			
13	2,89E-05			
14	1,66E-06	**3**	Rotterdam Parksluizen	1.66E-06
15	2,48E-07	**4**	Schiedam Sluis Buitenhaven	1.00E-05
16	9,44E-07			
17	1,87E-06			
18	3,74E-06			
19	1,85E-06			
20	-			
21	2,72E-07			
22	5,50E-07			
23	9,28E-08			
24	3,07E-07			
25	4,80E-08			
26	9,51E-08			

Table 40: Flood scenario overview for an above normative scenario for 4 failure locations (after: LIWO)

Failure location	Affected people (inside Rotterdam North)	Flooded area in Rotterdam North	Water depth at locations in Rotterdam North	Flow velocity at locations in Rotterdam North	Rise speed at locations in Rotterdam North
Capelle-West Nijverheidstraat	150.000 (38.000)	The neighbourhoods: Het Lage Land, Prinsenland, 's Gravenland and Oosterflank	Ranging from 1 to 3 m	< 0.5 m/s	< 0.5 m/hr
Rotterdam Boerengatsluis	28.000 (28.000)	Parts of: Stadsdriehoek, Kralingen West, Kralingen Oost, Struisenburg, Cool and Rubroek	In most cases < 0.5 m. At Struisenburg and Stadsdriehoek up to 3.5 m	< 0.5 m/s with a few very local flow velocities up to 3.8 m/s near the failure location	< 0.5 m/hr. Nearby failure location speeds up to 4 m/hr
Rotterdam Parksluizen	230.000 (160.000)	Flooded reaches the majority of the neighbourhoods in Rotterdam North, except neighbourhoods to the east and Tussendijken (which is located relatively high)	In this city centre up to 4.7 m. For the rest mainly between 0.5 and 2 m	< 0.5 m/s for most cases. Nearby failure location up to 1.5 m/s	For the neighbourhoods in the city centre up to 3.5 m/hr. For the rest < 0.5 m/hr
Schiedam Sluis Buitenhaven	100.000 (30.000)	The neighbourhoods: Oud-Mathenesse, Wittedorp, part of Blijdorp, Agniessebuurt and Provenierswijk	In most cases < 0.5 m, at some locations 0.5 – 1 m	< 0.5 m/s	Mainly < 0.5 m/hr

Table 41: Average flood characteristics (water depth and rise speed) per zone and per flood scenarios in Rotterdam North. (A blank cell means a value of zero)

			Schiedam Sluis Buitenhaven		**Rotterdam Parksluizen**		**Rotterdam Boerngatsluis**		**Capelle West Nijverhijdstraat**	
Neighbourhood	Number of inhabitants	Public sheltering capacity	Water depth [m]	Rise speed [m/hr]	Water depth [m]	Rise speed [m/hr]	Water depth [m]	Rise speed [m/hr]	Water depth [m]	Rise speed [m/hr]
Agniesebuurt	4115	17091			0,1	<0,5				
Bergpolder	7985	0	0,6	<0,5	1,7	<0,5				
Blijdorp	10160	1274	0,3	<0,5	2,1	<0,5				
Bospolder	7135	2100								
Cool	5395	14000			3,1	>0,5				
Cs Kwartier	1060	1100			1	<0,5				
De Esch	4420	2500								
Delfshaven	6835	2118			1,3	>0,5				
Dijkzigt	710	11415			3,4	>0,5				
Het lage land	10550	1652							3,4	>0,5
Hillegersberg Noord	7820	4000			0,2	<0,5				
Hillegersberg Zuid	7965	1100			0,2	<0,5				
Kleinpolder	7525	500			2,2	<0,5				
Kralingen Oost	7995	15000					0,2	<0,5		
Kralingen West	15785	1500					0,2	<0,5		
Landzicht	380	0			1,2	<0,5				
Liskwartier	7620	1200			0,1	<0,5				
Middelland	11985	3500			3,2	>0,5				
Molenlaankwartier	7955	3500								
Nesselande	12425	2000								
Nieuw Crooswijk	2950	1500								
Nieuwe westen	19260	3500			3,3	>0,5				
Ommoord	25150	1700							0,7	<0,5
Oosterflank	10500	1700							2,8	>0,5
Oud Crooswijk	8080	1200			0,4	<0,5				
Oud Mathenesse	7155	1500	0,7	<0,5	3,5	>0,5				
Oude Noorden	16995	1500								
Oude westen	9350	3500			3,5	>0,5				
Overschie	6710	1500	0,1	<0,5	1,9	<0,5				
Prinsenland	9950	1600							2,4	>0,5
Provenierswijk	4685	2209	0,7	<0,5	2,4	<0,5				
Rubroek	8310	2500			0,7	<0,5				
S Gravenland	8205	500							1,5	>0,5
Schiebroek	16305	3500			0,7	<0,5				
Schieveen	335	0			1,5	<0,5				
Spangen	10285	1200	0,5	<0,5	3,2	>0,5				
Stadsdriehoek	14825	17890			0,3	<0,5	0,3	<0,5		
Struisenburg	5505	3000					1,5	>0,5		
Terbregge	3525	500			0,2	<0,5			1,3	<0,5
Tussendijken	7045	2500								
Witte Dorp	575	0	1	<0,5	3,6	>0,5				
Zestienhoven	2090	2500			1,4	<0,5				
Zevenkamp	16125	1600							0,2	<0,5

