Decision-making in the case of a flood-threat

Implementation of the new risk-approach

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Final report

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Preface

As part of the Master thesis at the faculty of Civil Engineering and Geo-sciences of Delft University of Technology this report is conducted. The research studied the influence of the new risk approach on emergency-procedures in case of a flood-threat in the Netherlands. HKV-consultants, located in Lelystad and Delft, supported the development of this research. I would like to thank my graduation-committee Prof.dr.ir.M. Kok, Prof.dr.ir.S.N. Jonkman, Dr.ir.B. Kolen, Ir. W.L.A. ter Horst and Ir. D. Riedstra for their supervision and support.

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Executive summary

Introduction

Flood-defence structures are required in the Netherlands, since two-thirds of the country is at risk of flooding. Formerly, strengthening of these defence structures occurred in a response to flooding. The crests of levees were designed in respect to the highest observed waterlevel. After the flood disaster of 1953, the Delta-commission proposed a new vision, where the costs of reinforcements should be weighed against the reduction of flood-risk. However, due to insufficient computing-power and lack of knowledge, risk could not be calculated accurately. Therefore, design criteria were based on a waterlevel-threshold, where a levee was supposed not to fail below this waterlevel. In reality however, dikes can fail due to all sorts of failure-mechanisms. The new risk-approach therefore explicitly included this knowledge, to better guarantee safety. The VNK-project (Dutch: Veiligheid Nederland in Kaart) was introduced as a consequence of the new risk-approach. Its main objective was to examine current defence-structures by mapping the flood-risk of 58 levee systems in the Netherlands. The project pointed many weak spots in these levee-systems because dike-strength and economic value of the protected areas was often underestimated.

Objectives

Evacuation is a measure to reduce the consequences of a flood, by preventing loss of life and damage to movable goods. These benefits are uncertain since flooding is uncertain. On the other hand, costs are involved if evacuation is called. People are requested to leave the threatened area, and are therefore not able to contribute to economy for a while. The consideration of evacuation is stated in a national emergency-protocol. The protocol makes use of threshold-waterlevels for up-scaling, to indicate the degree of alertness in a threatening situation. These up-scaling criteria function as indicators and therefore not tell to take action at a specific moment. However, the emergency-protocol still relies on the old approach, based on threshold-waterlevels. The question arises if the measure evacuation is still considered in time.

Accordingly, literature showed that decision-makers are in need of supportive information in the case of a flood-threat. Therefore, [Kolen, 2013] proposed an evacuation-decision diagram, which tells whether evacuation is satisfied, based on the number of prevented fatalities. However, the diagram does not explicitly include the required time for evacuation, as well as the uncertain time until the flood-event.

This study focuses on the development of a decision-method, to find an alarm-waterlevel to call for evacuation in the case of a flood-threat for dikering-areas in the Netherlands. The aim is to include uncertainty of failure and waterlevel-forecasts explicitly, to deliberately decide for evacuation. Finally, the method is applied to dikering-area 43 in the Netherlands in order to evaluate current emergency-procedures with an alarm-waterlevel to call for evacuation.

Decision-method

The decision-method is proposed as a supportive tool to decide for evacuation. It is based on the same risk-management approach as used to define the new safety standards. Three important aspects are required:

1. Firstly, costs and benefits of the measure evacuation need to be defined. Although the measure has the opportunity to save loss of life, it is costly as well. A social cost-benefit analysis therefore is applied, where a monetary value is assigned to a (prevented) fatality after [Bockarjova et al., 2010, Bockarjova et al., 2012]. Costs are related to economy if inhabitants are requested to leave the threatened area. Besides, some fatalities will occur because of evacuation itself, due to a chaotic response.

Benefits are defined by prevented loss of life and the value of moved goods. These aspects are related to the available time to take measures, in respect to the uncertain event of flooding.

2. Secondly, forecasts of high waterlevels are used as indicator to call for evacuation. The method uses a representative waterlevel-development over time, to mimic waterlevel-forecasts. Waterlevels are forecasted for a maximum time-frame of four days, where the expected waterlevels follow the development of the design-wave.

3. Lastly, information of dike-strength is required to account for failure-probabilities. Fragility-curves represent the conditional failure-probability as a function of the waterlevel for a given failure-mechanism. This report only accounted for failure-mechanisms piping and overflow/overtopping for dike-strength representation.

If a call for evacuation is made, there will be no way back. However, one is uncertain when and if the flood hits. When the decision-maker decided to wait and no flood occurred, a new decision can be made the next day with updated information. To support these decisions, the method assesses a moment relative to the representative waterlevel-development over time, where the decision is economically satisfied. This moment is based on a threshold, described by the first day the expected costs for *evacuation* are smaller than the expected costs for *no evacuation*. To account for the time needed for decision-making, warning and response [Barendregt and van Noortwijk, 2004], one should start considering evacuation 24 hours in advance.

The decision-method is assessed to a simplified dikering-area, where a uniform dikering is assumed. Accordingly, only one flood-scenario holds, described by the number of affected people and damage. A base-case is provided as numerical example, to understand the main considerations. Next, a detailed sensitivity analysis treats the implications of chosen parameters and assumptions. This allows to check model-behaviours.

Finally, a case-study of dikering 43 in the Netherlands is provided. The study gives an overview of the local emergency-procedures and focuses on the evacuation-consideration specifically. The methodology as described in the VNK-report is used to define flood-scenarios and dike-strength information. These aspects result in evacuation-considerations of the Eastern and Western part of the dikering, due to the sloping surface of the protected area. For breaching in the Eastern part, the entire area needs to be evacuated. If the dikering breaches in the Western part, only the Western part of the dikering needs to be evacuated. This study shows that the evacuation-consideration of the Eastern part is normative, since a worthwhile decision for this area relates to the lowest alarm-waterlevel. This alarm-waterlevel is compared with current emergency-procedures, stated in the national emergency-protocol (LDHO) and the protocol of water-board *Rivierenland*.

Conclusions

The study focused on the development of a decision-method to find an alarm-waterlevel to call for evacuation in the case of a flood-threat, for dikering-areas in the Netherlands. The model and its implications resulted in the following conclusions:

- An alarm-waterlevel to call for evacuation relies on the performance of the evacuation-process. If more people can be saved within the same amount of time, the possible benefits of an evacuation increase. This puts more favour to the decision *evacuation* over *no evacuation* for the same loading- and strength-conditions. Concluding, if the performance of evacuation improves, a lower alarm-waterlevel is economically satisfied.

- The strength of a dike influences the evacuation-decision. If strength of the dikering is affected by a failure-mechanism as piping, conditional failure-probabilities become significant for lower waterlevels. Therefore, if the same waterlevel-forecasts are expected for a weaker dike, failure will be more likely to occur. As a result, a worthwhile decision for evacuation is made for a lower alarm-waterlevel.

- The decision-method is applied for dikering 43 in the Netherlands. The analysis used dike-strength information according to [Rijkswaterstaat VNK Project, 2015] and evacuation-estimates of [Kolen et al., 2013] to quantify the possible benefits of evacuation in this area. The analysis made clear that an evacuation-consideration can be made at lower waterlevels than currently stated in the national emergency-protocol.

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Chapter 1

Introduction

The Netherlands relies strongly on its flood defences since two-thirds of the country is at risk of flooding. Large proportions lie below sea-level, where high river-discharges and storms at the North-sea may cause major disasters. To guarantee safety in some extent, approximately 3,500 kilometers of primary defence-structures are built for protection. Formerly, defences were strengthened in a response to flooding, where the new crest of levees was designed with respect to the highest observed waterlevel. It was until the flood of 1953 this reactive way of thinking was about to change. After this major disaster, the Delta-commission proposed a new vision, where stricter requirements needed to provide a higher safety-level. The main concept was to weigh the costs of reinforcements against the reduction of flood risk. Although the idea of the commission was very clear, unfortunately one was not able to calculate risk accurately due to insufficient data on strength of levees and hydraulic loads. Therefore, a more simplified approach was proposed which only made use of waterlevels. The method prescribed that levees should be designed on basis of design waterlevels they needed to withstand. In this way, it was assumed that failure was only likely to occur above these threshold-values. Accordingly, regions with the highest economic value were assigned with the most rigid norm-values.

Figure 1.1: Picture of 1953 flood in the Netherlands ("de Watersnoodramp")

Experience, improvement of knowledge and the development of computing power resulted in more insights regarding dike-failure and possible flood-scenarios. This awareness resulted in a better need for understanding of flood risk in the Netherlands. As a consequence, the new risk-approach was introduced. The approach pursues a control of flood risk on a social-political accepted level, which takes account of the economic value of fatalities. Norm-values are expressed as a maximum accepted risk of flooding, which equals to a risk of failure within a defence-trajectory, leading to a flood in the protected area. Based on these norm-values, design-criteria for defence-structures can be developed.

The new risk-approach changed the safety standards in the Dutch Water-Act. First, the norm used to be an exceedance probability of the design waterlevel, and the flood defence was supposed not to fail for all waterlevels below this level. Now, the standard is based on three risk-metrics (economic-, individual-, societal-risk), which includes the probability of failure. This enables to explicitly include all sorts of failure-mechanisms in the design-criteria of defence-structures. The VNK-project (Dutch: Veiligheid Nederland in Kaart) was introduced as a consequence of the new risk-approach. Its main objective was to examine current defence-structures, by mapping the current flood risk in 58 levee systems in the Netherlands. The results pointed many weak spots along dike-ring areas because strength and economic value was often underestimated. Accordingly, the project claimed that mostly the *width* of levees (instead of their *height*) needs to be revised to meet the new standard [Rijkswaterstaat VNK Project, 2015].

Although improvements of the flood defences already started, the Dutch safety protocol for emergency measures still relies on the old approach, based on threshold-waterlevels. The protocol prescribes phases (marked with colours) for up-scaling, which generally holds that flood-awareness increases for higher scales. In the case of a flood-threat, the involved parties are in this way designated with certain duties to reduce possible consequences. Evacuation is one of these measures. It is defined as the process of alerting, warning, deciding, preparing, departing and (temporarily) holding people, animals, personal belongings and corporate stock and supplies from an unsafe location at a relatively safer location, given the actual circumstances [Kolen, 2013]. Currently, this measure is in the protocols not clearly indicated with an alarm-waterlevel and only considered in the most extreme situations. Therefore, the question arises if evacuation is considered in time.

1.1 Problem statement

Evacuation is a measure to reduce the possible consequences of flooding. In the case of a flood-threat, decision-makers are asked to make the right decision. On the one hand, there is an opportunity to reduce possible fatalities, but flood-events and dike breaches are often uncertain until they happen. Simultaneously, costs are involved if a call for evacuation is made. Guidelines for decision-making are provided in the Dutch emergency-protocol for flood-threats. This protocol is still based on the old approach, where threshold-values of waterlevels serve as phases for alertness. These waterlevels function as indicators, and do not represent clear moments for taking action. The consideration of evacuation is currently only stated in the most extreme situations.

Accordingly, literature showed that decision-makers are in need of supportive information during a flood-threat. Since no clear indicators for evacuation are provided, one is uncertain about the righteousness of such a high impact decision. The study of [Kolen, 2013] therefore proposed an evacuation-decision diagram for flood-threats. It explains if an evacuation-decision is satisfied and explicable. Based on the number of prevented loss of life, an evacuation-threshold can be composed for a dikering-area. However, the diagram not explicitly includes the available and required time for evacuation. It is therefore hard to explain a clear moment of leaving.

A satisfied alarm-waterlevel to call for evacuation therefore needs to be composed, which explicitly includes the involved time-aspects. Accordingly, information of dike-strength needs to be used, as is done in VNK-studies. This enables to include all sorts of failure-mechanisms, instead of solely focusing on height. Such a method has the opportunity to support decision-makers in threatening situations, and allows to evaluate current emergency-procedures rationally.

1.2 Research question

How can, in the case of a flood threat, an alarm-waterlevel for evacuation be developed if the new flood risk-approach is applied?

1.3 Objectives and scope of the study

The main goal of this study is to develop a method to find an alarm-waterlevel to call for evacuation in the case of a flood-threat for dikering-areas in the Netherlands. Four objectives are composed to support this goal:

1. Investigation of the implications of the new risk approach regarding the design of flood-defences and its impact on evacuation-considerations.
2. Investigation and development of a simplified model to obtain an alarm-waterlevel to call for evacuation in the case of a flood-threat.
3. Analysis of implications of a decision-model for evacuation based on a social cost-benefit analysis and probabilistic forecasting.
4. Application of the decision-method on a dikering-area in the Netherlands, to evaluate current emergency-procedures with an alarm-waterlevel to call for evacuation.

1.4 Research overview

The document starts with a an introduction and is finalised with conclusions a discussion and recommendations. Chapter 2 gives a summary of relevant theory and background information. This chapter treats general knowledge regarding the new risk approach and the main results according to the VNK-report (section 2.2). Subsequently, literature will be treated regarding emergency-management and its main concepts in the case of a flood-threat (section 2.3). This section also explains the fundamentals of an evacuation-decision diagram after [Kolen and Wegman, 2016], and refers to appendix A for a numerical example.

Chapter 3 presents a simplified study to explain the main concepts of the decision-method. First, section 3.2 presents the requirements of the decision-method, using fictive dikering-area for simplicity. A social cost-benefit-analysis will be used after [Kolen, 2013] to present a rational evacuation-consideration. Second, section 3.3 moves into a general description of the decision-model and its main assumptions. This part treats a base-case as numerical example. Finally, an alarm-waterlevel to call for evacuation will be composed, based on this simplified study. The base-case will be used as reference-situation.

Results of the base-case are used in chapter 4. This chapter presents a sensitivity-analysis of the proposed decision-method. The model will be "checked" on logical outcomes and behaviours. Section 4.2 moves into this topic. This behaviours will become clear by changing parameters relative to the base-case of Chapter 3. Second, the influence of other important model-assumptions will be treated in section 4.3. This information is needed to understand which topics should be studied in more detail related to the case-study of chapter 5.

The decision-method is applied in chapter 5 for dikering 43 in the Netherlands. A description of current emergency-procedures within this region is given in section 5.2. It gives an overview of current up-scaling criteria and the ability of evacuation. Section 5.3 presents a the interpretation of the new risk approach by a summery of the VNK-report regarding the area under study. The used methodology and its main results are presented in this section. Some simplifications are required to apply the decision-method. Section 5.4 lists these model-assumptions and simplifications. Finally, the results will be presented in two separate sections (section B and section 5.5). They present the evacuation-decisions related to specific segments of the dikering and a substantiated evacuation-decision for the entire dikering-area.

Chapter 2

Theory and background information

2.1 Introduction

This chapter provides a first insight in the already completed subject-related research. The presented topics cover basic knowledge which is needed to understand upcoming statements and considerations. Firstly, the development of the new risk approach will be explained in section 2.2. This part covers topics as the Water-Act, the indicators of risk and the design of defence structures. Section 2.3 moves into the aspects of emergency management and the main considerations of a decision maker in the case of a flood threat.

This chapter covers the first objective, according to section 1.3: *Investigation of the implications of the new risk approach regarding the design of flood-defences and its impact on evacuation-considerations.*

2.2 The new risk approach further explained

Since computing power and knowledge regarding defence structures improved in recent years, one became able to calculate risk of flooding more accurately. The VNK-project (Dutch: Veiligheid Nederland in Kaart) calculated for every dike-ring area in the Netherlands the actual risk of flooding. These insights were evaluated against the norms in the Dutch Water Act, since safety against flooding currently has a legal character. The key points of this act will be discussed in section 2.2.1. Accordingly, the implications of the new risk approach will be discussed in more detail in sections 2.2.2, 2.2.3 and 2.2.4. Finally, the main findings of the new risk approach will be summarized in section 2.2.5.

2.2.1 The Dutch Water Act

The Dutch Water Act has been officially approved since the year 2009, where eight separate acts were merged. Its main aim is to do justice to the many relationships and interests involved with national water resources. Related to the topic of this research, it is important to know that the act formulates the standards for water systems in order to prevent unacceptable consequences of flooding. All norm-values for primary flood defence-structures are defined in the act itself [Zeilsta, 2009].

Formerly, norm-values were based on exceeding-probabilities of a design waterlevel. The flood-defence was supposed not to fail for all waterlevels below this level. Since knowledge regarding the actual strength of flood-defences improved, it became clear that failure could occur due to all sorts of failure-mechanisms. The legal implementation of the new risk approach therefore proposed to include this knowledge, to better guarantee safety against flooding. This approach includes norm-values to be based on the three indicators of risk: economic risk, individual risk and societal risk. Section 2.2.2 discusses these indicators in more detail. Flood-risks for the protected areas are translated to norm-values for primary defence-structures. By doing so, one desires to accomplish a basic safety-level for the protected areas.

2.2.2 Aspects of the new risk approach

Because of new technical research, much more information is available about the loading of flood defences, how strong they are and the consequences when breaching occurs. Therefore, the project VNK improved the risk approach by calculating the flood risk more precisely. The fundamentals of this new approach are derived from the all-known risk formulation:

$$\text{Risk} = \text{Probability} \times \text{Consequences}$$

The VNK-project elaborated for different defence elements the probability of failure including the consequences if failure occurs. This probabilistic way of thinking is required since failure is not only likely to occur if a waterlevel exceeds the design-waterlevel. All sorts of failure-mechanisms can contribute to the failure-process, which brings many uncertainties. For instance: the moment of failure, the location of failure and the forecast of waterlevels. The probabilistic approach gives the possibility to account for these uncertainties and loads explicitly. In the new approach, failure probabilities and consequences are combined in three different measures of risk [Vnk, 2014]:

- **Economic risk**: Expressing the yearly expected value of economic losses, in Euros per year. This number is often used in cost-benefit considerations regarding investing in flood protection versus the reduction of risk (as a result of these investments).
- **Individual risk**: This number represents the annual probability that an imaginary person at a particular place in the protected area will die as a result of flooding in the area. This is number is calculated for the situation where the possibility of evacuation is considered and is independent of the actual presence of people in the protected area. The norm describes a maximum tolerable individual risk of $10^{-}5$ per year.
- **Societal risk**: The societal risk measures the number of flood fatalities for a given flood frequency. For instance, when a rare flood occurs it will be more likely to cause large numbers of fatalities compared with a more frequent flood. Such an event therefore has a greater societal impact.