B.6 Effectiveness of evacuation types individually

Table 42: Effectiveness of evacuation types per neighbourhood and per flood scenario for Rotterdam North (a blank cell means a value of zero) for above normative flood scenarios

				Li (Schiedam sluis buitenhaven)			*Li* (Rotterdam Parksluizen)			*Li* (Rottedam Boerngatsluis)			*Li* (Capelle west nijverhijdstraat)		
Neighbourhood	Number of inhabitants	Public sheltering capacity	Required evacuation time [hours]	Not prepared	Vertical	Preventive	Not prepared	Vertical	Preventive	Not prepared	Vertical	Preventive	Not prepared	Vertical	Preventive
Agniesebuurt	4115	17091	1,2			0,0	1,2	2,1	0,0			0,0			0,0
Bergpolder	7985	0	2,3	25,3	6,4	0,1	80,9	20,5	0,1			0,1			0,1
Blijdorp	10160	1274	2,9	13,6	3,8	0,1	128,0	29,0	0,1			0,1			0,1
Bospolder	7135	2100	2,7			0,1			0,1			0,1			0,1
Cool	5395	14000	1,5			0,1	983,1	2,7	0,1			0,1			0,1
Cs Kwartier	1060	1100	0,6			0,0	6,1	0,5	0,0			0,0			0,0
De Esch	4420	2500	1,7			0,0			0,0			0,0			0,0
Delfshaven	6835	2118	1,9			0,1	52,1	10,1	0,1			0,1			0,1
Dijkzigt	710	11415	0,4			0,0	217,7	0,4	0,0			0,0			0,0
Het lage land	10550	1652	4,0			0,1			0,1			0,1	3235,3	869,7	0,1
Hillegersberg Noord	7820	4000	4,4			0,1	6,2	2,8	0,1			0,1			0,1
Hillegersberg Zuid	7965	1100	4,5			0,1	6,3	2,0	0,1			0,1			0,1
Kleinpolder	7525	500	4,3			0,1	99,3	23,8	0,1			0,1			0,1
Kralingen Oost	7995	15000	2,3			0,1			0,1	6,3	4,0	0,1			0,1
Kralingen West	15785	1500	4,5			0,2			0,2	12,4	3,8	0,2			0,2
Landzicht	380	0	0,2			0,0	2,7	0,7	0,0			0,0			0,0
Liskwartier	7620	1200	2,2			0,1	2,3	1,1	0,1			0,1			0,1
Middelland	11985	3500	4,5			0,1	2648,4	609,9	0,1			0,1			0,1
Molenlaankwartier	7955	3500	3,0			0,1			0,1			0,1			0,1
Nesselande	12425	2000	3,5			0,1			0,1			0,1			0,1
Nieuw Crooswijk	2950	1500	0,8			0,0			0,0			0,0			0,0
Nieuwe Westen	19260	3500	7,3			0,2	5059,1	1327,2	0,2			0,2			0,2
Ommoord	25150	1700	9,5			0,3			0,3			0,3	95,6	23,5	0,3
Oosterflank	10500	1700	4,0			0,1			0,1			0,1	930,2	293,9	0,1
Oud Crooswijk	8080	1200	2,3			0,1	15,6	4,0	0,1			0,1			0,1
Oud Mathenesse	7155	1500	2,7	27,2	6,2	0,1	2520,2	635,6	0,1			0,1			0,1
Oude Noorden	16995	1500	4,8			0,2			0,2			0,2			0,2
Oude Westen	9350	3500	3,5			0,1	3293,4	658,5	0,1			0,1			0,1
Overschie	6710	1500	3,8	2,0	1,2	0,1	76,3	15,7	0,1			0,1			0,1
Prinsenland	9950	1600	5,7			0,1			0,1			0,1	216,0	99,6	0,1
Provenierswijk	4685	2209	1,3	17,8	3,5	0,0	67,5	10,2	0,0			0,0			0,0
Rubroek	8310	2500	2,4			0,1	31,6	6,9	0,1			0,1			0,1
S Gravenland	8205	500	2,3			0,1			0,1			0,1	72,9	17,5	0,1
Schiebroek	16305	3500	9,3			0,2	62,0	14,1	0,2			0,2			0,2
Schieveen	335	0	0,4			0,0	3,0	0,8	0,0			0,0			0,0
Spangen	10285	1200	2,9	26,2	6,5	0,1	2272,7	651,7	0,1			0,1			0,1
Stadsdriehoek	14825	17890	4,2			0,1	19,9	7,4	0,1	19,9	7,4	0,1			0,1
Struisenburg	5505	3000	1,6			0,1			0,1	48,9	7,1	0,1			0,1
Terbregge	3525	500	4,0			0,0	2,8	0,9	0,0			0,0	26,9	6,1	0,0
Tussendijken	7045	2500	2,0			0,1			0,1			0,1			0,1
Witte Dorp	575	0	0,3	3,3	0,8	0,0	229,2	73,6	0,0			0,0			0,0
Zestienhoven	2090	2500	2,4			0,0	17,3	1,0	0,0			0,0			0,0
Zevenkamp	16125	1600	4,6			0,2			0,2			0,2	12,7	3,9	0,2