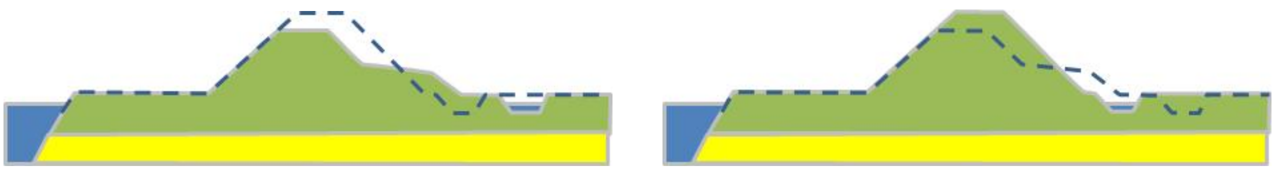
These risk metrics can support the Dutch government in decision-making about new flood safety standards. The report of [Jonkman et al., 2011] discusses the results of the potential of the risk-measures individual and societal risk. The following sections will describe how these risks are calculated with information about the strength of defence-structures and the consequences of flooding.

Figure 2.1: Graphical representation of the new risk approach, after [Rijkswaterstaat VNK Project, 2015]

2.2.3 Impact of the new risk approach on the design of defence structures

The design of dikerings in the Netherlands relies on previously elaborated risk approach. A strong dikering represents in this sense a small probability of failure. The structure contains a continuous line of flood defences (dunes, levees and/or retaining walls). Guidelines are therefore conducted to guarantee the required safety. Failure can occur if the strength of the retaining structure is smaller than the the working load. This happens in all sorts of ways, described by failure mechanisms. To calculate the probability of failure (thus flooding) accurately, a structure needs to be firstly divided in (nearly) homogeneous dike-sections. The failure-probability of these dike-sections can afterwards be derived from loading- and strength-statistics.

Failure mechanisms and dike-design Referring to former norm-values it seemed that various parts of the dikering not all contributed in the same degree to its failure-probability. Several other failure mechanisms than overflow/overtopping seemed to be dominant or played a much greater role than previously assumed. To account for this insight, new dike designs are made by use of failure budgets (Dutch: *faalkansbegroting*). To do so, every failure-mechanism contributes to the final standard to a certain degree. The total failure-budget finally determines the shape of the construction [Knoeff, 2015] (see figure 2.2).



(a) Mechanisms *overtopping and overflow* determine design (lower and wider dike)

(b) Mechanism *stability* determines design (narrow and high dike)

Figure 2.2: Two dike-shapes determined by a dominant failure mechanism, after [Knoeff, 2015]

To check whether current dikes meet the new standards, a detailed test for every dike-section is required. The outcomes tell whether strengthening (thus investing) is satisfied.

The length effect When a flood appears, one is unsure about the breaching-location in the threatened dikering. Accordingly, failure is more likely to occur *somewhere* in the dike-reach than at a specific point. Therefore, guards control the dike if high waters appear along the reach, to spot possible breaching locations. *The length effect* explains how dike-designs should be accounted for this phenomena. A design should be included with the following role-playing factors [Jongejan, 2015]:

- The fraction of the dike-trajectory sensitive for a particular mechanism, formulated with parameter a
- An indicator for the intensity of the length-effect for this fraction, formulated with paramter b

These factors contribute to maximum tolerable failure probability P in the following way:

$$P_{max,cross-section} = \frac{P_{max,trajectory}}{1 + a \times \frac{L}{b}} \tag{2.1}$$

The length-effect is an important property for the failure-mechanism piping. Uncertainty exists about the presence of pipes and where they occur. Norm-values therefore need to be stricter if piping plays a larger role in the dike-trajectory under study. Equation 2.1 explains this principle in the following way: if a larger fraction of the dike-trajectory is sensible to piping (parameter a), the maximum tolerable failure-probability on cross-section level decreases. I.e. the norm becomes more rigid.

2.2.4 Consequences of flooding

Second aspect of the new risk approach are the better insights in the consequences of flooding. After breaching, water flows into the hinterland, which threatens human life and property and has the ability to have a major impact on society. However, the location of breaching is of major importance. Therefore the study of [Rijkswaterstaat VNK Project, 2015] studied many scenarios. Flood patterns can be described by three different categories, to be known:

- **Flat polder type**: These are areas with very little slope and no large linear objects. The flood causes always an entirely inundated hinterland, irrespective of the location of the breach. Accordingly, consequences (expressed in Euros) and the location of the breach are virtually unrelated to each other.
- **Sloping surface area**: A sloping surface is often found along rivers. When breaching occurs downstream of the river, only limited parts of the area will be flooded. If the defences breach upstream, the entire protected area is affected.
- **Variable**: This category represents areas where flood behaviour varies in the area. This is mainly the cause of elevation differences, presence of regional defences or raised roads and railways.

The affected area experiences damages to their economy and loss of life. Referring to economic losses one can think of damage to infrastructure, houses and offices (unmovable goods) or cars and animals (movable goods). Next to that, indirect losses will appear because economic activity outside the affected area becomes dead end as well.

Loss of life in flood scenarios is calculated on basis of the number of inhabitants, combined with flood characteristics. One can think of flood-velocities or waterlevel rise in the hinterland. Consequences of flooding can significantly be decreased by taking preventive evacuation into account. This aspect will be discussed in section 2.3.

2.2.5 Outcomes of the new risk approach

This part will briefly discuss the major outcomes of the VNK-report. These outcomes show that the current dike-designs not always fulfill the new standards. Most frightening is the fact that currently major differences in flood risk appear within the same protected area. The main conclusions are:

- **Safe coastal areas**: The report of VNK showed that the coastal areas have a relatively low risk of flooding. This is because of relatively wide dunes, leading to low failure probabilities.
- **High flood risk along rivers**: Current norm-values along the rivers are less strict compared with the coastal areas. Research showed however that levee breaches are likely to occur in this areas. Levees are narrow, leading to high failure probabilities for a mechanism as piping. Accordingly, high values of the hinterland (economic and inhabitants) may lead to enormous consequences.

As already showed will the obtained knowledge be used to revise the design of safety-structures in the Netherlands. The next question is if these new insights also contribute to a revised emergency system. The next section shows some key-factors regarding emergency management, with preventive evacuation in specific.

2.3 Dealing with flood threats

Although investing in strength of defence structures most of the times might be the best thing to do, the probability of flooding cannot be reduced to zero. When extreme weather is expected, some weak spots in the dike-rings will appear. To reduce the possible consequences of flooding, it is necessary to look into emergency measures. This section discusses these aspects, where most attention will be paid on evacuation. Firstly, the concepts of evacuation planning will be discussed in section 2.3.1. Secondly, decision making and current protocols will be discussed in section 2.3.2.

2.3.1 Concepts of evacuation planning

Evacuation is defined as a measure to potentially reduce the loss of life and damage to movable goods [Kolen, 2013]. In the case of an unforeseen flood-event, people will respond unprepared and stakeholders need to act instantaneously. They will be directly faced with the consequences. Threat-driven response takes place when a flood can be detected beforehand. Authorities and citizens are in this way able to act. Effectiveness of response depends on time and the way people perform. These factors can be influenced and improved. The following phases in the evacuation process can be derived:

- *Phase 0*: This is known as the time-frame before warning. It therefore represents normal-life situation, where planning and design of the safety system can take place.
- *Phase 1*: The period between detection and sense-making after early warning.
- *Phase 2*: Decision-makers and citizens will act to prepare for a possible evacuation or mitigation measure.
- *Phase 3*: The period of moving to safe places.

Four elements can be formulated to describe the effectiveness of these phases. The following paragraphs will briefly discuss their role. [Kolen, 2013] is used as reference study.

Element 1: Threat and impact Understanding about the impact of the upcoming flood event is necessary since it clarifies the need for evacuation planning. Classes are therefore provided to mark timescales and sizes (flooded area, no. of people). Classes, describing impact of events (small-, design-, extreme- and worst credible events), are used to develop scenario's, and reflect the representation of hydraulic loads with respect to design levels. In the same way *time* can be classified. Time available for preventive evacuation is uncertain, since it relies on the uncertain flood-event. The required time for the evacuation-process versus the available time based on forecasts needs to be known. Available and required time for evacuation is studied in [Barendregt and van Noortwijk, 2004]. This is represented in figure 2.3. The available time for evacuation with respect to the required time, can be classified as best-case, expected case- or worst-case scenario (where there is no time left for evacuation).

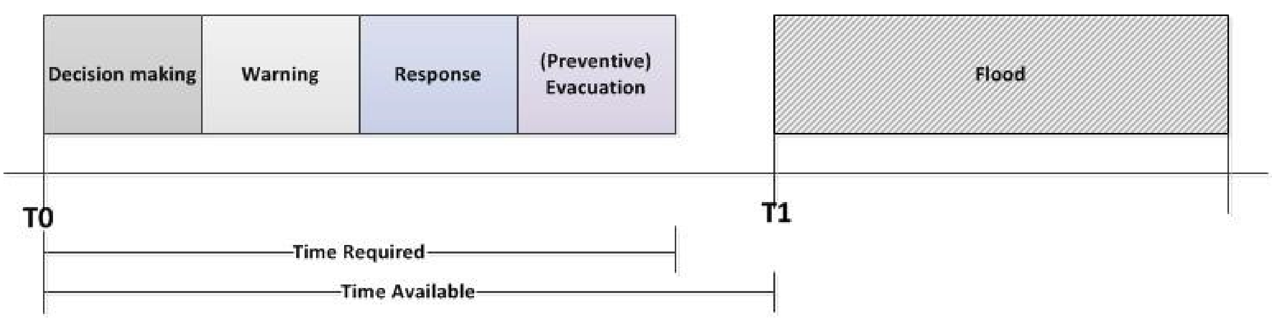


Figure 2.3: Representation of the time required and available for evacuation, after [Barendregt and van Noortwijk, 2004]

Element 2: Decision making by authorities During the transition phase, top strategic decisions will be made. How and when to respond is a central issue for authorities and the public. Focus is applied on the process of decision making and the transition phase. Possible strategies to be applied are:

- *Preventive evacuation*: The organisation and movement of people form a (potentially) exposed area to a safe location;
- *Vertical evacuation*: The organisation and movement of people to upper levels of residential buildings before the beginning of the floods at location;
- *Shelter in place*: The organisation and movement of people inside the area under threat to shelters or safe havens.

Authorities are challenged to deal with consequences. Regarding evacuation, they are faced with potentially reducing loss of life (positive consequences) and economic and social disruption (negative consequences) in combination with the uncertainty a flood occurs. Using a survey, insight is obtained from decision makers and crisis managers in the Netherlands. The following is questioned:

- The importance of certain parameters in the decision-making process;
- Factors determining whether an evacuation decision was “right” in a situation after a flood occurred and when a flood did not occurred;
- Impact of other events on decision making process for mass-evacuation;
- What actions should be taken (developing alternatives, advising public, evacuation) when one is certain to some degree (as a percentage) the flooding event will take place in 4 days (considered as enough time for preventive evacuation);
- What probability of flooding is necessary to be able to choose a certain type of evacuation, when there is limited time for evacuation;
- How decision makers and crisis managers should respond in the case they were a citizen (as a member of a family), when they should have the possibility for preventive evacuation, but authorities ordered to respond alternatively.

The survey makes clear that there is need for simplification of the decision making process in the case of a mass evacuation. If the time for decision making can be reduced, more time will be available for evacuation itself. Risks, costs and benefits should be properly addressed as well as their uncertainties.

Element 3: The environment and traffic-infrastructure Effectiveness of an evacuation can be described as the proportion of people who can reach the intended destination in time or by the number of loss of life. The first definition is strongly related to the available physical infrastructure in an area. For decision-making and evacuation planning, information is required about the available time and required time for evacuation [Barendregt and van Noortwijk, 2004, Jonkman, 2007] . Next to that, studies have shown that the location where people are exposed is related to the probability for loss of life.

Example strategies are used to give insight in the consequences of different parameters in the effectiveness of an evacuation. Seven strategies are applied in the used research, varying between optimistic and pessimistic evacuation scenarios. These scenarios are based on the way people will be divided around the traffic network (free of choice = pessimistic, optimal division based on exit capacity = optimistic).

When people act differently and start with preventive evacuation, a possible shadow evacuation will start. This form limits the evacuation of others, thus exposes more people at risk. It is shown in the analysis of casualties that people in cars are more vulnerable than others. It is therefore necessary to consider other evacuation strategies (vertical, shelter in place) in time. In the Netherlands, limited experience with evacuation is available due to the high safety standards. It is therefore advised for planners, to think about consequences of several optimistic and pessimistic scenarios.

Element 4: Citizens response In the case of a flood threat, the performance of an evacuation relates to the impact of the response of citizens. Response is defined as all actions taken to prepare for disasters and major incidents, as well as during as after these events, with the intent of helping themselves and others to limit the effects of the disaster or major accident [Helsloot and Ruitenberg, 2004]. It is shown that most people will rescue themselves in the case of a mass evacuation. Authorities are there to support this process. Concerning the travel time, the moment of departure and the available road capacity are important factors to account for. The number of cars, including the number of people in a car, must be taken into account. Other relevant factors are:

- The occurrence of accidents;
- The lack of fuel;
- The use of emergency services instead of own transport.

[Kolen, 2013] used a case study to get better insight into the consequences of different behaviours. In this way one should be able to identify the contribution or reduction to the performance of evacuation. Information of this study can be used to estimate uncertainties and consequences of evacuation.

2.3.2 Decision making for evacuation

Previous paragraph already showed the complexity of evacuation. For instance uncertainties in the failure process and its consequences are influencing factors. As already showed, time is one of the most important components in this process. Postponing a possible decision for evacuation results in more certainty about the event, but less time to evacuate. The following explains studies where the measure evacuation is considered. As already explained are decision-makers in need of supportive information in the case of a threatening event. Surveys and evacuation-exercises prove the difficulty of decision-making in [Kolen, 2013]. The studies of [Kolen, 2013] and [Kolen and Wegman, 2016] therefore introduce an evacuation-decision diagram, which will be explained. Current emergency management are discussed afterwards.

Introduction of an evacuation-decision diagram The report of [Kolen and Wegman, 2016] is based on previous research of [Kolen, 2013]. Both explain the fundamentals of a method to support an evacuation-decision in the case of a flood-threat. The corresponding diagram is presented in figure 2.4, in Dutch. The vertical axis presents the conditional probability of flooding, the horizontal axis represents the number of prevented loss of life (the benefits of evacuation). Costs induced by evacuation if no flooding occurred, are represented by the yellow area. The area explains a worst- and best-case situation of these costs.

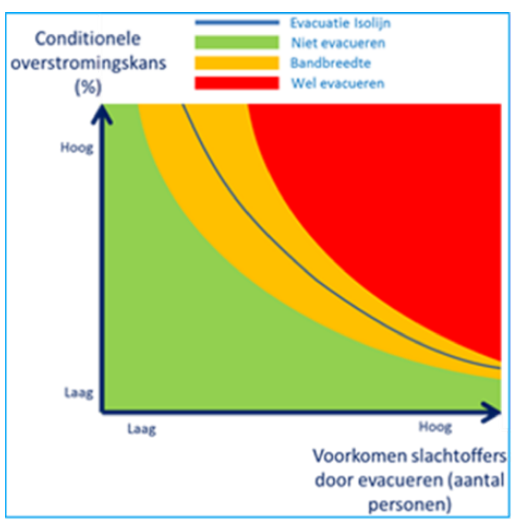


Figure 2.4: Evacuation-decision diagram, after [Kolen and Wegman, 2016]

The diagram is based on the same approach as is used in current crisis-management. In the case of a flood-threat, it explains if an evacuation-decision is satisfied and explicable. The green area suggests *do not evacuate* and the red area *evacuate*. The more people can be saved, the lower conditional probability of flooding is satisfied to support evacuation. Simultaneously, if less time is available until the critical event, less people can be saved. In that case evacuation is only allowed for a higher conditional probability of flooding. Therefore it can be suggested to read the figure from right to left over time.

The reports of [Kolen, 2013, Kolen and Wegman, 2016] make clear that an evacuation-decision diagram can be composed per dikering-area. Appendix A therefore treats a numerical example.

Nowadays emergency management In the Netherlands an emergency protocol is conducted for threatening situations. A threat is recognized on basis of forecasts of discharges and waterlevels. The protocol describes four phases: green, yellow, orange, red. Every phase functions as a support for exchange of information, adjusting of measures and adjusting of communication to the public. Moving from one phase to another (from green to yellow for instance) is called up-scaling (Dutch: opschalen). Important to understand, is that phases are used as indicators, not for taking measures. This implies that specific measures (as evacuation) are considered in certain phases, but not necessarily exercised. The phases are explained in figure 2.5.

Phase:	**Green**
	Normal-life situation
Phase:	**Yellow**
	Expected waterlevels are somewhat higher.
	Superintendents: Normal measures will be taken. Use of the waterways may be, as shipping and activities in the wash-land, may be limited.
Frequency:	Several times per year.
Phase:	**Orange**
	Expected high water-threat becomes more likely.
	Superintendents: more advanced measures will be taken. If necessary, drastic measures will be prepared. Use of waterways will be limited. Defence works may be faced to (light) damage.
Frequency:	Once per five years.
Phase:	**Red**
	Earnest and extraordinary situation.
	Large scale measures will probably start. Damage is likely to occur. National safety might be in danger.
Frequency:	Once every 20 - 100 years (depends per erea).