Table 43: Assumed conditional flood scenarios probabilities

Dike segment/ flood scenario	Conditional flood scenario probability at T-0
Schiedam Sluis Buitenhaven	17,5%
Rotterdam Parksluizen	15%
Rotterdam Boerengatsluis	20%
Capelle West Nijverheidstraat	12,5%

Table 44: Expected loss of life for evacuation types per neighbourhood for Rotterdam North for above normative flood scenarios assuming the flood scenario probabilities as shown in Table 43

Neighbourhood	Number of inhabitants	Public sheltering capacity	Expected loss of life: Not prepared	Vertical	Preventive
Agniesebuurt	4115	17091	0	0	0
Bergpolder	7985	0	17	4	0
Blijdorp	10160	1274	22	5	0
Bospolder	7135	2100	0	0	0
Cool	5395	14000	147	0	0
Cs Kwartier	1060	1100	1	0	0
De Esch	4420	2500	0	0	0
Delfshaven	6835	2118	8	2	0
Dijkzigt	710	11415	33	0	0
Het lage land	10550	1652	404	109	0
Hillegersberg Noord	7820	4000	1	0	0
Hillegersberg Zuid	7965	1100	1	0	0
Kleinpolder	7525	500	15	4	0
Kralingen Oost	7995	15000	1	1	0
Kralingen West	15785	1500	2	1	0
Landzicht	380	0	0	0	0
Liskwartier	7620	1200	0	0	0
Middelland	11985	3500	397	91	0
Molenlaankwartier	7955	3500	0	0	0
Nesselande	12425	2000	0	0	0
Nieuw Crooswijk	2950	1500	0	0	0
Nieuwe Westen	19260	3500	759	199	0
Ommoord	25150	1700	12	3	0
Oosterflank	10500	1700	116	37	0
Oud Crooswijk	8080	1200	2	1	0
Oud Mathenesse	7155	1500	383	96	0
Oude Noorden	16995	1500	0	0	0
Oude Westen	9350	3500	494	99	0
Overschie	6710	1500	12	3	0
Prinsenland	9950	1600	27	12	0
Provenierswijk	4685	2209	13	2	0
Rubroek	8310	2500	5	1	0
S Gravenland	8205	500	9	2	0
Schiebroek	16305	3500	9	2	0
Schieveen	335	0	0	0	0
Spangen	10285	1200	345	99	0
Stadsdriehoek	14825	17890	7	3	0
Struisenburg	5505	3000	10	1	0
Terbregge	3525	500	4	1	0
Tussendijken	7045	2500	0	0	0
Witte Dorp	575	0	35	11	0
Zestienhoven	2090	2500	3	0	0
Zevenkamp	16125	1600	2	0	0
Total	359735	142649	3300	790	2

B.7 Optimum evacuation strategy

Table 45: Optimum evacuation strategy for a given evacuation time of 42 and 18 hours for Rotterdam North

	Evacuation time: 42 hours			Evacuation time: 18 hours		
Neighbourhood	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life
Agniesebuurt		0	0,3		0	0,3
Bergpolder	Preventive	7985	0,1	Preventive	7985	0,1
Blijdorp	Preventive	10160	0,1	Preventive	10160	0,1
Bospolder		0	0,0		0	0,0
Cool		0	0,4		0	0,4
Cs Kwartier	Preventive	1060	0,0		0	0,1
De Esch		0	0,0		0	0,0
Delfshaven	Preventive	6835	0,1		0	1,5
Dijkzigt		0	0,1	Preventive	710	0,0
Het lage land	Preventive	10550	0,1	Preventive	10550	0,1
Hillegersberg Noord		0	0,4		0	0,4
Hillegersberg Zuid		0	0,3		0	0,3
Kleinpolder	Preventive	7525	0,1	Preventive	7525	0,1
Kralingen Oost	Preventive	7995	0,1		0	0,8
Kralingen West		0	0,8		0	0,8
Landzicht	Preventive	380	0,0	Preventive	380	0,0
Liskwartier		0	0,2		0	0,2
Middelland	Preventive	11985	0,1	Preventive	11985	0,1
Molenlaankwartier		0	0,0		0	0,0
Nesselande		0	0,0		0	0,0
Nieuw Crooswijk		0	0,0		0	0,0
Nieuwe Westen	Preventive	19260	0,2	Preventive	19260	0,2
Ommoord		0	2,9		0	2,9
Oosterflank	Preventive	10500	0,1	Preventive	10500	0,1
Oud Crooswijk		0	0,6		0	0,6
Oud Mathenesse	Preventive	7155	0,1	Preventive	7155	0,1
Oude Noorden		0	0,0		0	0,0
Oude Westen	Preventive	9350	0,1	Preventive	9350	0,1
Overschie	Preventive	6710	0,1		0	2,6
Prinsenland	Preventive	9950	0,1	Preventive	9950	0,1
Provenierswijk	Preventive	4685	0,0		0	2,1
Rubroek	Preventive	8310	0,1		0	1,0
S Gravenland	Preventive	8205	0,1		0	2,2
Schiebroek	Preventive	16305	0,2		0	2,1
Schieveen	Preventive	335	0,0	Preventive	335	0,0
Spangen	Preventive	10285	0,1	Preventive	10285	0,1
Stadsdriehoek	Preventive	14825	0,1		0	2,6
Struisenburg	Preventive	5505	0,1		0	1,4
Terbregge	Preventive	3525	0,0		0	0,9
Tussendijken		0	0,0		0	0,0
Witte Dorp	Preventive	575	0,0	Preventive	575	0,0
Zestienhoven	Preventive	2090	0,0		0	0,2
Zevenkamp		0	0,5		0	0,5
Total		202045	8		116705	25

Table 46: Optimum evacuation strategy for a given evacuation time of 5 and 0 hours for Rotterdam North

	Evacuation time: 5 hours			Evacuation time: 0 hours		
Neighbourhood	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life
Agniesebuurt		0	0,3		0	0,3
Bergpolder		0	4,2		0	4,2
Blijdorp		0	5,0		0	5,0
Bospolder		0	0,0		0	0,0
Cool		0	0,4		0	0,4
Cs Kwartier	Preventive	1060	0,0		0	0,1
De Esch		0	0,0		0	0,0
Delfshaven		0	1,5		0	1,5
Dijkzigt		0	0,1		0	0,1
Het lage land	Preventive	10550	0,1		0	108,7
Hillegersberg Noord		0	0,4		0	0,4
Hillegersberg Zuid		0	0,3		0	0,3
Kleinpolder		0	3,6		0	3,6
Kralingen Oost		0	0,8		0	0,8
Kralingen West		0	0,8		0	0,8
Landzicht	Preventive	380	0,0		0	0,1
Liskwartier		0	0,2		0	0,2
Middelland		0	91,5		0	91,5
Molenlaankwartier		0	0,0		0	0,0
Nesselande		0	0,0		0	0,0
Nieuw Crooswijk		0	0,0		0	0,0
Nieuwe Westen		0	199,1		0	199,1
Ommoord		0	2,9		0	2,9
Oosterflank		0	36,7		0	36,7
Oud Crooswijk		0	0,6		0	0,6
Oud Mathenesse	Preventive	7155	0,1		0	96,4
Oude Noorden		0	0,0		0	0,0
Oude Westen	Preventive	9350	0,1		0	98,8
Overschie		0	2,6		0	2,6
Prinsenland		0	12,4		0	12,4
Provenierswijk		0	2,1		0	2,1
Rubroek		0	1,0		0	1,0
S Gravenland		0	2,2		0	2,2
Schiebroek		0	2,1		0	2,1
Schieveen	Preventive	335	0,0		0	0,1
Spangen		0	98,9		0	98,9
Stadsdriehoek		0	2,6		0	2,6
Struisenburg		0	1,4		0	1,4
Terbregge		0	0,9		0	0,9
Tussendijken		0	0,0		0	0,0
Witte Dorp	Preventive	575	0,0		0	11,2
Zestienhoven		0	0,2		0	0,2
Zevenkamp		0	0,5		0	0,5
Total		29405	476		0	791

B.8 Prioritization of neighbourhoods

Table 47: Prioritization of neighbourhoods ranging from first priority (1) to least priority (43) based on the expected mortality rate when opting for vertical evacuation

		Road capacity & available evacuation time		Water depth		Public sheltering capacity		Flood probability	
Neighbourhood	Base case	Best-case	Worst-case	Best-case	Worst-case	Best-case	Worst-case	Best-case	Worst-case
Agniesebuurt	28	28	28	28	29	28	28	26	26
Bergpolder	10	10	10	9	10	10	10	10	10
Blijdorp	11	11	11	10	11	11	12	11	11
Bospolder	37	37	37	37	37	37	37	37	37
Cool	26	26	26	26	27	26	26	25	27
Cs Kwartier	27	27	27	27	28	27	27	27	28
De Esch	38	38	38	38	38	38	38	38	38
Delfshaven	20	20	20	20	20	20	20	19	20
Dijkzigt	29	29	29	29	30	29	29	28	29
Het lage land	5	5	5	4	4	3	5	7	3
Hillegersberg Noord	32	32	32	32	32	32	32	33	32
Hillegersberg Zuid	34	34	34	34	34	34	34	34	34
Kleinpolder	12	12	12	11	12	12	13	13	12
Kralingen Oost	25	25	25	24	25	25	25	22	25
Kralingen West	33	33	33	33	33	33	33	31	33
Landzicht	17	17	17	18	17	16	18	17	18
Liskwartier	36	36	36	36	36	36	36	35	36
Middelland	7	7	7	7	7	7	7	6	7
Molenlaankwartier	39	39	39	39	39	39	39	39	39
Nesselande	40	40	40	40	40	40	40	40	40
Nieuw Crooswijk	41	41	41	41	41	41	41	41	41
Nieuwe Westen	4	4	4	5	3	4	4	4	5
Ommoord	24	24	24	25	24	24	24	32	23
Oosterflank	8	8	8	8	8	8	8	8	8
Oud Crooswijk	31	31	31	31	26	31	31	30	31
Oud Mathenesse	2	2	2	2	2	2	2	2	2
Oude Noorden	42	42	42	42	42	42	42	42	42
Oude Westen	3	3	3	3	6	6	3	3	4
Overschie	14	14	14	13	14	14	14	14	14
Prinsenland	9	9	9	15	9	9	9	9	9
Provenierswijk	13	13	13	12	13	13	11	12	13
Rubroek	23	23	23	23	23	23	23	24	24
S Gravenland	16	16	16	17	16	17	17	21	16
Schiebroek	22	22	22	22	22	22	22	23	22
Schieveen	15	15	15	14	15	15	15	16	15
Spangen	6	6	6	6	5	5	6	5	6
Stadsdriehoek	21	21	21	21	21	21	21	18	21
Struisenburg	18	18	18	16	19	19	16	15	19
Terbregge	19	19	19	19	18	18	19	20	17
Tussendijken	43	43	43	43	43	43	43	43	43
Witte Dorp	1	1	1	1	1	1	1	1	1
Zestienhoven	30	30	30	30	31	30	30	29	30
Zevenkamp	35	35	35	35	35	35	35	36	35