Figure 2.5: Description of phases according to the emergency protocol for the Netherlands, after [Nieuwenhuis et al., 2015]

The threshold-values for up-scaling, still rely on design-waterlevels. The failure-probability of a dikering is therefore not yet included in nowadays emergency-protocols. Accordingly, surveys and evacuation-exercises showed that decision-makers are in need of (more) support if a call for evacuation needs to be made. This study therefore tries to use information of dike-strength to find an alarm-waterlevel to call for evacuation. In this way, knowledge of the new risk-approach will be used to support decision-makers in the case of a threatening event.

Chapter 3

Simplified study

3.1 Introduction

In the Netherlands, the consideration of evacuation as emergency-measure is explained in a national protocol. This protocol uses waterlevel-thresholds to explain the degree of alertness in the case of a flood-threat. These thresholds correspond with the design-criteria for defence structures, where only failure due to overtopping/overflow was considered. The new risk approach revised this assumption by considering failure due to all sorts of failure-mechanisms. With respect to the emergency-protocol, knowledge of failure-mechanisms can be used as support to find an alarm waterlevel to call for evacuation. The simplified study therefore serves as an example how an evacuation-decision can be justified.

Figure 3.1 gives an overview of the simplified study. The figure represents a dikering, surrounded by a river with a downstream flow. People are living within the protected area where they contribute to their economy during normal life (indicated with Euro-signs). Accordingly, goods are located in the area. These can be subdivided in movable (such as animals and cars) and non-movable goods (houses, industrial buildings). The arrows indicate routes or opportunities to evacuate people and movable goods to higher grounds or other dikering areas in the case of a flood threat.

This study focuses on the evacuation-decision in the case of a flood-threat. The first section treats the requirements for a decision-method. Secondly, the decision-method will generally be explained. A base-case will be treated as numerical example, which serves as reference for further sensitivity-studies.

This chapter refers to the second objective of this research, according to section 1.3: *Investigation and development of a simplified model to obtain an alarm-waterlevel to call for evacuation in the case of a flood-threat.*

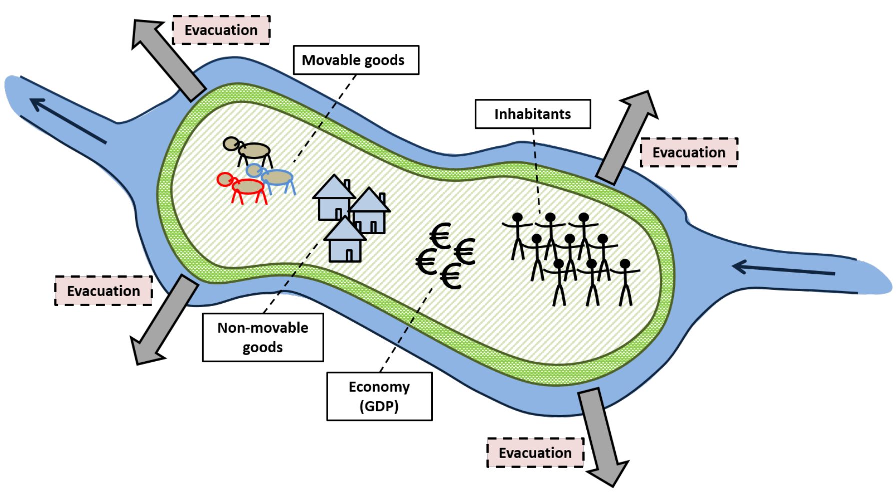


Figure 3.1: Overview of simplified study

3.2 Requirements decision-method

A dikering as presented in figure 3.1, prevents the river from flowing into a protected area. When a possible flood is expected based on waterlevel-forecasts, decision makers and crisis managers will make decisions to reduce possible consequences. Evacuation has the opportunity to save human lives, but may result on the other hand in a loss of credibility, money and time [Kolen et al., 2012]. Therefore, a decision-method will be proposed, based on the simplified dikering. The main goal of this method is to find an alarm waterlevel to decide for evacuation. Three topics will be treated:

- **The costs and benefits of evacuation:** Information is required regarding the values and numbers within the dikering-area. An evacuation-decision has the opportunity to save people and movable goods. Therefore damage-scenarios, population numbers and the performance of a possible evacuation are required. On the other hand, several cost-factors come into play during the evacuation-period. People are not able to contribute to (local) economy for a while, which comes together with costs incurred by evacuees (transport, accommodation). Realistic outlines of evacuation-events must therefore be available.
- **Forecasts of high-waterlevels:** This is instinctively the first indicator for preventive evacuation. If high waterlevels are expected, people within the dikering-area decide to leave. In real-life, forecasts of waterlevels are made every day, where uncertainty of a forecast increases for longer time-frames.
- **Conditional dike-strength information:** Regarding the new risk-approach in the Netherlands, defence structures need to meet new standards. The approach prescribes several risk-indicators. Therefore, conditional failure probabilities of these structures needs to be determined. The actual dike-strength is emphasized by fragility curves, which represent the conditional failure probability as a function of a given load (waterlevels). These curves must be available to draw clear conclusions with respect to the necessity of evacuation.

3.2.1 The costs and benefits of evacuation

One of the considerations for a decision-maker in the case of a threatening event is the worthiness of a preventive evacuation. The measure has the opportunity to save loss of life. The occurrence of a flood-event however, is uncertain. On the other hand, if evacuation is called, the incurred costs are certain. People will not be able to contribute to economy (business interruption) and costs are incurred by evacuees (transport, accommodation). Although a decision-maker is intended to save as many lives as possible, always a consideration with the incurred costs will be made. In this study, the evacuation-decision is therefore supported by a social cost-benefit analysis, where a monetary value is addressed to a fatality. This approach is in accordance with the new risk-approach in the Netherlands. The following explains the model-parameters, which will be used in the decision-method.

- **Expressing loss of life**: In the case of a flood threat, decision makers and crisis managers may give the call for evacuation. Depending on their perception of the opposing risk, groups of people will leave the area by using the available infrastructure. At the same time people decide to stay and therefore might get flooded. The number of evacuated people can be expressed as a percentage of the number of the affected people. This percentage relates to the available time for evacuation and the capacity of the available traffic network.

  $$\mathrm{E} = a \times I \tag{3.1}$$

  Where a represents the evacuation percentage, E the number of evacuated people and I the number of people affected by a flood. In case of a flood, the number of loss of life depends on whether evacuation is called by decision makers. For sake of simplicity, a mortality rate r will be multiplied with the number of people remaining in the area to express the loss of life (LoL). To express mortality in monetary units, these numbers will be multiplied with V (the value of a victim).

  $$\mathrm{F1} = r \times I \times V, \quad \text{Value of LoL when no evacuation is called, given a flood} \tag{3.2}$$

  $$\mathrm{F2} = r \times (1-a) \times I \times V, \quad \text{Value of LoL when evacuation is called, given a flood} \tag{3.3}$$

Besides, some loss of life will occur because of the evacuation-process itself. One can imagine that evacuation will cause a chaotic response of people. Thereby, international experience showed that some loss of life will occur because of traffic accidents and people with special needs [Kolen, 2013]. This factor, *F3*, is expressed as a percentage b of the number of affected people.

$$\mathrm{F3} = b \times I \times V, \quad \text{Value of LoL caused by the evacuation-process} \tag{3.4}$$

- **Business interruption**: During a normal life situation, people contribute to the economy by producing goods or providing services. Usually, this effect is expressed by the Gross Domestic Product (GDP) of a country. It can be imagined that evacuation of these inhabitants will affect the economy, since one is temporary not able to produce goods or provide services. Accordingly, costs are incurred by evacuees for transport and accommodation. The following expression will be used to describe the costs for business interruption as a consequence of evacuation. Parameter m represents the fraction of the GDP affected by absence of people due to evacuation.

$$\mathrm{C} = m \times \mathrm{GDP}, \quad \text{Costs of business interruption caused by evacuation} \tag{3.5}$$

- **Goods**: As stated in the introduction of this chapter, goods can be subdivided into two categories:
  - *Non-movable goods*:Examples are houses, industrial buildings or infrastructure. When a flood occurs, one is not able to bring these goods to safe places, and are therefore instantly faced with damage. The measure evacuation has no influence on this aspect.
  - *Movable goods*: Movable goods are goods which can be brought to safe places. Animals, cars or personal belongings are examples of this category. The value of goods saved by evacuation (M) will be expressed as a fraction k of all damage (D) (movable- and non-movable goods) in terms of Euros. This factor must be considered as a *benefit*.

$$\mathrm{M} = k \times D \tag{3.6}$$

Benefits of evacuation are uncertain, since the flood-event is uncertain. Accordingly, equation 3.3 showed that loss of life depends on the percentage (parameter a) of evacuated people. This percentage relates to the amount of time available until the critical event and the required time to take measures.

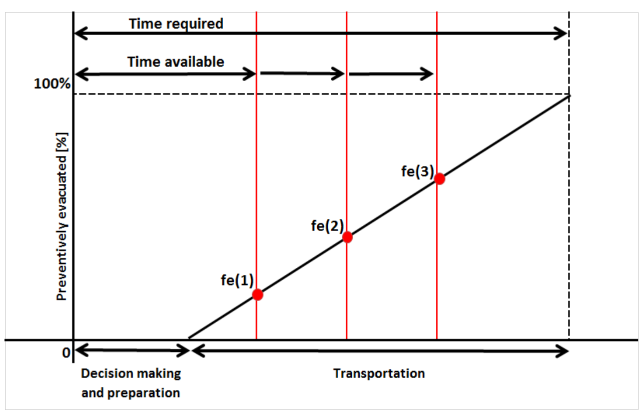


Figure 3.2: Representation of available and required time for evacuation [Wojciechowska, 2015], after [Barendregt and van Noortwijk, 2004]

Available time: The available time for evacuation is defined as the time between the first instant the water-defences no longer serve, until complete failure.
Required time: This is known as the time needed for decision-making, warning of people, response, preparation and moving to safe places.

Figure 3.2 on page 15 presents how both time-frames result in these percentages. If more time is available until the critical event, more people can be evacuated. The figure assumes a linear development of preventive evacuated people in time. The required time to evacuate all people and goods can be estimated with surveys or recent experience (decision-making and preparation), accompanied with traffic-models (transportation).

Many literature can be found regarding this topic. The report of [Barendregt and van Noortwijk, 2004] discussed these time-frames in more detail by expert judgement. This is mainly done due to limited failure-observations, since flood-events rarely occur. The same methodology was applied in the study of [Kolen et al., 2013], where the influence of the available and required time on the evacuation-percentage for different regions in the Netherlands is estimated.

Evacuation-percentage: Description of the expected number of people able to leave the threatened area within a certain amount of time.

This study uses the introduced model-parameters and evacuation-percentages to develop decision-scenarios. Scenarios will be used to support a decision (whether it is *evacuation* or *no evacuation*). Section 3.3.1 explains how these scenarios are used as supportive tool.

3.2.2 Forecasts of high waterlevels

Second requirement for the decision-method is a waterlevel-forecast. Since a call for evacuation relies on the likeliness of a threatening event, the development of waterlevels will be of main importance. In real-life, forecasting models are used to predict near-future waterlevels. These forecasts are in nowadays flood management established by using ensemble techniques [Verkade, 2015]. This study uses a representative waterlevel-development over time to mimic a forecasting-model. Forecasts of waterlevels will be made, based on an expected development as presented in figure 3.3. How this wave will be used to mimic forecasts, is extensively explained in section 3.3.

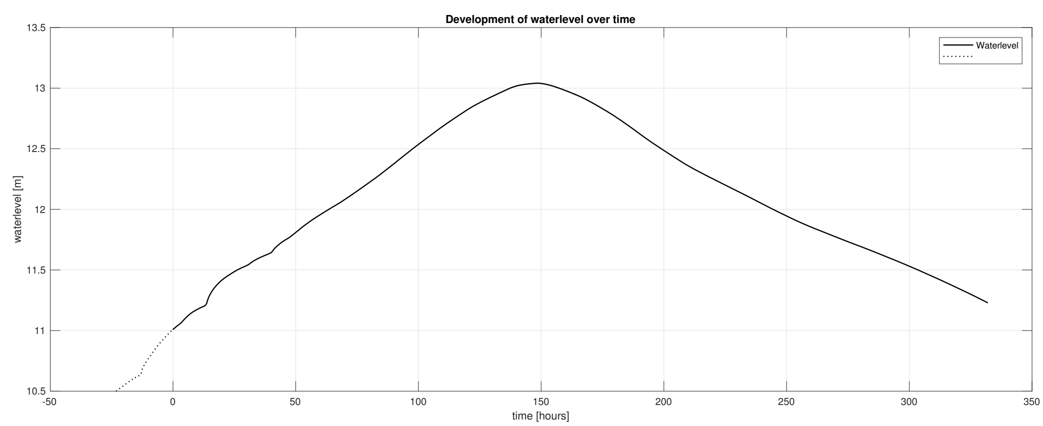


Figure 3.3: An example waterlevel-development over time

3.2.3 Conditional dike-strength properties

Final aspect of the decision-model are conditional dike-strength properties. Since the new risk-approach uses this information to evaluate defence-structures, theories regarding dike-failure will be used for the evacuation-consideration. For simplicity reasons, *the dikering consist of a uniform dike*, with absence of other structures such as walls and sluices. A typical cross-section is showed in figure 3.4. In the case of a flood threat, one would like to know the probability a failure-mechanism starts to act.

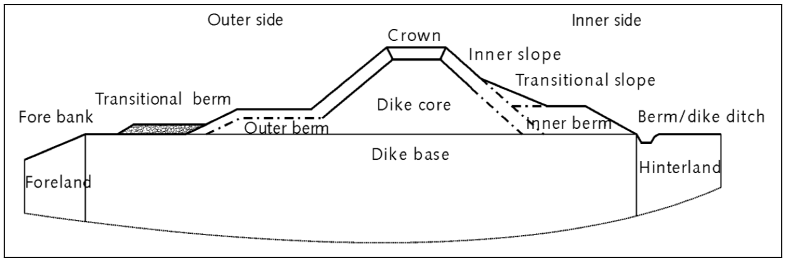


Figure 3.4: A general profile of a sea/river dike without special elements, after [Tonneijck and Weijers, 2009]

The presented dike profile shows possible combinations of elements of a dike. The geometry and design of this cross-section determines resistance of failure-mechanisms. This principle is presented in chapter 2. However, since the old risk-approach assumed only dike-height as design-criteria, many dike-sections are weaker than previously thought. The influence of dike-geometry on dike-failure will be explained by two failure-mechanisms: overflow/overtopping and piping.

Overflow/overtopping: Waterlevels and/or waves exceed the crest height of the dike. This mechanism causes damage to the inner slope of the levee. When as a result the core of the levee becomes exposed, a breach may occur because of erosion. Even sliding of the inner slope can occur when the core becomes saturated. This mechanism appears for high waterlevels.

Piping: Piping can be the result if a high water level persists for a longer time. In that case, water will flow under the levee. Channels (or pipes) will form and undermine the levee structure. As a result, the levee subsides and collapses. This mechanism is relatively important for lower waterlevels.

Initiation of failure can be the cause of (a combination of) wind-, wave- or waterlevel-loading. An increasing load will lead to an increasing probability of failure. However, every failure mechanism responds differently to these loading parameters. Fragility curves will therefore be used to represent the conditional failure probability as a function of the hydraulic load acting on the dike.

Theory: Fragility curves This report discusses an area where loading is related to waterlevels in the river (i.e. no wind or tide). This corresponds with an area in the upper river-branches of the Netherlands. However, failure-mechanisms differ in their response to waterlevel-rise. These differences can be emphasized with fragility curves. They represent a function from a set of loads, acting on the dike, to the set of conditional dike failure probabilities [Wojciechowska, 2015]. A basic expression:

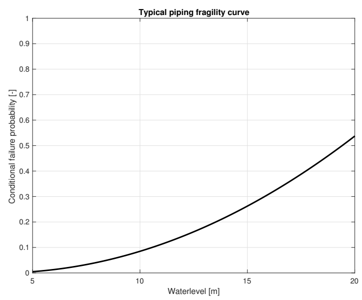
$$(x_i, ..., x_m) \rightarrow P\big\{Z\big(X_1, X_2, ..., X_n\big) < 0 | X_i = x_i, ..., X_m = x_m\big\} \tag{3.7}$$

Where $(x_i, ..., x_m,)$ can be seen as a realisation of the load $\big(X_i, ..., X_m\big)$ and $P\big\{Z\big(X_1, X, 2, ..., X_n\big) < 0 | X_i = x_i, ..., X_m = x_m\big\}$ is the conditional probability of failure of a dike due to a failure mechanism, which is described by limit state function Z, given $(x_i, ..., x_m)$. Properties of a fragility curve are [Wojciechowska, 2015]:

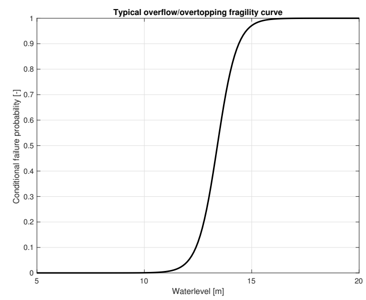
- The function is bounded between zero and one;
- It must be an increasing function, since increase of the conditional load (waterlevel rise) leads to a decrease in the dike's reliability;
- The degree of uncertainty is revealed by the gradient of the function. The lower the gradient, the higher the uncertainty will be.