Table 47 (part II): Prioritization of neighbourhoods ranging from first priority (1) to least priority (43) based on the expected mortality rate when opting for vertical evacuation for three what-if scenarios

Neighbourhood	Base case	100% public sheltering is possible for the top-four critical neighbourhoods	Failure probability for one potential failure location is extremely high	4 neighbourhoods already started evacuating preventively, independent of the base strategy and decisions by the authority
Agniesebuurt	28	27	28	28
Bergpolder	10	6	10	10
Blijdorp	11	7	12	11
Bospolder	37	37	37	37
Cool	26	24	26	26
Cs Kwartier	27	25	27	27
De Esch	38	38	38	38
Delfshaven	20	16	20	20
Dijkzigt	29	28	29	29
Het lage land	5	1	5	5
Hillegersberg Noord	32	32	32	32
Hillegersberg Zuid	34	34	34	34
Kleinpolder	12	8	14	12
Kralingen Oost	25	23	25	25
Kralingen West	33	33	33	33
Landzicht	17	13	17	17
Liskwartier	36	36	36	36
Middelland	7	3	7	7
Molenlaankwartier	39	39	39	39
Nesselande	40	40	40	40
Nieuw Crooswijk	41	41	41	41
Nieuwe Westen	4	26	4	4
Ommoord	24	22	24	24
Oosterflank	8	4	8	8
Oud Crooswijk	31	31	31	31
Oud Mathenesse	2	18	2	2
Oude Noorden	42	42	42	42
Oude Westen	3	29	3	3
Overschie	14	10	13	14
Prinsenland	9	5	9	9
Provenierswijk	13	9	11	13
Rubroek	23	21	23	23
S Gravenland	16	12	16	16
Schiebroek	22	20	22	22
Schieveen	15	11	15	15
Spangen	6	2	6	6
Stadsdriehoek	21	17	21	21
Struisenburg	18	14	18	18
Terbregge	19	15	19	19
Tussendijken	43	43	43	43
Witte Dorp	1	19	1	1
Zestienhoven	30	30	30	30
Zevenkamp	35	35	35	35

B.9 Sensitivity analysis

Table 48: Optimum strategy for Rotterdam North considering a bes- case and worst-case for the road capacity

	Best-case road capacity			Worst-case road capacity		
Neighbourhood	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life
Agniesebuurt		0	0,3		0	0,3
Bergpolder	Preventive	7985	0,1		0	4,2
Blijdorp	Preventive	10160	0,1		0	5,0
Bospolder		0	0,0		0	0,0
Cool		0	0,4		0	0,4
Cs Kwartier	Preventive	1060	0,0		0	0,1
De Esch		0	0,0		0	0,0
Delfshaven	Preventive	6835	0,1		0	1,5
Dijkzigt		0	0,1		0	0,1
Het lage land	Preventive	10550	0,1	Preventive	10550	0,1
Hillegersberg Noord		0	0,4		0	0,4
Hillegersberg Zuid		0	0,3		0	0,3
Kleinpolder	Preventive	7525	0,1		0	3,6
Kralingen Oost		0	0,8		0	0,8
Kralingen West		0	0,8		0	0,8
Landzicht	Preventive	380	0,0	Preventive	380	0,0
Liskwartier		0	0,2		0	0,2
Middelland	Preventive	11985	0,1	Preventive	11985	0,1
Molenlaankwartier		0	0,0		0	0,0
Nesselande		0	0,0		0	0,0
Nieuw Crooswijk		0	0,0		0	0,0
Nieuwe Westen	Preventive	19260	0,2	Preventive	19260	0,2
Ommoord		0	2,9		0	2,9
Oosterflank	Preventive	10500	0,1	Preventive	10500	0,1
Oud Crooswijk		0	0,6		0	0,6
Oud Mathenesse	Preventive	7155	0,1	Preventive	7155	0,1
Oude Noorden		0	0,0		0	0,0
Oude Westen	Preventive	9350	0,1	Preventive	9350	0,1
Overschie	Preventive	6710	0,1		0	2,6
Prinsenland	Preventive	9950	0,1		0	12,4
Provenierswijk	Preventive	4685	0,0	Preventive	4685	0,0
Rubroek	Preventive	8310	0,1		0	1,0
S Gravenland	Preventive	8205	0,1		0	2,2
Schiebroek		0	2,1		0	2,1
Schieveen	Preventive	335	0,0	Preventive	335	0,0
Spangen	Preventive	10285	0,1	Preventive	10285	0,1
Stadsdriehoek		0	2,6		0	2,6
Struisenburg	Preventive	5505	0,1		0	1,4
Terbregge	Preventive	3525	0,0		0	0,9
Tussendijken		0	0,0		0	0,0
Witte Dorp	Preventive	575	0,0	Preventive	575	0,0
Zestienhoven		0	0,2		0	0,2
Zevenkamp		0	0,5		0	0,5
Total		160830	14		85060	48