Since a uniform dikering is assumed, the fragility curves represent the strength of the entire dikering. Three fragility curves are presented in figure 3.5. They serve as examples for the mechanisms piping (figure 3.5a), overflow/overtopping (figure 3.5b) and their combined curve (figure 3.5c). The gradient of these graphs clearly show that failure by piping is relatively uncertain compared to overflow/overtopping. Dike inspections are therefore needed in the case of high water-events to notice the occurrence of pipes. Presence of overflow/overtopping is easier to predict, since waterlevels and waves need to exceed the crest-height. However, a dike-section can to fail by all sorts of mechanisms. Therefore a combined curve can be conducted, where the two mechanisms are present. This curve is be created by the statistical rule:

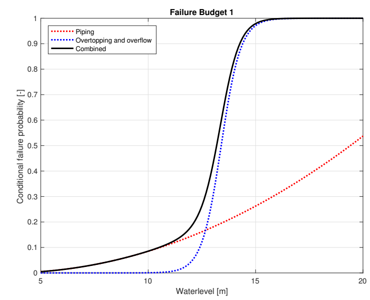
$$P(Combined) = P(E_1) + P(E_2) - P(E_1) \times P(E_2)$$



(a) Example typical piping fragility curve (E_1)



(b) Typical overflow/overtopping fragility curve (E_2)



(c) Fragility curve, combination of failure mechanisms

Figure 3.5: Two example fragility curves (3.5a and 3.5b) and their combined curve 3.5c

Although these curves can be used to relate conditional failure-probabilities to corresponding waterlevels, they do not represent a real-life situation in complete detail. The duration of occurring waterlevels is an influencing factor, but neglected in the figures. For instance, piping is more likely to develop for longer periods of high-water. This study will neglect this effect.

3.3 Method description

The decision-method is based on previously discussed aspects:

- First, the costs and benefits involved with the evacuation-decision need to be determined for the dikering under study. These factors are related to loss of life, business interruption and the value of movable goods. The performance of evacuation, determined by the evacuation-percentage determines the potential of this measure. If more people can be saved in the available time, the value of loss of life will decrease.
- Secondly, failure-probabilities depend on expected high waterlevels. Forecasts of waterlevels will be mimicked by use of a representative waterlevel development over time for the upper river-branches of the Netherlands.
- Lastly, conditional dike-strength is required to examine the failure-probability of the dikering. Fragility-curves represent this conditional failure probability as a function of a given load. In this study, failure-probabilities are given as a function of waterlevels.

Figure 3.6 gives an overview of the method description, which will be further explained in this section. Previously discussed aspects are used as input for the decision-method. The alarm-waterlevel will be obtained in four steps: *First*, scenarios will be conducted to schematize the worthiness of a possible evacuation. The *second step* is to mimic daily waterlevel-forecasting, based on a representative waterlevel-development over time. These forecasts will be used in *step 3* to calculate the expected flooding-probabilities, using dike-strength information from fragility-curves. The final step (*step 4*) combines scenarios with corresponding failure-probabilities to evaluate the decisions *evacuation* and *no evacuation* per time-step.

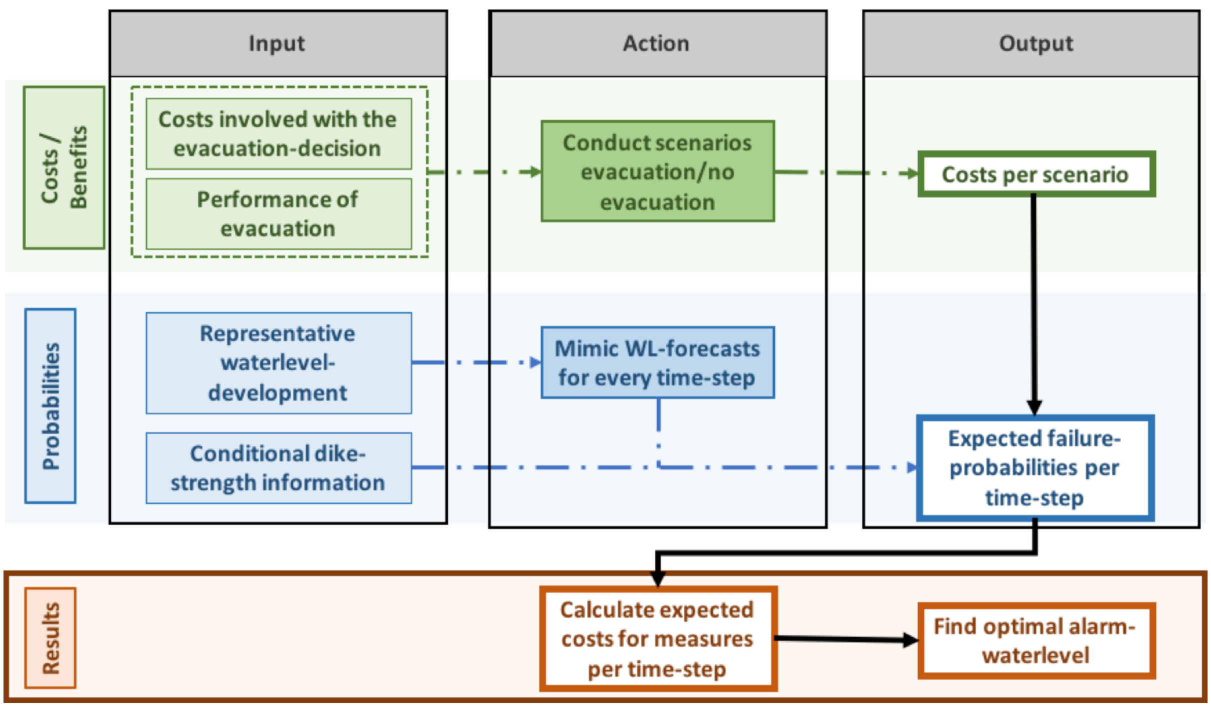


Figure 3.6: Overview of method-description to obtain an alarm-waterlevel to call for evacuation

The four steps to find an alarm-waterlevel to call for evacuation will mathematically be explained in section 3.3.1. Second, a base-case is introduced in section 3.3.2. The base-case serves as example and as reference study for a sensitivity-analysis in next chapter. Final section moves into the main conclusions.

3.3.1 General explanation of decision-method

If a high-water is expected, a decision-maker acts on basis of the available information on that moment in time. Although uncertainties exist, the public expects a right decision. The process of decision-making however, is not a continuous process. Some information is available only for discrete time-steps. The decision-model therefore focuses on these sources of information that are actually available, and not necessarily optimal. The following will hold:

- Models provide forecasts on day $t = i$ of waterlevels ($\hat{h}$) for days $t = i + k$ as $\hat{h}(t = i + k)$, where k presents the lead-time of a forecast. The degree of uncertainty increases, as the lead-time increases. A maximum time-frame of $k = 4$ days will be assumed as a reliable forecast, where forecasts are made for time-frames of one day, thus $k = [1 : 4]$;
- A decision (whether it is "Evacuation" or "No evacuation") is made every 24 hours. One will decide for preventive evacuation only if the expected costs of "Evacuation" are smaller than the expected costs of "No evacuation".
- The decision "Evacuation" is assumed to be an irreversible decision. Once called for evacuation, there will be no way back. If one decides "No evacuation" *and* no flood has occurred, the next day a new decision can be made.;

Four steps will be introduced to come up with the alarm-waterlevel to decide for evacuation.

Step 1 - Conduct scenarios evacuation/no evacuation: To illustrate the process of decision-making, a representation of decision time-frames is given on a discrete time-line in figure 3.7. For example: on day $t = 0$, the evacuation decision will be composed of information from forecasts of days $k = 1$ till $k = 4$. This process will be repeated every day. Generally, an evacuation-decision will be made on day $t = i$, based on forecasts of days $t = i + k$, for $k = [1 : 4]$.

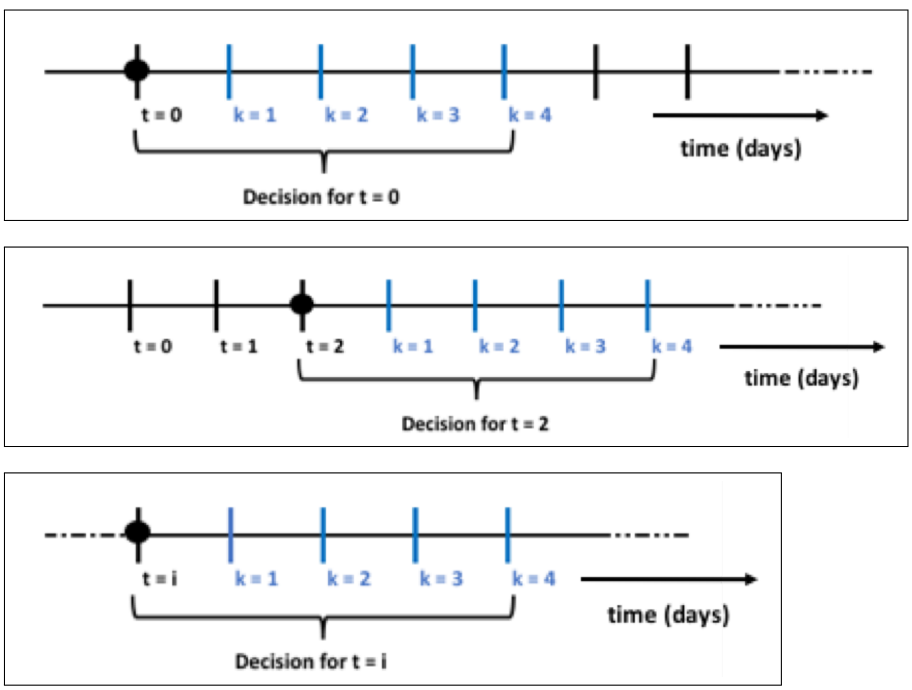


Figure 3.7: Representation of decision time-frames

An evacuation-decision on $t = i$ is based on the available information of forecasts $k = 1$ till $k = 4$. If evacuation is called, there will be no way back. However, the amount of available time is uncertain. More people can be saved if a flood occurs on day $k = 3$, compared to a flood on day $k = 1$. If no flood occurred after day $k = 4$, the measure evacuation only incurred costs. In this way, *seven different scenarios* can be composed, where a monetary value is addressed to a fatality. Based on the strength of the dike and waterlevel-forecasts, failure-probabilities can be calculated for these days. Figure 3.8 gives an overview of decision-making on day $t = i$. The flooding-probability for day $k = 1$ is represented as $P1$, et cetera.

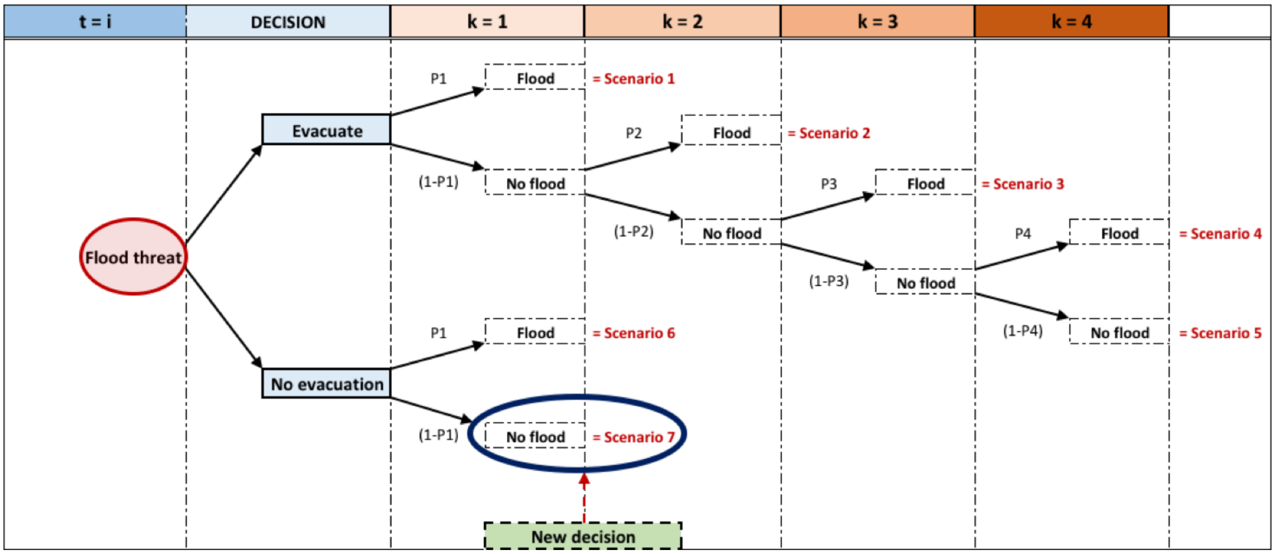


Figure 3.8: Representation of decision-making on day $t = i$

Every scenario corresponds with a set of cost-indicators as presented in section 3.2.1. These scenarios depend on the actual moment of flooding. The number of fatalities decreases as the available time for evacuation increases. Therefore, the number of flood-fatalities is *variable*. Accordingly, some fatalities will occur because of evacuation itself, and are therefore not time-dependent. This cost-indicator, $F3$, is *fixed*. The costs related to business interruption (C) and the value of movable goods (M), are explained as *other*.

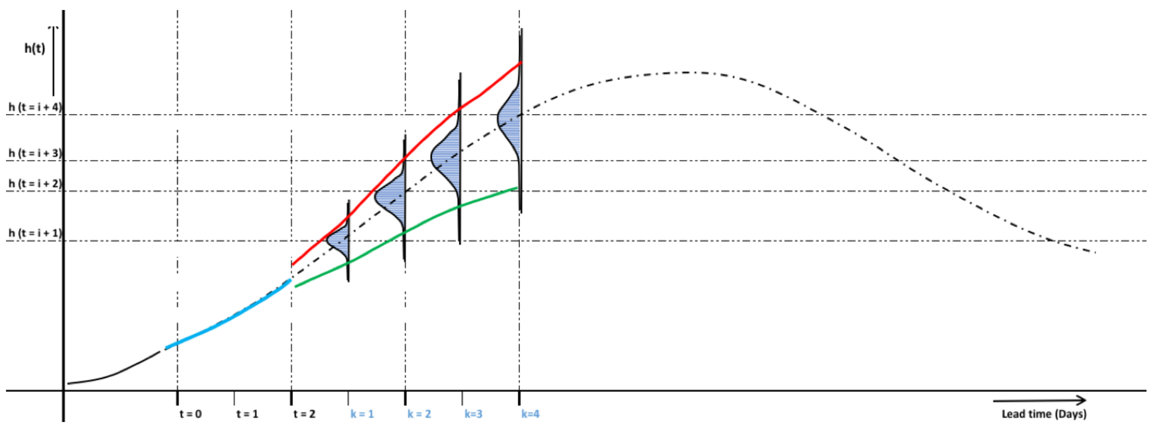
Cost-indicators per scenario as presented in figure 3.8			
	Fatalities, variable [€]	Fatalities, fixed [€]	Other, fixed [€]
Evacuation			
Scenario 1	$F2$(1 day)	$F3$	$C - M$
Scenario 2	$F2$(2 days)	$F3$	$C - M$
Scenario 3	$F2$(3 days)	$F3$	$C - M$
Scenario 4	$F2$(4 days)	$F3$	$C - M$
Scenario 5	0	$F3$	C
No evacuation			
Scenario 6	0	$F1$	0
Scenario 7	0	0	0

Table 3.1: Costs scenarios for evacuation decision-method

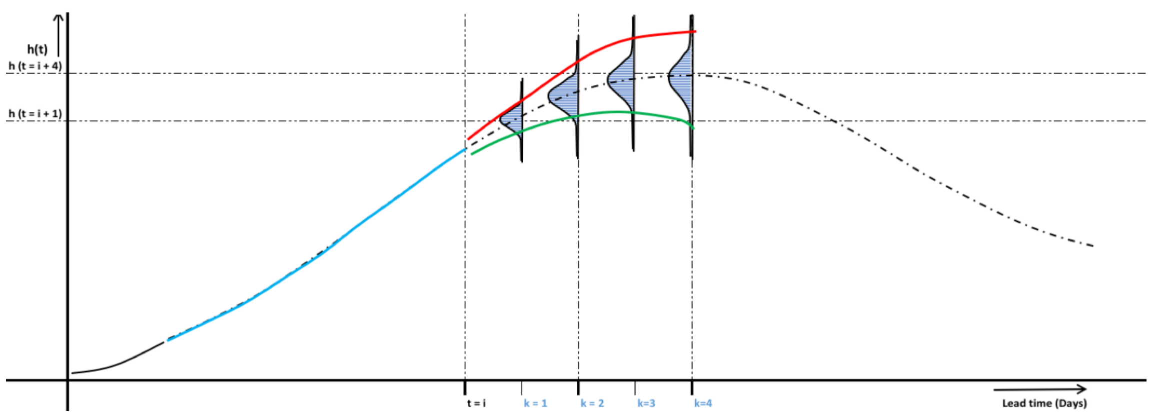
Step 2: Mimic waterlevel-forecasts: As already explained are forecasts of waterlevels used to obtain failure-probabilities. The probability of flooding on day $t = i + k$ can be retrieved from fragility-curves, where the waterlevel-forecast $\hat{h}(t = i + k)$ is required as input-parameter. To imitate the process of waterlevel-forecasting, a representative waterlevel-development over time for the Dutch river-system will be used. The peak-discharge, corresponding with these waterlevels, occurs on day $t = 10$. Thereafter, the waterlevel starts to decrease again. A waterlevel-forecast for day $t = i + k$ represents a range of possible waterlevels. In this case, all forecasts are assumed to be normally distributed, following:

$$h_{t=i+k} \sim \mathcal{N}(\mu_{t=i+k}, \sigma_k^2)$$

Where $\mu_{t=i+k} = \hat{h}_{t=i+k}$ for $k = [1 : 4]$. Uncertainty of forecasts increases if the lead-time of a forecast increases. This property is included by the standard-deviation, where σ_k increases if k increases. Figure 3.9 on page 22 shows how these forecasts should be interpreted for evacuation-decisions on days $t = 2$ and $t = i$.