Table 49: Optimum strategy for Rotterdam North considering a best-case and worst-case for the water depth

	Best-case water depth			**Worst-case water depth**		
Neighbourhood	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life
Agniesebuurt		0	0,3		0	0,3
Bergpolder	Preventive	7985	0,1	Preventive	7985	0,1
Blijdorp	Preventive	10160	0,1	Preventive	10160	0,1
Bospolder		0	0,0		0	0,0
Cool		0	0,4		0	0,4
Cs Kwartier		0	0,1		0	0,1
De Esch		0	0,0		0	0,0
Delfshaven		0	1,2		0	1,8
Dijkzigt		0	0,1	Preventive	710	0,0
Het lage land	Preventive	10550	0,1	Preventive	10550	0,1
Hillegersberg Noord		0	0,4		0	0,5
Hillegersberg Zuid		0	0,2		0	0,4
Kleinpolder	Preventive	7525	0,1	Preventive	7525	0,1
Kralingen Oost		0	0,8		0	0,8
Kralingen West		0	0,6		0	0,9
Landzicht		0	0,1	Preventive	380	0,0
Liskwartier		0	0,1		0	0,2
Middelland	Preventive	11985	0,1	Preventive	11985	0,1
Molenlaankwartier		0	0,0		0	0,0
Nesselande		0	0,0		0	0,0
Nieuw Crooswijk		0	0,0		0	0,0
Nieuwe Westen	Preventive	19260	0,2	Preventive	19260	0,2
Ommoord		0	2,3		0	3,6
Oosterflank	Preventive	10500	0,1	Preventive	10500	0,1
Oud Crooswijk		0	0,5		0	0,7
Oud Mathenesse	Preventive	7155	0,1	Preventive	7155	0,1
Oude Noorden		0	0,0		0	0,0
Oude Westen	Preventive	9350	0,1	Preventive	9350	0,1
Overschie	Preventive	6710	0,1		0	3,1
Prinsenland		0	2,2	Preventive	9950	0,1
Provenierswijk	Preventive	4685	0,0		0	2,5
Rubroek		0	0,8		0	1,2
S Gravenland		0	1,7		0	2,7
Schiebroek		0	1,7		0	2,5
Schieveen		0	0,1	Preventive	335	0,0
Spangen	Preventive	10285	0,1	Preventive	10285	0,1
Stadsdriehoek		0	2,6		0	2,6
Struisenburg		0	1,2		0	1,7
Terbregge		0	0,7		0	1,1
Tussendijken		0	0,0		0	0,0
Witte Dorp	Preventive	575	0,0	Preventive	575	0,0
Zestienhoven		0	0,2		0	0,2
Zevenkamp		0	0,4		0	0,6
Total		116725	20		116705	29

Table 50: Optimum strategy for Rotterdam North considering a best-case and worst-case for the public sheltering capacity

	Best-case public sheltering capacity			Worst-case public sheltering capacity		
Neighbourhood	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life
Agniesebuurt		0	0,3		0	0,3
Bergpolder	Preventive	7985	0,1	Preventive	7985	0,1
Blijdorp	Preventive	10160	0,1	Preventive	10160	0,1
Bospolder		0	0,0		0	0,0
Cool		0	0,4		0	0,4
Cs Kwartier		0	0,1		0	0,1
De Esch		0	0,0		0	0,0
Delfshaven		0	1,4		0	1,6
Dijkzigt	Preventive	710	0,0	Preventive	710	0,0
Het lage land	Preventive	10550	0,1	Preventive	10550	0,1
Hillegersberg Noord		0	0,5		0	0,4
Hillegersberg Zuid		0	0,3		0	0,3
Kleinpolder	Preventive	7525	0,1	Preventive	7525	0,1
Kralingen Oost		0	0,8		0	0,8
Kralingen West		0	0,8		0	0,7
Landzicht	Preventive	380	0,0	Preventive	380	0,0
Liskwartier		0	0,2		0	0,2
Middelland	Preventive	11985	0,1	Preventive	11985	0,1
Molenlaankwartier		0	0,0		0	0,0
Nesselande		0	0,0		0	0,0
Nieuw Crooswijk		0	0,0		0	0,0
Nieuwe Westen	Preventive	19260	0,2	Preventive	19260	0,2
Ommoord		0	2,9		0	3,0
Oosterflank	Preventive	10500	0,1	Preventive	10500	0,1
Oud Crooswijk		0	0,6		0	0,6
Oud Mathenesse	Preventive	7155	0,1	Preventive	7155	0,1
Oude Noorden		0	0,0		0	0,0
Oude Westen	Preventive	9350	0,1	Preventive	9350	0,1
Overschie		0	2,5		0	2,7
Prinsenland	Preventive	9950	0,1	Preventive	9950	0,1
Provenierswijk		0	1,9		0	2,4
Rubroek		0	1,0		0	1,1
S Gravenland		0	2,2		0	2,2
Schiebroek		0	2,1		0	2,2
Schieveen	Preventive	335	0,0	Preventive	335	0,0
Spangen	Preventive	10285	0,1	Preventive	10285	0,1
Stadsdriehoek		0	2,6		0	2,6
Struisenburg		0	1,2		0	1,6
Terbregge		0	0,9		0	0,9
Tussendijken		0	0,0		0	0,0
Witte Dorp	Preventive	575	0,0	Preventive	575	0,0
Zestienhoven		0	0,2		0	0,2
Zevenkamp		0	0,5		0	0,5
Total		116705	24		116705	26

Table 51: Optimum strategy for Rotterdam North considering a best-case and worst-case for the flood probability

	Best-case flood probability			Worst-case flood probability		
Neighbourhood	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life
Agniesebuurt		0	0,1		0	0,5
Bergpolder	Preventive	7985	0,1	Preventive	7985	0,1
Blijdorp	Preventive	10160	0,1	Preventive	10160	0,1
Bospolder		0	0,0		0	0,0
Cool		0	0,1		0	0,7
Cs Kwartier		0	0,0		0	0,1
De Esch		0	0,0		0	0,0
Delfshaven		0	0,5		0	2,5
Dijkzigt	Preventive	710	0,0	Preventive	710	0,0
Het lage land	Preventive	10550	0,1	Preventive	10550	0,1
Hillegersberg Noord		0	0,1		0	0,7
Hillegersberg Zuid		0	0,1		0	0,5
Kleinpolder	Preventive	7525	0,1	Preventive	7525	0,1
Kralingen Oost		0	0,4		0	1,2
Kralingen West		0	0,4		0	1,1
Landzicht	Preventive	380	0,0	Preventive	380	0,0
Liskwartier		0	0,1		0	0,3
Middelland	Preventive	11985	0,1	Preventive	11985	0,1
Molenlaankwartier		0	0,0		0	0,0
Nesselande		0	0,0		0	0,0
Nieuw Crooswijk		0	0,0		0	0,0
Nieuwe Westen	Preventive	19260	0,2	Preventive	19260	0,2
Ommoord		0	0,6		0	5,3
Oosterflank	Preventive	10500	0,1	Preventive	10500	0,1
Oud Crooswijk		0	0,2		0	1,0
Oud Mathenesse	Preventive	7155	0,1	Preventive	7155	0,1
Oude Noorden		0	0,0		0	0,0
Oude Westen	Preventive	9350	0,1	Preventive	9350	0,1
Overschie		0	0,9		0	4,3
Prinsenland	Preventive	9950	0,1	Preventive	9950	0,1
Provenierswijk		0	0,8		0	3,5
Rubroek		0	0,3		0	1,7
S Gravenland		0	0,4		0	3,9
Schiebroek		0	0,7		0	3,5
Schieveen	Preventive	335	0,0	Preventive	335	0,0
Spangen	Preventive	10285	0,1	Preventive	10285	0,1
Stadsdriehoek		0	1,1		0	4,1
Struisenburg		0	0,7		0	2,1
Terbregge		0	0,2		0	1,6
Tussendijken		0	0,0		0	0,0
Witte Dorp	Preventive	575	0,0	Preventive	575	0,0
Zestienhoven		0	0,1		0	0,3
Zevenkamp		0	0,1		0	0,9
Total		116705	9		116705	41

Table 52: Optimum strategy for Rotterdam North considering a best-case and worst-case for the available evacuation time

	Best-case available evacuation time			Worst-case available evacuation time		
Neighbourhood	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life
Agniesebuurt		0	0,3		0	0,3
Bergpolder	Preventive	7985	0,1		0	4,2
Blijdorp	Preventive	10160	0,1		0	5,0
Bospolder		0	0,0		0	0,0
Cool		0	0,4		0	0,4
Cs Kwartier		0	0,1		0	0,1
De Esch		0	0,0		0	0,0
Delfshaven		0	1,5		0	1,5
Dijkzigt		0	0,1		0	0,1
Het lage land	Preventive	10550	0,1	Preventive	10550	0,1
Hillegersberg Noord		0	0,4		0	0,4
Hillegersberg Zuid		0	0,3		0	0,3
Kleinpolder	Preventive	7525	0,1		0	3,6
Kralingen Oost		0	0,8		0	0,8
Kralingen West		0	0,8		0	0,8
Landzicht		0	0,1		0	0,1
Liskwartier		0	0,2		0	0,2
Middelland	Preventive	11985	0,1	Preventive	11985	0,1
Molenlaankwartier		0	0,0		0	0,0
Nesselande		0	0,0		0	0,0
Nieuw Crooswijk		0	0,0		0	0,0
Nieuwe Westen	Preventive	19260	0,2	Preventive	19260	0,2
Ommoord		0	2,9		0	2,9
Oosterflank	Preventive	10500	0,1	Preventive	10500	0,1
Oud Crooswijk		0	0,6		0	0,6
Oud Mathenesse	Preventive	7155	0,1	Preventive	7155	0,1
Oude Noorden		0	0,0		0	0,0
Oude Westen	Preventive	9350	0,1	Preventive	9350	0,1
Overschie	Preventive	6710	0,1		0	2,6
Prinsenland	Preventive	9950	0,1	Preventive	9950	0,1
Provenierswijk	Preventive	4685	0,0	Preventive	4685	0,0
Rubroek		0	1,0		0	1,0
S Gravenland	Preventive	8205	0,1		0	2,2
Schiebroek		0	2,1		0	2,1
Schieveen	Preventive	335	0,0		0	0,1
Spangen	Preventive	10285	0,1	Preventive	10285	0,1
Stadsdriehoek		0	2,6		0	2,6
Struisenburg		0	1,4		0	1,4
Terbregge	Preventive	3525	0,0		0	0,9
Tussendijken		0	0,0		0	0,0
Witte Dorp	Preventive	575	0,0	Preventive	575	0,0
Zestienhoven		0	0,2		0	0,2
Zevenkamp		0	0,5		0	0,5
Total		138740	18		94295	36