(a) Waterlevel forecasts for $t = 2$



(b) Waterlevel forecasts for $t = i$

Figure 3.9: Representation of imitating waterlevel forecasts

Step 3 - Translate forecasts to failure-probabilities: Accordingly, one needs to come up with corresponding failure-probabilities for every predicted time-step. To do so, the 98% confidence interval of the normally-distributed waterlevels will be used to integrate under the fragility-curve. This is done in the following way (shown in figure 3.10).

$$P_{f,t=i+k} = \int_{\alpha=0.01}^{\alpha=0.99} P\big(Z < 0|h_{t=i+k}\big) \cdot f(h_{t=i+k})\mathrm{d}h \tag{3.8}$$

Which can be numerically approximated by:

$$P_{f,t=i+k} = \sum_{j=1}^{N} P\big(Z < 0|h_j\big) \cdot f(h_{j|t=i+k}) \cdot \Delta h \tag{3.9}$$

Where the interval $j = 1 : N$ with step-size Δh, corresponds with the set of waterlevels within the 98% confidence-interval, $P\big(Z < 0|h_j\big)$ the conditional failure-probability for waterlevel h_j (fragility-curve) and $f(h)$ the probability-density function for waterlevels at $t = i + k$.

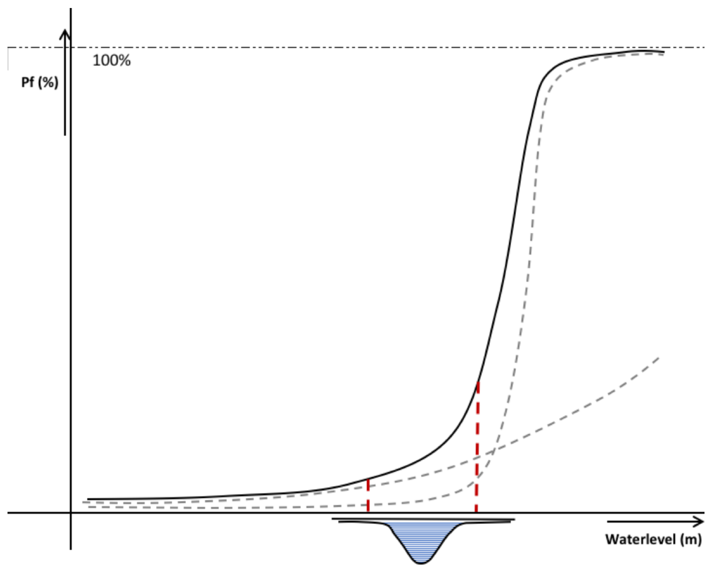


Figure 3.10: Calculating the failure-probability $P_{f,t=i+k}$

Table 3.2 gives a summary of how the conditional probability of a scenario can be calculated, as presented in figure 3.8.

Calculating probabilities per scenario, according to figure 3.8	
Evacuation	
Scenario 1	$P_{f(t=i,k=1)}$
Scenario 2	$(1 - P_{f(t=i,k=1)}) \times P_{f(t=i,k=2)}$
Scenario 3	$(1 - P_{f(t=i,k=1)}) \times (1 - P_{f(t=i,k=2)}) \times P_{f(t=i,k=3)}$
Scenario 4	$(1 - P_{f(t=i,k=1)}) \times ... \times (1 - P_{f(t=i,k=3)}) \times P_{f(t=i,k=4)}$
Scenario 5	$(1 - P_{f(t=i,k=1)}) \times ... \times (1 - P_{f(t=i,k=4)})$
No evacuation	
Scenario 6	$P_{f(t=i,k=1)}$
Scenario 7	$(1 - P_{f(t=i,k=1)})$

Table 3.2: Conditional flooding-probabilities per scenario, according to figure 3.8

Step 4 - Find the alarm-waterlevel to call for evacuation: Finally, the *expected costs* of measures *evacuation* and *no evacuation* on day $t = i$ can be calculated. To do so, scenario costs, according to table 3.1 are multiplied with the conditional probabilities, as calculated following table 3.2. The alarm-waterlevel is now defined as follows:

"The *first day*, corresponding with the representative waterlevel-development over time, the expected costs for *evacuation* are smaller than the expected costs for *no evacuation*".

Next section will use a base-case as reference study to show how an alarm-waterlevel can be calculated for the simplified dikering-area.

3.3.2 The base-case as reference study

The base-case makes use of the previously introduced cost-indicators. These parameters will be used to determine the costs for scenarios, following table 3.1. Table 3.3 gives a short summary of these cost-indicators and their values.

Summary of dikering parameters		
Parameter	Value, Unit	Description
V	6.7×10^6 €	Value of a victim
F3	25 persons	Fatalities by evacuation
M	12.5×10^6 €	Value goods, saved by evacuation
C	1.500×10^6 €	Costs due to business interruption

Table 3.3: Summary of dikering parameters simplified study

For now it is assumed that $I = 300,000$, which is the number of affected people by a possible flood. Thereby, many research is done to estimate mortality rates of people in the case of floods. Literature showed that rates appear in the range of 0.1 - 1%, as a fraction of the number of affected people [Jonkman and Vrijling, 2008, Jonkman, 2007, Boyd, 2006] . This study assumes a mortality rate m of 1.0 %.

Finally, *evacuation estimates* are required to quantify the evacuation-process. It is assumed people leave the area after the evacuation-decision has been made. The more time is available until the critical event, the more people can be saved. However, there will always be a non-compliance rate since people decide to stay. This study assumes a non-compliance rate of 10%, which corresponds with studies as [Kolen et al., 2013]. Lastly, 10% of the inhabitants evacuate preventively in the case of an unexpected flood. Table 3.4 gives an overview of the assumed percentages as a function of the available time.

Assumed evacuation-estimates in the base-case	
Available time [Days	Evacuation-estimate a [-]
1	0.70
2	0.75
3	0.85
4	0.90
No time	0.10

Table 3.4: Assumed evacuation-estimates in base-case

Step 1 - Relate costs with scenarios: Now all parameter-magnitudes are known, it is possible to calculate scenario costs (not to be confused with the *expected scenario costs*). An overview of these outcomes is presented in table 3.5.

Scenario costs ($\times 10^8$ €) following table 3.1			
	Fatalities, variable [€]	Fatalities, fixed [€]	Other, fixed [€]
Evacuation			
Scenario 1	F2(1 day) = 60.30	$F3 = 1.68$	$C - M = 14.88$
Scenario 2	F2(2 days) = 50.25	$F3 = 1.68$	$C - M = 14.88$
Scenario 3	F2(3 days) = 30.15	$F3 = 1.68$	$C - M = 14.88$
Scenario 4	F2(4 days) = 20.10	$F3 = 1.68$	$C - M = 14.88$
Scenario 5	0	$F3 = 1.68$	$C = 15.00$
No evacuation			
Scenario 6	0	$F1 = 180.90$	0
Scenario 7	0	0	0

Table 3.5: Costs related to every scenario

Step 2 - Mimic waterlevel-forecasts: The next step is to sample waterlevel-forecasts on basis of a representative waterlevel-development over time. These waterlevels will develop until day $t = 10$, until the peak-discharge has reached. The expected waterlevel this day is **14,50 metres**. Figure 3.11 presents an image of the waterlevel-development $\hat{h}_{t=i}$ over time.

Forecasts of waterlevels will be mimicked, based on this waterlevel-development. The standard-deviations for river-forecasts are assumed after [Frieser, 2004]. These accuracies are presented in table 3.6.

lead-time k	**std. deviation,** σ_k
1 day	$+/- 10cm$
2 days	$+/- 15cm$
3 days	$+/- 20cm$
4 days	$+/- 40cm$

Table 3.6: Desired accuracy forecasting models, after [Frieser, 2004]

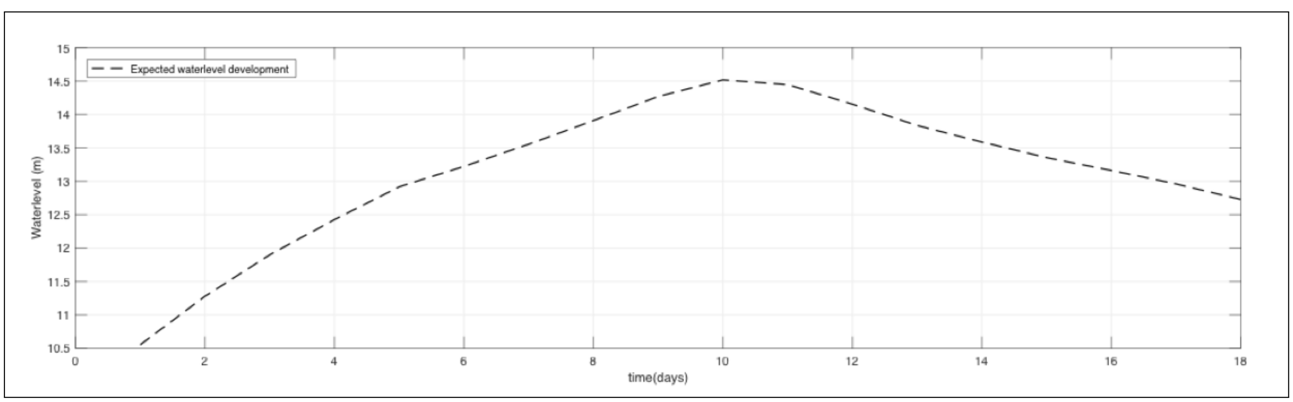


Figure 3.11: A representative waterlevel-development over time for the Dutch river-system, $\hat{h}_{t=i}$

Step 3 - Translate forecasts to conditional failure-probabilities The waterlevel-distributions combined with the assumed fragility curves lead to conditional failure probabilities at every time-step. Figure 3.12 presents the assumed fragility-curves for the base-case. The figure clearly indicates the dominant role of piping for lower waterlevels, indicated with the red line. For all waterlevels smaller than 14.00 metres, piping is the main contributor to the total failure-probability. From that point, mechanism overtopping/overflow starts to play a more significant role. The crest of the dike is **15.00 metres**, which is slightly higher than the highest expected waterlevel of 14.50 metres.

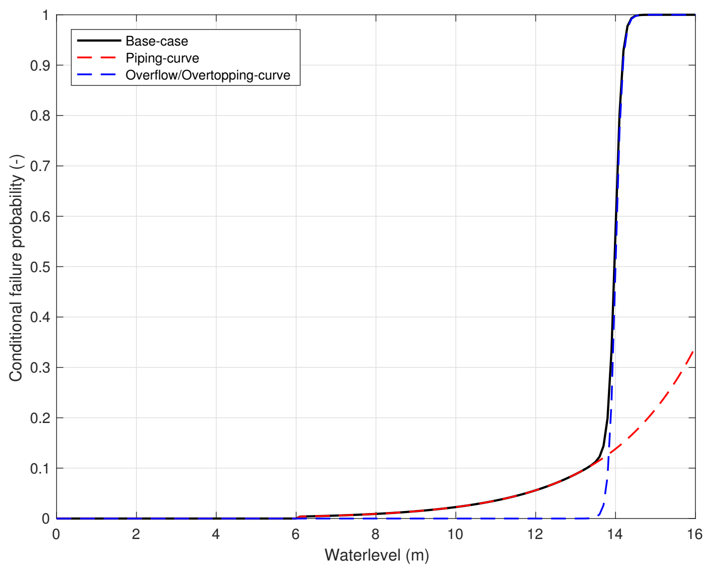


Figure 3.12: Fragility-curve for the base-case

Table 3.7 gives an overview of the calculated conditional failure-probabilities for the base-case. The table clearly indicates an increase of the conditional failure-probabilities for an expected waterlevel-rise in the river.

Calculated failure-probabilities $P_{f,t=i+k}$ (-) for the base-case

Day$(t=i)$	$k=1$	$k=2$	$k=3$	$k=4$	Day$(t=i)$	$k=1$	$k=2$	$k=3$	$k=4$
1	0.040	0.053	0.067	0.086	8	0.925	0.974	0.953	0.675
2	0.053	0.067	0.083	0.119	9	0.977	0.966	0.757	0.416
3	0.067	0.083	0.097	0.232	10	0.972	0.788	0.338	0.250
4	0.083	0.096	0.140	0.475	11	0.822	0.307	0.151	0.151
5	0.096	0.126	0.429	0.758	12	0.275	0.134	0.105	0.109
6	0.119	0.408	0.866	0.890	13	0.125	0.103	0.094	0.088
7	0.384	0.898	0.967	0.860	14	0.102	0.093	0.085	0.078

Table 3.7: Failure-probabilities for the base-case

Step 4 - Find the alarm-waterlevel to call for evacuation: The final step is to find the alarm-waterlevel to call for evacuation. This point is recognized as the first moment, corresponding with the representative waterlevel-development over time, the expected costs for *evacuation* are smaller than the expected costs for *no evacuation*. To do so, the calculated failure-probabilities of table 3.7 on page 26 are combined with the costs for scenarios. This principle is shown as an example for day $t = 1$, presented in table 3.8.

Calculating expected scenario-costs at $t = 1$

	Calculating probabilities	Summation costs ($\times 10^8$)	$\times 10^8$ €
Scenario 1	$0.040\times$	€(60.30+1.68+14.88) =	3.05
Scenario 2	$(1-0.040)\times 0.053\times$	€ (50.25+1.68+14.88) =	3.37
Scenario 3	$(1-0.040)\times(1-0.053)\times 0.067\times$	€(30.15+1.68+14.88) =	2.84
Scenario 4	$(1-0.040)\times ... \times(1-0.067)\times 0.086\times$	€(20.10+1.68+14.88) =	2.67
Scenario 5	$(1-0.040)\times ... \times(1-0.086)\times$	€(1.68+15.00) =	12.94
	Expected costs "Evacuation"		**24.88**
Scenario 6	$0.040\times$	€180.90 =	7.19
Scenario 7	$(1-0.040)\times$	0 =	0
	Expected costs "No evacuation"		**7.19**

Table 3.8: Expected costs of base-case at $t = 1$

According to day $t = 1$, the ratio Evacuation/No evacuation = 3.46, which is greater than one. The alarm-waterlevel to call for evacuation will be found on day $t = i$, where this ratio is smaller than one for the first time. Figure 3.13 shows the development of the evacuation-decision over time. On day $t = 7$, the measure *evacuation* is worthwhile for the first time. It is important to understand that the decision-line is composed, given *no flood* before the moment of decision-making. Since the conditional failure-probabilities increase until day $t = 10$, it will not be a wise decision to wait, although the ratio becomes more attractive. A delayed decision will increase the risk of fatalities, which will not be accepted by the public.

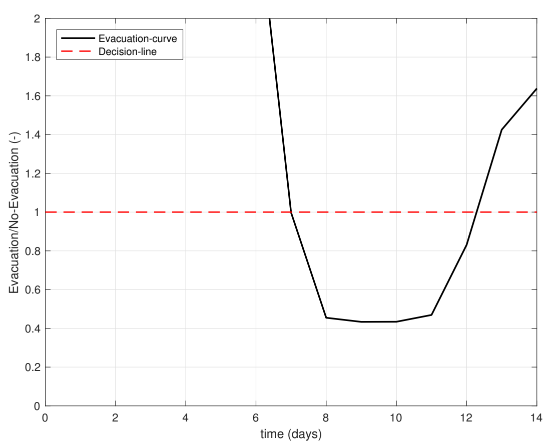


Figure 3.13: Development of ratio *evacuation* vs. *no evacuation* over time

Day $t = 7$ corresponds with a waterlevel in the given design-wave of figure 3.11 on page 25. Accordingly, this waterlevel corresponds with a conditional failure-probability as presented in the fragility-curve. The following information holds:

Start evacuation:	Day 7
Alarm-waterlevel, given no flood:	13.55 metres
Conditional failure-probability:	0.1226 (-)

3.3.3 Conclusions base-case

The final step of the decision-method showed how an alarm-waterlevel for the evacuation-decision can be obtained. The analysis resulted in an evacuation-decision for an alarm-waterlevel of **13.55 metres**. This section discusses how this waterlevel should be interpreted.

The alarm-waterlevel: This study explains the alarm-waterlevel to call for evacuation, as the first day the expected costs for evacuation are smaller than the expected costs for no evacuation. Figure 3.13 on page 27 nonetheless shows the ratio between both decisions further decreases in time. This would suggest to postpone the decision. However, the decision-line is composed, given *no flood* at the moment of decision-making. A delayed decision therefore corresponds with an increased probability of flooding, since further increase of waterlevels is expected. Accordingly, decision-makers tend to be risk-averse in the case of a flood-threat. Therefore, the first moment where the decision is (economically) satisfied will hold as moment to call for evacuation. This moment is therefore not necessarily the optimal ratio between the expected costs for *evacuation* and *no evacuation*.

Time to take measures: The calculated alarm-waterlevel to call for evacuation corresponds with the moment of *leaving*. As already explained in the literature-study of this report, time is also required for decision-making, warning and response [Barendregt and van Noortwijk, 2004]. To be able to call for evacuation in time, one should start considering evacuation **24 hours prior to the expected event of 13.55 metres**. This moment corresponds with the following information, referring to the assumed waterlevel-development over time and the fragility-curve:

Start considering evacuation:	Day 6
Alarm-waterlevel, given no flood:	13.22 metres
Conditional failure-probability:	0.096 (-)

The base-case assumed costs for flood-scenarios, the shape of fragility-curves and a waterlevel-development over time. These assumptions have influenced the results of this study. Next chapter therefore moves into the sensitivities of these assumptions, with respect to the alarm-waterlevel to call for evacuation.

Chapter 4

Sensitivity analysis

4.1 Introduction

This chapter provides an overview of how parameter-choices, the design-wave and the assumed dike-strength influence the evacuation-decision. The optimal decision is in this study described as: *the first moment in the design wave, the expected costs for evacuation are smaller than the expected costs for no-evacuation.* This moment corresponds with an waterlevel to call for evacuation, which is the main objective for this case. This analysis only focuses on the moment of the start of evacuation. Therefore no attention will be paid on the first moment evacuation should be considered.

This chapter focuses on the third objective of section 1.3: *Analysis of implications of a decision-model for evacuation based on a social cost-benefit analysis and probabilistic forecasting.*

The alarm-waterlevel, obtained by the decision-method, can be influenced in three different ways:

- The costs for every scenario, which can be either *variable* (flood fatalities) or *fixed* (fatalities by evacuation, economic).
- The conditional flooding probability, following from fragility-curves.
- The conditional flooding probability, following from the waterlevel-forecast.

First, this chapter checks the method on logical outcomes (section 4.2). For instance: given the design-wave and dike-design, what happens if the evacuation-decision has a higher impact on economy? What if more people live in the threatened area? Second, a more detailed analysis is provided (section 4.3), related to the following assumptions:

- The assumed waterlevel-development over time. The analysis will add a steep design-wave and a long-design wave to the base-case.
- The influence of the assumed dike-design. Two fictive situations will be treated: a (fictive) dike where only failure by piping *or* overtopping/overflow is likely to occur.
- Forecasts of waterlevels are made with an increasing standard-deviation for increasing time-frames. The case "perfect-forecasting" will be added to the base-case.

Finally, section 4.4 moves into the conclusions of this chapter. By doing so, it becomes clear which parameters require a more detailed study when the case-study of dikering 43 will be treated.

4.2 Model-check by different cost-scenarios

As already explained in the introduction of this chapter, the evacuation-decision is based on expected costs. Expectations are retrieved from failure-probabilities for a given input (dike-design, waterlevel-forecast), whereas costs regarding the evacuation-decision can be explained by scenarios. In this section, the base-case will hold regarding failure-probabilities. The same design-wave and dike-design will be used. Scenario-costs are in the presented method divided in variable and fixed costs for fatalities. Fixed costs for fatalities are described as fatalities, caused by the evacuation-decision (F3 and F1). Variable costs are related to the uncertain event. The following cost-indicators were treated in previous chapter:

Cost-indicators per scenario as presented in figure 3.8			
	Fatalities, variable [€]	Fatalities, fixed [€]	Other, fixed [€]
Evacuation			
Scenario 1	$F2$(1 day)	$F3$	$C - M$
Scenario 2	$F2$(2 days)	$F3$	$C - M$
Scenario 3	$F2$(3 days)	$F3$	$C - M$
Scenario 4	$F2$(4 days)	$F3$	$C - M$
Scenario 5	0	$F3$	C
No evacuation			
Scenario 6	0	$F1$	0
Scenario 7	0	0	0

Table 4.1: Costs-scenarios and -indicators as presented in previous chapter

Each of these cost-indicators are influenced by certain parameter-choices. Table 4.2 shows which parameters belong to each indicator. This analysis will treat the three most significant cost-contributors: the costs for economy (C), the evacuation-performance (a) and the assumed costs for fatalities (whether it is inhabitants (I), the valuation of a victim (V) or the mortality rate (r)).

Overview of scenario cost-indicators			
Evacuation			
Cost-indicator	*fixed/variable*	*Parameters*	*Base-case values* $\times 10^8$ €
C		$m \times GDP$	15
M		$k\times$ Damage	0.13
F3	fixed	25 [pers] $\times V$	1.68
F2(1 day)	variable	$r \times (1 - a(1)) \times I \times V$	60.30
F2(2 days)	variable	$r \times (1 - a(2)) \times I \times V$	50.25
F2(3 days)	variable	$r \times (1 - a(3)) \times I \times V$	30.15
F2(4 days)	variable	$r \times (1 - a(4)) \times I \times V$	20.10
No Evacuation			
Cost-indicator	*fixed/variable*	*Parameters*	*Base-case values* $\times 10^8$ €
F1	fixed	$r \times (1 - a(0)) \times I \times V$	180.90

Table 4.2: Cost-indicators and values base-case

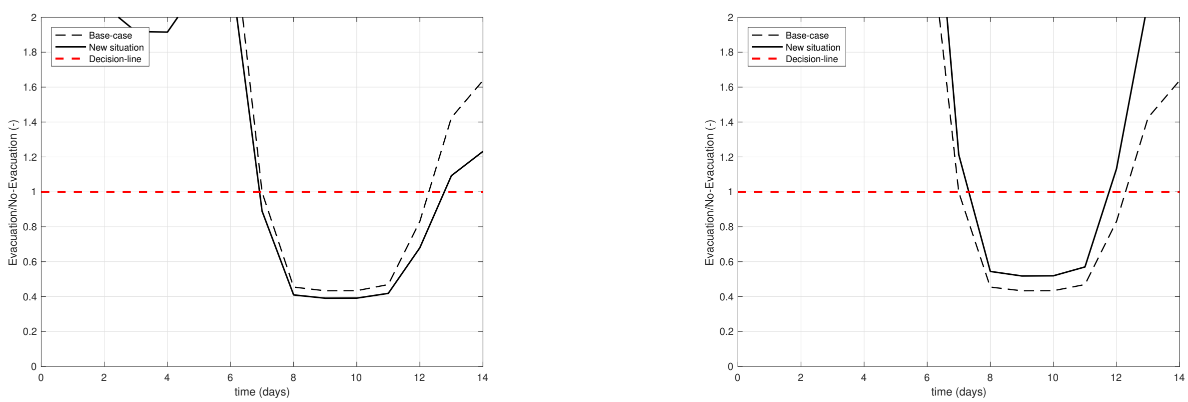
4.2.1 Business interruption

First, C as cost-indicator will be treated. This indicator is related to the GDP of a country. A fraction m of this GDP is assigned as a cost-factor, since people cannot contribute to economy if they are evacuated. The following assumptions were made in the base-case:

- It was assumed that in the case of preventive evacuation, people will return after a week to their homes (1/52 year).
- Almost 15 % of the country's economy is affected by evacuation of this dikering.
- The costs for economy are expressed as a fraction k of the GDP (which is in the order of 600 Billion € [CBS, 2016]. Fraction k is calculated by $1/52 \times 15\%$.

This analysis adds a worst- and best-case scenario to the base-case. The best-case holds that the costs are only 50% of the previously calculated costs. In the worst-case scenario, C is multiplied with a factor 2. The cause can be either a sooner/later return of people to the threatened area or a bigger/smaller contribution of the region to Dutch economy. Figure 4.1 shows how the evacuation-decision develops over time, related to the base-case.

- Figure 4.1a: If cost-indicator C decreases, the graph shifts downwards related to the base-case. This implies that the decision evacuation becomes more worthwhile, which is a logical outcome since this cost-indicator is directly related to this decision.
- Figure 4.1b: An increase of cost-indicator C relates to increasing costs for evacuation. The measure becomes less worthwhile, related to the decision *no evacuation*. Therefore, the graph shifts upwards. This finally results in a postponed decision (table 4.3).



(a) C: best-case (×1/2)

(b) C: worst-case (×2)

Figure 4.1: best- and worse-case scenario cost-indicator 'C'

Table 4.3 presents the numerical outcomes of the analysis. It must be taken into account that decisions are made on fixed moments (the first day the ratio becomes smaller than one).

Results sensitivity-analysis 'C'			
	Base-Case	50% $\times C$	200% $\times C$
Start evacuation (day)	7	7	8
Corresponding waterlevel (m)	13.55	13.55	13.91
Conditional failure probability (-)	0.1226	0.1226	0.5691

Table 4.3: Results sensitivity-analysis 'C'

4.2.2 The impact of the evacuation-process

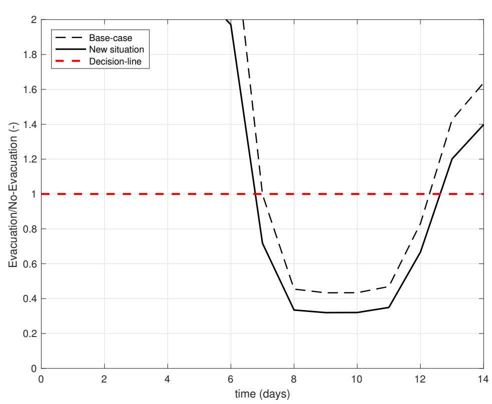
If the decision-maker calls for preventive evacuation, people will start leaving the threatened area. As is explained in the background-study (chapter 2), time is needed to activate this process. In the base-case, evacuation-percentages were given, where it was assumed that everyone should be able to leave the area after four days. In this sensitivity-analysis, again two additional scenarios will be provided. These scenarios are based on two fictive situations:

scenarios evacuation-percentages			
	Base-case	Best-Case	Worst-Case
a(1)	70%	80%	30%
a(2)	75%	85%	60%
a(3)	85%	90%	70%
a(4)	90%	90%	90%

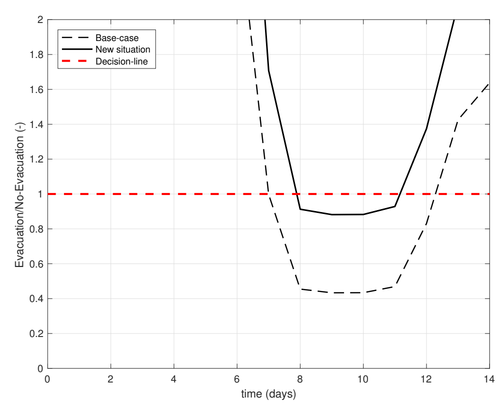
Table 4.4: Scenarios evacuation-percentages

The best- and worst-case scenarios were obtained by assuming again a non-compliance rate of 10% (the percentage of inhabitants deciding to stay, even if a call for evacuation is made). Finally, these changes lead to figures 4.2a and 4.2b. The results are summarized in table 4.5.

- Figure 4.2a: If the response to the call for evacuation improves, less flood fatalities will occur if a flood hits after one, two or three days if a call for evacuation has been made. The possible benefits of the measure evacuation therefore increase. The graph shifts downwards, corresponding with a better ratio of evacuation versus no evacuation.
- Figure 4.2b: Accordingly, a slow response of people relates to a risky measure, where the possible benefits of evacuation are declined. The graph shifts upwards, corresponding with a situation where the measure evacuation becomes less worthwhile.



(a) Best-case evacuation



(b) Worst-caste evacuation

Figure 4.2: best- and worse-case evacuation-scenarios

Results sensitivity-analysis 'the evacuation-process'			
	Base-Case	Best-case	Worst-case
Start evacuation (day)	7	7	8
Corresponding waterlevel (m)	13.55	13.55	13.91
Conditional failure probability (-)	0.1226	0.1226	0.5691

Table 4.5: Results sensitivity-analysis 'the evacuation-process'

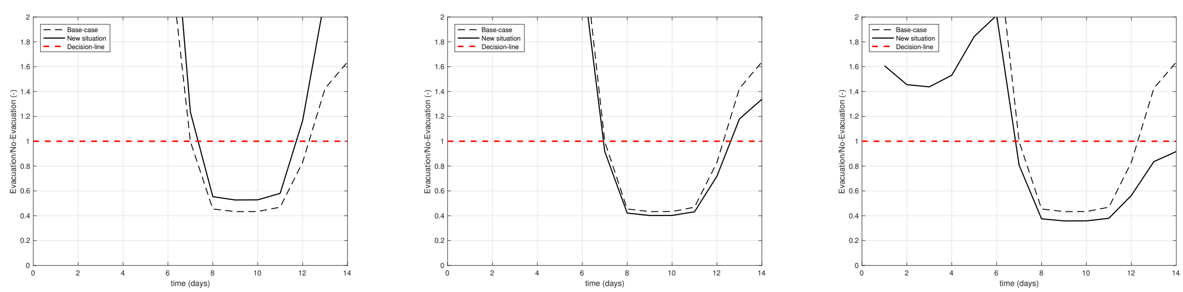
4.2.3 Inhabitants, mortality and valuation of a victim

As can be seen in table 4.2 are parameters I, V and r linearly related to the costs for fatalities for every cost-scenario. Therefore, the sensitivity analysis will not provide a detailed study of each of these parameters individually. This section only moves into the questions:

- What happens if the costs for fatalities decrease (Decrease of I, r or V)?
- What happens if the costs for fatalities increase (Increase of I, r or V)?

These questions are very interesting for decision-makers: a real-life dikering-area can be less dense populated, or one would like to address more value to a victim. These aspects will become clear in three figures 4.3a, 4.3b and 4.3c.

- Figure 4.3a: When less people are affected by a possible flood, less fatalities can occur in the case of an unexpected flood. Therefore, the expected costs of the measure *no evacuation* will reduce. On the other hand, less people can be saved, leading to a decrease of possible benefits for the measure *evacuation* as well. The figure shows a greater impact on the benefits, leading to a postponed decision.
- Figure 4.3b: Increasing costs for possible fatalities lead to a (small) downward shift of the curve. The measure *evacuation* becomes more attractive, since more people can be saved. However, the costs for fatalities also increase if no evacuation has been called. The ratio therefore nearly remains constant.
- Figure 4.3c: When the number of affected people is increased by a factor five, the shape of the curve for lower waterlevels becomes visible. When increased waterlevels are expected within a lead-time k of 4, 3 or 2 days, only the expected costs for *evacuation* will increase. This is due to the fact that the expected costs for *no evacuation* only rely on the one-day forecast. As a consequence, the curve starts to rise. When the expected waterlevel within one day ($k = 1$) results in a significant conditional failure-probability, these expected costs start to increase as well. Accordingly, the curve drops again and follows the same contours as in the base-case. After all, the measure *evacuation* will not become worthwhile sooner.



(a) Decreasing fatality-costs ($I \times 1/2$) (b) Increasing fatality-costs ($I \times 3/2$) (c) Extreme fatality-costs ($I \times 5$)

Figure 4.3: Decreasing and increasing costs for fatalities (I, r or V)

Results sensitivity-analysis 'costs for fatalities'				
	Base-Case	Decrease	Increase	Extreme
Start evacuation (day)	7	8	7	7
Corresponding waterlevel (m)	13.55	13.91	13.55	13.55
Conditional failure probability (-)	0.1226	0.5691	0.1226	0.1226

Table 4.6: Results sensitivity-analysis 'fatality-costs'

4.3 Sensitivity related to important model-assumptions

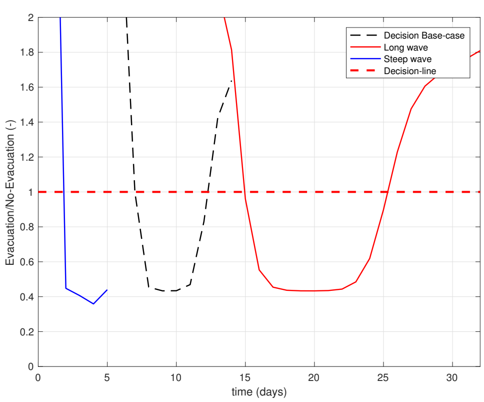
The second section will move into important assumptions related to the decision-model. Therefore, three seperate analysis will be provided: the influence of the design-wave, the influence of the dike-design and how uncertainty of forecasts affects the decision-model. Cost-indicators will be used from the base-case and remain constant.

4.3.1 The influence of the assumed waterlevel development

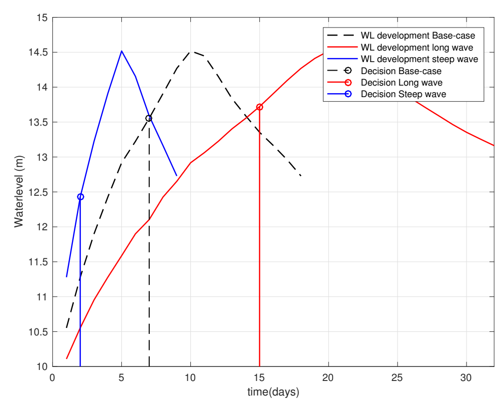
To understand the decision-model, a steep- and long-wave will be discussed. To do so, the travel speed of both waves is multiplied with a factor 2 (blue) and a factor 1/2 (red) respectively, related to the original wave. Figures 4.4a and 4.4b show these model-changes .

- Figure 4.4a: This figure shows that the moment of decision-making logically changes if the travel-speed of the design-wave changes. Accordingly, the measure *evacuation* remains worthwhile for a longer period if the waterlevel develops slowly.

- Figure 4.4b: This figure presents corresponding waterlevels for the evacuation-decisions graphically. The graphs clearly indicate that the decision-waterlevel decreases for a faster design-wave (indicated in blue). If the travel-speed of the design-wave slows down, the corresponding waterlevel for evacuation nearly remains constant. These observations relate to the forecasts of waterlevels for these situations. If high waterlevels are expected within a short period of time, one needs to decide in time to prevent loss of life. When the design-wave corresponds with a slow waterlevel-development, expected failure-probabilities will slowly increase. The waterlevel-threshold for decision-making therefore moves upwards.



(a) Wave-steepness: Development of evacuation-decision over time



(b) Wave-steepness: Corresponding waterlevels for decision-moment

Figure 4.4: Wave-steepness: influence of design-wave on evacuation-decision

Results sensitivity-analysis 'wave-steepness'			
	Base-Case	steep wave (blue)	long wave (red)
Start evacuation (day)	7	2	15
Corresponding waterlevel (m)	13.55	12.43	13.72
Conditional failure probability (-)	0.1226	0.0703	0.1990

Table 4.7: Results sensitivity-analysis 'wave-steepness'

4.3.2 The influence of dike-design

The base-case assumed a dike-design where both piping and overflow/overtopping where relevant mechanisms to account for. This section will move into a situation where the failure-mechanism piping is excluded. Figure 4.5 shows an updated fragility-curve where only failure due to overtopping/overflow is likely to occur. The dashed line shows the fragility-curve of the base-case, where piping plays a significant role for lower waterlevels.