Table 53: Optimum strategy for Rotterdam North considering three what-if scenarios

	100% public sheltering is possible for the top-four critical neighbourhoods			**Failure probability for one potential failure location is extremely high**			**4 neighbourhoods already started evacuating preventively, independent of the base strategy and decisions by the authority**		
Neighbourhood	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life	Evacuation type (blank cell= vertical)	Number of preventive evacuees	Expected loss of life
Agniesebuurt		0	0,3		0	0,3		0	0,3
Bergpolder	Preventive	7985	0,1	Preventive	7985	0,1		0	4,2
Blijdorp	Preventive	10160	0,1	Preventive	10160	0,1		0	5,0
Bospolder		0	0,0		0	0,0		0	0,0
Cool		0	0,4		0	0,4	Preventive*	5395	0,1
Cs Kwartier	Preventive	1060	0,0		0	0,1		0	0,1
De Esch		0	0,0		0	0,0		0	0,0
Delfshaven	Preventive	6835	0,1		0	1,5		0	1,5
Dijkzigt		0	0,1	Preventive	710	0,0	Preventive	710	0,0
Het lage land	Preventive	10550	0,1	Preventive	10550	0,1	Preventive*	10550	0,1
Hillegersberg Noord		0	0,4		0	0,4	Preventive*	7820	0,1
Hillegersberg Zuid		0	0,3		0	0,3	Preventive*	7965	0,1
Kleinpolder	Preventive	7525	0,1	Preventive	7525	0,1		0	3,6
Kralingen Oost		0	0,8		0	0,8		0	0,8
Kralingen West		0	0,8		0	0,8		0	0,8
Landzicht	Preventive	380	0,0	Preventive	380	0,0		0	0,1
Liskwartier		0	0,2		0	0,2		0	0,2
Middelland	Preventive	11985	0,1	Preventive	11985	0,1	Preventive	11985	0,1
Molenlaankwartier		0	0,0		0	0,0		0	0,0
Nesselande		0	0,0		0	0,0		0	0,0
Nieuw Crooswijk		0	0,0		0	0,0		0	0,0
Nieuwe Westen		0	1,4	Preventive	19260	0,2	Preventive	19260	0,2
Ommoord		0	2,9		0	2,9		0	2,9
Oosterflank	Preventive	10500	0,1	Preventive	10500	0,1	Preventive	10500	0,1
Oud Crooswijk		0	0,6		0	0,6		0	0,6
Oud Mathenesse		0	1,2	Preventive	7155	0,1	Preventive	7155	0,1
Oude Noorden		0	0,0		0	0,0		0	0,0
Oude Westen		0	0,7	Preventive	9350	0,1	Preventive	9350	0,1
Overschie	Preventive	6710	0,1		0	3,4		0	2,6
Prinsenland	Preventive	9950	0,1	Preventive	9950	0,1	Preventive	9950	0,1
Provenierswijk	Preventive	4685	0,0		0	4,5	Preventive	4685	0,0
Rubroek		0	1,0		0	1,0		0	1,0
S Gravenland	Preventive	8205	0,1		0	2,2		0	2,2
Schiebroek		0	2,1		0	2,1		0	2,1
Schieveen	Preventive	335	0,0	Preventive	335	0,0	Preventive	335	0,0
Spangen	Preventive	10285	0,1	Preventive	10285	0,1	Preventive	10285	0,1
Stadsdriehoek		0	2,6		0	2,6		0	2,6
Struisenburg	Preventive	5505	0,1		0	1,4		0	1,4
Terbregge	Preventive	3525	0,0		0	0,9		0	0,9
Tussendijken		0	0,0		0	0,0		0	0,0
Witte Dorp	Preventive	575	0,0	Preventive	575	0,0	Preventive	575	0,0
Zestienhoven		0	0,2		0	0,2		0	0,2
Zevenkamp		0	0,5		0	0,5		0	0,5
Total		116755	18		116705	28		116520	35

Appendix C

List of symbols

The following list summarizes the main symbols that have been used in this thesis.

Symbol	Dimension	Description
L_i	[persons]	Number of fatalities for zone i
i	[-]	Zone
j	[-]	Evacuation type
t	[hours]	Lead time
m	[-]	Number of zones in the whole system
n	[-]	Number of strategies
N_i	[persons]	Number of people in zone i
E_i	[persons]	Outflow of evacuees from zone i to the connecting road
IN	[persons]	Inflow of evacuees from n zones to the overall infrastructure
$STORAGE$	[persons]	Occupation of the connecting road at start of evacuation
OUT	[persons]	Outflow capacity of the connecting road
C_{road}	[persons]	Connecting road capacity without congestion for lead time t
C_{exit}	[persons]	Capacity of connecting road exit point for lead time t
C_i	[persons]	Capacity of the road(s) within zone i
c	[-]	Flood scenario
z	[-]	Number of flood scenarios
y	[-]	Dike section
p	[-]	Number of dike sections
h	[meter]	Water level upstream of water defence
Pf_y	[-]	Conditional failure probability of dike section y