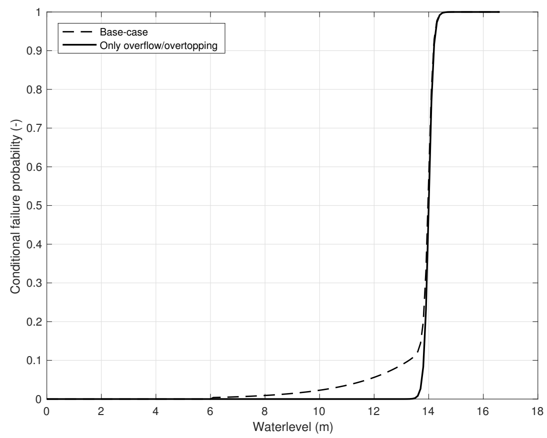


Figure 4.5: New fragility-curve where mechanism piping is excluded

This example is relevant for decision-makers, since the outcome tells something about the relevance of dike-strengthening programs with respect to the evacuation-procedure. Figure 4.6 how the new evacuation-decision develops over time.

- Figure 4.6: The figure shows that excluding piping from the original fragility-curve leads to a steeper decision-curve. If only overflow/overtopping plays a role, the fragility-curve almost instantly increases from zero to one. This property can be found in the decision-curve, where the measure *evacuation* almost instantly becomes worthwhile. Generally, uncertainty regarding failure (as is the case with piping) leads to a gentle decision-curve. The measure evacuation in that case becomes worthwhile for lower waterlevels. Excluding failure-uncertainty leads to a steeper decision-curve and a postponed decision. It can therefore be concluded that an evacuation-decision is related to dike-strength.

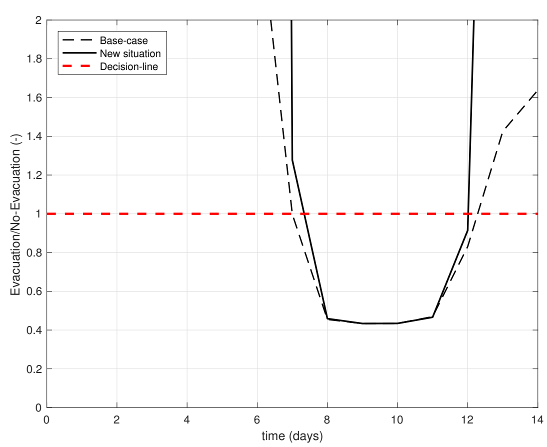


Figure 4.6: Piping excluded

4.3.3 The influence of forecast-uncertainty

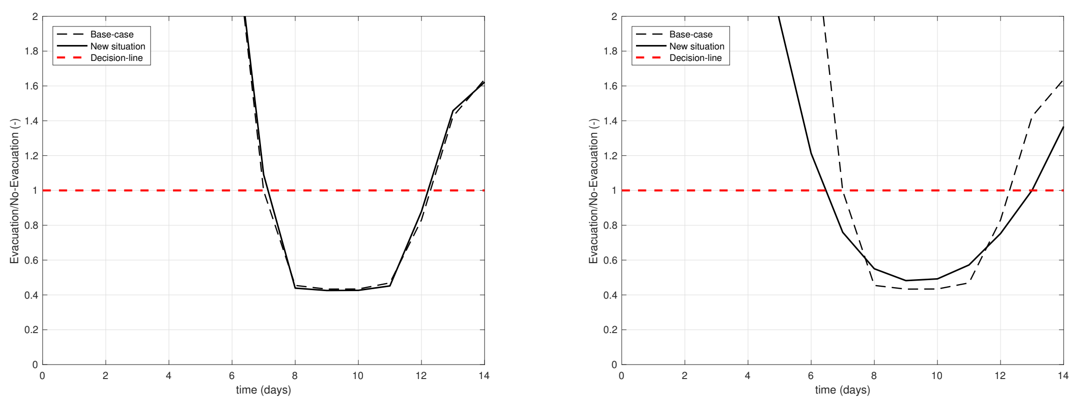
The method makes use of a representative waterlevel-development. Based on this development, waterlevel-forecasts are mimicked. These forecasts are made every 24 hours, for a maximum of four days ($k = [1 : 4]$). It is assumed that uncertainty of these forecasts increase, for an increasing lead-time. Accordingly, it is assumed that these forecasts are normally distributed, with standard-deviations σ_k. The standard-deviations used in the base-case (after [Frieser, 2004]) are presented in table 4.8. Two additional situations will be provided: a perfect forecast (i.e. no uncertainty) and a situation with increased uncertainty.

lead-time (k)	**σ_k, base-case**	**σ_k, increased uncertainty**
1 day	$+/10cm$	$+/50cm$
2 days	$+/15cm$	$+/100cm$
3 days	$+/20cm$	$+/150cm$
4 days	$+/40cm$	$+/200cm$

Table 4.8: Standard deviations for base-case and increased uncertainty

Figure 4.7 shows the result of both situations. The figure presents the development of the evacuation-decision over time.

- Figure 4.7a: It becomes clear that the forecasts of the base-case are relatively certain. Both evacuation-decisions follow the same pattern.
- Figure 4.7b: In the case of increased forecast-uncertainty, the shape of the decision-curve becomes smoother. This is due to the fact that extreme waterlevels are sooner observed as a possible waterlevel-development. This results in a more gentle shape of the evacuation-decision, where the decision *evacuation* becomes worthwhile sooner.



(a) Perfect forecast

(b) Increased uncertainty

Figure 4.7: Influence of certainty and uncertainty of forecasting waterlevels on the evacuation-decision

4.4 Conclusions sensitivity-analysis

Previous sections showed how the output of the decision-method (i.e. the alarm-waterlevel to decide for evacuation) changes, if the input of the decision-method changes. Short summaries of the following sensitivity-studies will be presented:

- The costs for business interruption;
- The influence of evacuation-performance;
- The costs for fatalities, expressed by cost-indicators I, r or V;
- The assumed waterlevel-development over time;
- The assumed dike-strength;
- The assumed forecast-uncertainty.

The summaries present an overview of the main results and conclusions of the sensitivity-analysis. Accordingly, they explain how these topics will be included in the case-study of next chapter.

Business interruption:	
Representation:	This cost-indicator is used to quantify the value of business-interruption due to a call for evacuation. In that case people will not be able to contribute to (local) economy for a while.
Observation:	If the magnitude of this cost-indicator increases, the evacuation-decision is postponed. The graph of the decision-development moves upwards.
Explanation:	A change of this cost-indicator only influences the expected costs for the measure *evacuation*. The curve therefore moves upwards or downwards in accordance with an increased or decreased value for cost-indicator C.
Case	This cost-indicator is a rough estimate, but will not be studied in more detail. The case-study therefore uses the same approximations as in the simplified study, which is in accordance with [Kolen, 2013].

Evacuation-performance:	
Representation:	The performance of an evacuation is enclosed within evacuation-percentages. These numbers represent the required time for people to leave the threatened area, related to the number of affected people. If more time is available, more people can be saved. It is assumed that everyone is able to evacuate within four days.
Observation:	If the performance of evacuation is improved, the measure *evacuation* becomes worthwhile sooner.
Explanation:	When more people can be saved within 1, 2 or 3 days, expected benefits of evacuation increase. The measure therefore becomes more attractive. Accordingly, when people respond slowly, benefits will reduce, leading to a postponed decision.
Case:	The estimates for evacuation-performances will be used from [Kolen et al., 2013], and are therefore not studied in more detail.

I, r or V (the costs for fatalities):

Representation:	These parameters are linearly related to the cost for fatalities for both decisions *evacuation* and *no evacuation*. This study only provides an analysis of a significant increase and decrease of the number of affected people, to understand the role of these parameters.
Observation:	The ratio of the expected costs for evacuation versus the expected costs for no evacuation is not much affected if this number changes. When the number of affected people increases, the decision becomes worthwhile slightly sooner. Only if this number increases with an extreme factor, the graph shows some changes. Especially for lower waterlevel-forecasts (thus failure-probabilities), the ratio drops, but remains in favour of *no evacuation*.
Explanation:	As already explained, affects an increase or decrease of the costs for fatalities the expected costs for both *evacuation* and *no evacuation*. The ratio therefore nearly remains constant.
Case:	Parameter I will be based on the number of affected people by a flood, which is publically available from LIWO (Dutch: Landelijk Informatiesysteem Water en Overstromingen). Parameter r depends on the area under study. Therefore, factsheets of the VNK-report will be used from [Slootjes and Wagenaar, 2016]. The value of a fatality, determined by [Bockarjova et al., 2010] and [Bockarjova et al., 2012], is politically accepted in the Netherlands. Therefore, the value will not be studied in more detail.

The speed of waterlevel-development over time

Representation:	The waterlevel-development over time is in this study used to mimic forecasts. Forecasts with a maximum lead-time of four days are made, based on these expected waterlevels. The sensitivity-analysis changes the travel-speed of these waves, to study the influence on the evacuation-decision.
Observation:	The moment of decision-making logically changes for a steep- and long-wave. Accordingly, a steeper design-wave results in an evacuation-decision for a lower alarm-waterlevel, whereas the evacuation-decision for a long-wave is worthwhile for an increased alarm-waterlevel.
Explanation:	A waterlevel-forecast represents a range of normally-distributed values. These values and occurrence-probabilities are used to calculate expected conditional failure-probabilities, given in the fragility-curve. If it is expected that the waterlevel strongly increases the following days, this will result in increased failure-probabilities. A steeper wave therefore results in a decision where evacuation is worthwhile for lower waterlevels and vice-versa.
Case:	The case will make use of the wave-speed of the base-case, since this is a representative development for the Dutch river-system. However, it must be noticed that the shape of the wave influences the final result.

The influence of dike-design:

Representation:	The dike-design represents the strength of the dike. To calculate the expected costs of a measure, the probability of failure, given a waterlevel-forecast, needs to be determined. Presence of failure-mechanism piping influences the failure-probability for lower waterlevels. The influence of this aspect on the alarm-waterlevel to call for evacuation is studied.
Observation:	If piping is excluded from the fragility-curve, the decision-development becomes steeper. The evacuation-decision is postponed.
Explanation:	If only overtopping/overflow is present, the fragility curves almost instantly increases from zero to one. The decision-curve follows the same pattern, where the measure *evacuation* becomes almost instantly worthwhile. If a mechanism as piping is included, the conditional failure-probability more gradually increases. The combination of failure-probabilities for the given lead-times therefore results in a sooner evacuation-decision.
Case:	Since the simplified study assumed a uniform dikering, a detailed analysis needs to be made of a dikering where multiple dike-sections are present. How this aspect will be included in the decision-method will be presented in the following chapter.

Forecasting-models:

Representation:	Forecasts of waterlevels are based on a given waterlevel-development over time. A maximum lead-time of four days is assumed to be a reliable forecast. The range of possible values is assumed to be normally distributed, with standard deviations after [Frieser, 2004]. The sensitivity-analysis adds a study with a perfect forecast, and
Observation:	The base-case follows almost the same pattern as the perfect forecast. If the uncertainty of the forecast increases, the decision-curve becomes wider. The evacuation-decision in that case becomes sooner worthwhile.
Explanation:	Extreme waterlevels are sooner observed as a possible outcome, if the uncertainty of a forecast is increased. This results in a situation that expected failure-probabilities sooner starts to increase.
Case:	The case-study will make use of the same standard-deviations as mentioned in [Frieser, 2004].

Chapter 5

Case-study: dikering 43

Dikerings in the Netherlands provide safety against flooding. These protected areas are surrounded by primary defence structures such as dikes, dunes and sluices. Although these works are designed to withstand extreme events, failure might occur some day. As already explained in previous chapters can evacuation be a measure to reduce the consequences of flooding. However, an evacuation-decision is currently based on exceedance probabilities instead of dike-failure. This holds that one only assumes dike-failure when a threshold-waterlevel is exceeded. Only if this event becomes likely to occur, decision-makers will start talking about an evacuation-procedure. Experts provide in those situations an estimate of the actual strength of a dikering in the case of a threatening event. A decision-maker will base a call for evacuation on these expert opinions. The new risk approach enables to evaluate current emergency-protocols. Therefore, a decision-method is proposed in chapter 3. This method will be used to show the influence of the new risk approach un current emergency-procedures. Dikering 43 is chosen as case-study.

This chapter therefore relates to the fourth objective, according to section 1.3: *Application of the decision-method on a dikering-area in the Netherlands, to evaluate current emergency-procedures with an alarm-waterlevel to call for evacuation.*

First section gives a short overview of the dikering-area under study. Subsequent sections will treat further specifications with respect to current evacuation-decision (emergency-protocols and the interpretation of the new risk approach). Section 5.4 elaborates how dikering 43 is adapted in the decision-model, which will be followed by conclusions.

Figure 5.1: Location of dikering 43

5.1 Introduction

The area enclosed by dikering 43, is better known as the *Betuwe, Tieler- and Culemborgerwaard.* It is located within the provinces of Gelderland and Zuid-Holland and forms a major part of the Dutch *Rivierengebied* (translated as "River Area"). From the start of the embankment-constructions around the 12^{th} and 13^{th} century, this area has experienced floods several times. Most recent threat occurred in January 1995, where high river-discharges (Rhine 12.000m^3/s, Meuse 2.870m^3/s) resulted in a preventive evacuation of over 250.000 people. After all, the dikes and retaining structures remained firm with the extreme conditions. After one week all inhabitants were allowed to return [Vnk, 2014]. Figure 5.2 gives an impression of the threat during that period. Some reports moved into the righteousness of that evacuation-decision, since no flooding occurred. However, an evacuation was by that time decided as the waterlevel prediction exceeded the threshold waterlevel to consider evacuation. Based on cost-benefit analysis and probabilistic forecasting-methods, [Frieser, 2004] concluded that an evacuation-decision was satisfied since the expected costs for "Evacuation" seemed to be smaller than the expected costs for "No evacuation". However, the report did not look into actual dike-strength information.

Figure 5.2: Flood threat *Rivierenland* in 1995, www.bd.nl

This report *will not* examine the decision of 1995, but *will* move into decision-making within this dikering-area. The decision-method including waterlevel forecasts and actual dike-strength information will be applied. This region is chosen as relevant case-study for several reasons:

- **The protected area:**The impact of river-floods can be enormous, since the area contains many inhabitants. Cities like Arnhem (148.000) and Tiel (42.000) are located within the dikering. The total number of inhabitants is approximatly 330.000 [Vnk, 2014].
- **The performance of evacuation:** Flood threats are likely to occur, which is proved in recent history. Accordingly, evacuation-studies show the effectiveness of preventive evacuation within this area. [Rijkswaterstaat, 2015] and [Kolen et al., 2013] presented the expected effectiveness of evacuation, expressed as a percentage of the number of inhabitants.
- **Waterlevel-forecasting** For this area only river-forecasts are of importance. The absence of tidal influence on waterlevels makes flood-prediction more reliable for longer time-intervals.
- **Dike-strength information:** Many desk- and field-research is already done to retrieve actual dike-strength information of this dikering. This information is required in the decision-method. Thereby,the VNK-study showed that some dike-sections do not meet the new safety standards. Therefore, the government has recently started with a strengthening-program.

5.2 Emergency procedures

The literature-study already provided some information regarding decision-making in the case of a flood-threat. Section 2.3.2 showed that a national emergency protocol is conducted on basis of colour-scales to exchange information, to adjust measures and to adjust communication to the public in the case of a threat with crisis-partners. These phases help to act consistently and effectively nation-wide. In addition, every institute related with emergency-measures conducted their own protocols for internal and regional purposes. All protocols are meant to operate on different organizational scales for crisis-situations. The following organizations are fulfilling tasks in the case of a flood threat near dikering 43: [Nieuwenhuis et al., 2015]:

- **Safety regions:** The Netherlands is divided in 25 different safety regions, which is a regional cooperation related to public order and safety (police, health-care, armed forces and local authorities). These regions fulfill tasks related to disaster-control. In the case of a flood-threat, a safety-region can provide information regarding the performance of a possible evacuation.
- **Municipalities:** Nearly 400 municipalities are present within the country. These institutions solely focus on tasks related to the interests of their inhabitants.
- **Watermanagement institute (WMCN):** This institute holds a collaboration between the meteorology institute and water-supervisors. Their main role is to inform and alarm expected waterlevels for relevant watersystems. The institute serves as central partner within the organizational structure.
- **Meteorology institute (KNMI):** The KNMI is a public institute, delivering meteorological and seismological services to governmental institutes, to support their duties and responsibilities with respect to safety.
- **Water-board *Rivierenland*:** Every board serves as watermanagement entity for a defined region. Management is generally related to watersystems (quantity, quality and defence structures) and purification. Since they are responsible for almost 80% of the primary defence-structures, will actual dike-strength information mainly be delivered by these institutions. The water-board provides therefore information regarding the strength of dikes, and the presence of failure-mechanisms.
- **Rijkswaterstaat:** This is the Dutch governmental institute, responsible for main road networks, the main waterway networks and watersystems. In the case of a flood-threat, mainly regional divisions of Rijkswaterstaat come into play. As trustee, they are responsible for well-functioning of main waterways and a part of the primary defence-structures (20%). Rijkswaterstaat (and its institute WMCN) will provide forecasts of waterlevels, and their reliability in the case of a threatening event.
- **Departmental centre for coordination crisis management infrastructure and environment (DCC IenM):** As crisis-centre, they coordinate information within the Ministry of Infrastructure and Environment (IenM) during a threat.
- **National Coordination-committee Flood-threats (LCO):** The committee plays a crucial role in early warning of threatened areas in the case of a possible flood.

The national emergency protocol for flood threats (Dutch: Landelijk Draaiboek Hoogwater en Overstromingen, LDHO) describes for every phase (colour) how these organizations and institutions should work together. Regarding the case-study, it is relevant to take a closer look at the water-board of *Rivierenland*. As already explained, are water-boards responsible for most of the defence-structures. With their knowledge, good estimates of the actual dike-strength can be provided. With this in mind, they conducted an emergency-protocol related to dike-strength for dikerings within their responsibility. On basis of waterlevels the protocol prescribes how to act against possible threatening events. The protocol serves therefore as guideline for controlled use of services and organizations of the engaged disciplines during flood-threats, to reduce loss of life, animals and belongings as much as possible [Knotter, 2013].

5.2.1 Emergency-protocol of water-board Rivierenland

The water-board is responsible for more than one dikering-area. Figure 5.3 shows that dikering 43 is one of the ten protected areas water-board *Rivierenland* is in charge of. These areas may become threatened by high waterlevels from the rivers Meuse, Rhine or their corresponding branches.

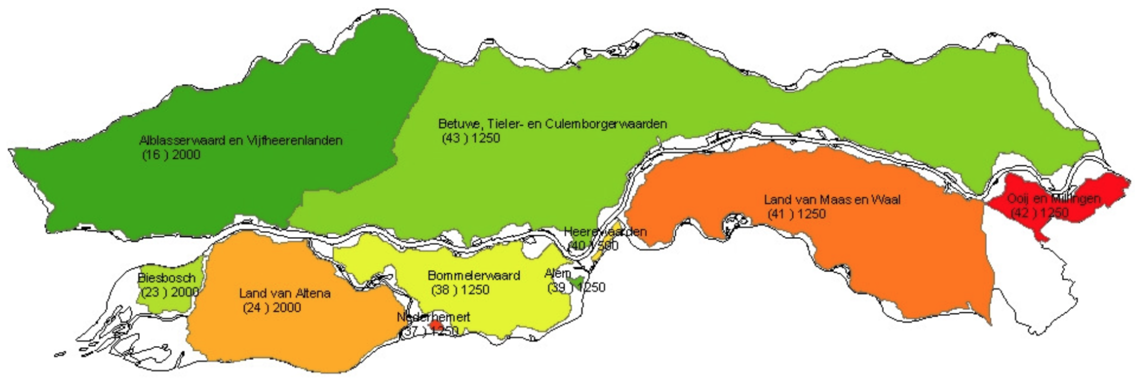


Figure 5.3: Present dikerings within the responsibility of the water-board *Rivierenland*, after [Knotter, 2013]

Regarding dikering 43, the rivers (or branches) Waal, the Nederrijn, the Pannerdens Kanaal and the river Lek are of main importance. Its dikes are currently designed to withstand an exceedance probability of 1/1.250 year. Threshold values of waterlevels from these rivers serve as:

- *Indicators:* An increased level of alertness (up-scaling). A scale-related measure is for example a congregation of decision-makers.
- *Criteria:* Order to take action. Such a measure could be an increasing level of dike-guardianship.

Up-scaling for the water-board is organized conform indicators for so-called coordination-phases (which are slightly different than the national colour-phases). According to these phases, the protocol prescribes the entire organizational structure, which will not further be treated in this report. However, the threshold-values can be used as a reference for the economically-optimal evacuation-decision.

Phase	**Description**	**Expected waterlevel at Lobith (m+ NAP), within 24h**
Warning phase	Preventive measures	14.00
Coordination-phase 1	Coordinated approach	15.00
Coordination-phase 2	Limited dike-surveillance	16.15
Coordination-phase 3	Permanent dike-surveillance	16.90
Coordination-phase 4	Complete dike-surveillance	17.65

Table 5.1: Coordination-phases water-board *Rivierenland*

The inter-municipal emergency-protocols are structured in the same way, and follow the same guidelines. However, all protocols only consider evacuation as an *optional* measure. The first moment evacuation will be considered is described in coordination-phase 4 (the most extreme situation).

5.2.2 Evacuation-studies

Commissioned by Rijkswaterstaat, [Kolen et al., 2013] conducted a report to estimate evacuation-percentages to examine the new risk approach for defence-structures in the Netherlands. These estimations were required for new risk-calculations. By use of expert-judgement, bandwidths are assigned to dike-trajectories where design-standards hold. Since a dikering may consist of multiple trajectories, a range of percentages may be applicable to the study-area.

As already discussed in the simplified study, are evacuation-percentages designed as estimates or expectations. These values and their likeliness are conducted by scenario-studies. All scenarios together represent all possible flood-events. These scenarios included the available and required time for preventive evacuation as well as the time needed for decision-making by authorities. However, since these numbers are based on expectations, a real evacuation might not exactly agree with this information. For flood-threats from the Rhine (Dutch river-system), the following estimates are provided:

Evacuation percentages for Dutch areas near river Rhine			
Available time for evacuation	Performance	Estimation	Inc. non-compliance (10%)
4 days	Maximum	100 %	90 %
4 days	Mean	100 %	90 %
4 days	Minimum	100 %	90 %
3 days	Maximum	100 %	90 %
3 days	Mean	100 %	90 %
3 days	Minimum	99 %	89 %
2 days	Maximum	100 %	90 %
2 days	Mean	98 %	88 %
2 days	Minimum	90 %	81 %
1 day	Maximum	96 %	86 %
1 day	Mean	85 %	77 %
1 day	Minimum	66 %	59%

Table 5.2: Evacuation percentages Case-study, after [Kolen et al., 2013]

The percentages of table 5.2 will be used in the case-study of dikering 43. Figure 5.4 presents these results in a graph. It can be seen that the performance of evacuation (maximum-, mean- or minimum) mostly affects the results for 1 or 2 days of available time.

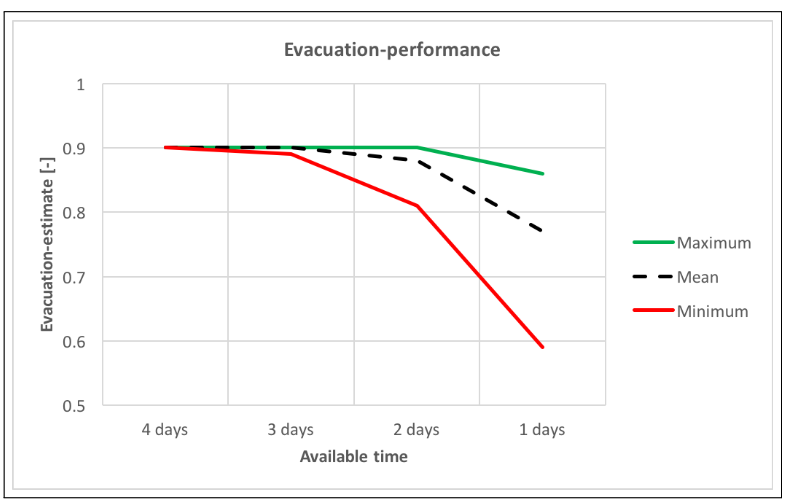


Figure 5.4: Representation of evacuation-performance of dikering 43, after [Kolen et al., 2013]

5.3 Interpretation of the new risk approach

As a consequence of the new risk approach, the VNK-project (Dutch: Veiligheid Nederland in Kaart) has been introduced. The main objective of the research was to implement the risk approach by mapping current flood risk in 58 levee systems in the Netherlands. A combination of failure-probabilities, flood-scenarios and area-studies provided these insights [Rijkswaterstaat VNK Project, 2015].

5.3.1 Methodology

The VNK-project evaluated the strength of defence-structures per dikering-area. The project followed the new risk-approach, where the failure-probabilities are interpreted as normative. In this way the state of the entire dikering can be displayed, where previously the exceedance-probabilities were only based on hydraulic conditions (waterlevels). Now, flood-risks are calculated by a combination of failure-scenarios with the related consequences. The description of this methodology represents two paths: first, constructing appropriate failure probabilities, and secondly, dealing with flood-consequences. This approach is used as guideline for this case-study.

First, the dikering is subdivided into small *sections*, representing (nearly) homogeneous strength- and loading properties. A group of sections is thereafter combined, representing the same flood-consequences independent of a breaching-location within this group. A group of dike-sections, representing the same flood-consequences is called a *segment*.

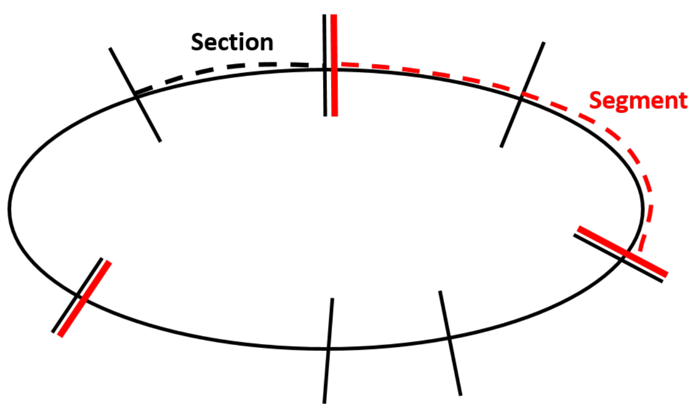


Figure 5.5: Risk-calculation: dike-sections (black) experience same loading and strength-conditions. A dike-segments (red) is a group of sections, representing the same flood-scenario.

- For every dike-section, a conditional failure-probability per failure-mechanism is conducted. The combination of these probabilities lead to the total conditional failure-probability per dike-section. This information lead to the flood-probability, somewhere in the dikering. By doing so, account is taken of dependence between mechanisms.
- Flood-consequences are defined by a combination of stream-patterns, water-depths and flow-velocities in case of a dike-breach in a segment. Accordingly, a set of flood-scenarios is conducted based on a unique combination of failing segments. All scenarios represent all possible floods within the dikering-area.
- The final step is the combination of scenarios (in terms of damage and fatalities) with scenario-probabilities. These combinations form together the expected values for damage and the number of fatalities in a dikering.

According to dikering 43, several breaching-locations are pointed out in the VNK-report. For each of these locations, different loading-situations and flood-calculations are conducted. The calculations resulted in an overview of the possible consequences in terms of damage and fatalities. The study took the possibility of evacuation into account.

5.3.2 Results VNK-study

Figure 5.6 shows all dike-segments with corresponding breaching-locations, studied in the report. As can be seen, fifteen segments are defined. For each of these locations, figures are conducted to represent an indication of the flooded area. Accordingly, numbers are provided of the expected damage and flood-fatalities.

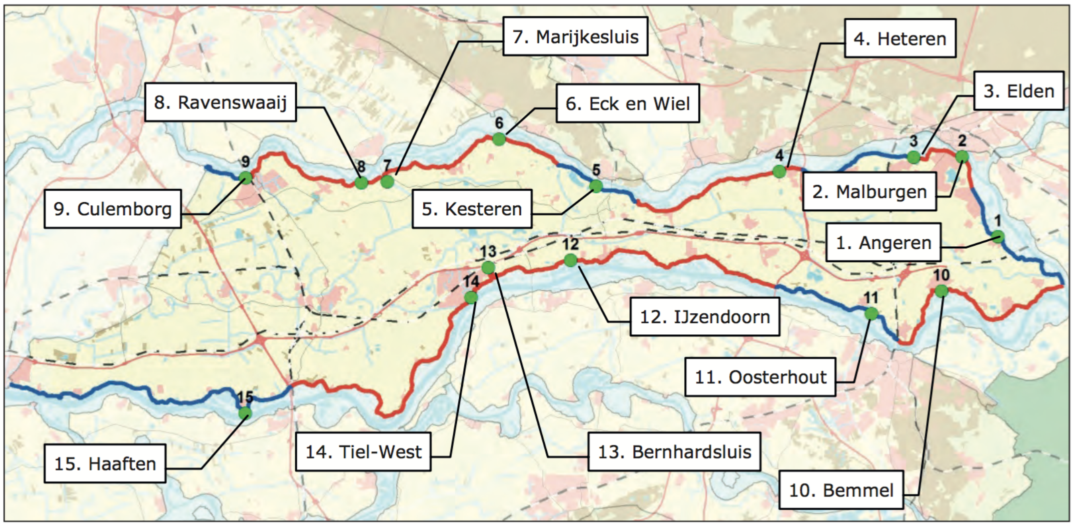
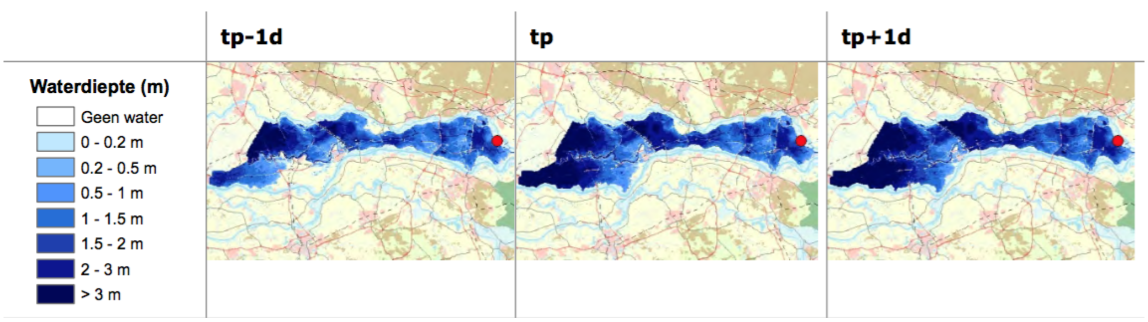
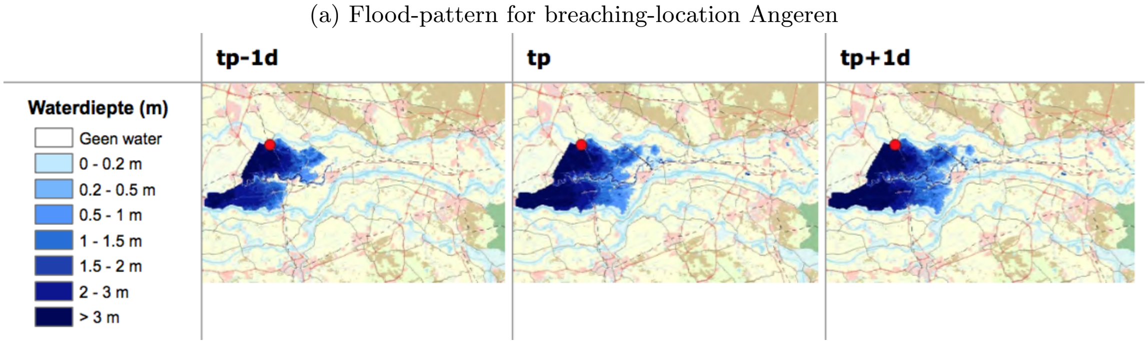


Figure 5.6: Breaching-locations dikering 43 as studied in the VNK-report

Two example-studies will be summarized to understand the flood-scenarios within this area. The figures of Angeren (location 1, East) and Culemborg (location 9, North-West) are shown below. For each of these locations, three loading-situations are worked out: the norm-level (tp) and increase or decrease of this norm-value with a factor 10 $\big((tp-1d)$ and $(tp+1d)\big)$.



(a) Flood-pattern for breaching-location Angeren



(b) Flood-pattern for breaching-location Culemborg

Figure 5.7: Flood patterns for two breaching-locations in dikering 43 [Rijkswaterstaat VNK Project, 2015]

The figures clearly show the difference of the flood-consequences for these locations. The dikering is characterized by its sloping surface, resulting in this wide variation in flood-scenarios. Table 5.3 summarized the expected damage and flood-fatalities for only thirteen breaching-locations, referring to figure 5.6. The locations *Marijkesluis* and *Bernhardsluis* are excluded in the presented table, since only dike-segments will be considered in this study. According to flood-fatalities, the report used a range between the worst- and best-case, taking the possibility of preventive evacuation into account. Worst-case is in this sense defined as an unexpected flood, leading to no preventive evacuation. Best-case is defined as the situation where a flood is expected and the evacuation-procedure is well-organized.

Summary of consequences for breaching-locations DR43					
			Loading-condition		
Segment	Location	Consequences	$tp - 1d$	tp	$tp + 1d$
1	Angeren	Damage ($\times 10^6$€)	8.810	12.310	14.045
		Number of fatalities	$70 - 645$	$150 - 955$	$125 - 1.130$
2	Malburgen	Damage ($\times 10^6$€)	6.620	9.665	10.875
		Number of fatalities	$60 - 535$	$150 - 960$	$145 - 1.320$
3	Elden	Damage ($\times 10^6$€)	6.805	9.880	11.395
		Number of fatalities	$55 - 515$	$90 - 815$	$110 - 1.000$
4	Heteren	Damage ($\times 10^6$€)	4.330	5.990	-
		Number of fatalities	$30 - 265$	$45 - 420$	-
5	Kesteren	Damage ($\times 10^6$€)	4.535	6.720	7.570
		Number of fatalities	$35 - 340$	$50 - 440$	$60 - 530$
6	Eck en Wiel	Damage ($\times 10^6$€)	4.285	6.095	7.275
		Number of fatalities	$35 - 305$	$50 - 440$	$60 - 530$
8	Ravenswaaij	Damage ($\times 10^6$€)	3.470	5.300	5.870
		Number of fatalities	$30 - 255$	$40 - 375$	$45 - 420$
9	Culemborg	Damage ($\times 10^6$€)	3.510	5.260	5.780
		Number of fatalities	$30 - 270$	$45 - 395$	$50 - 445$
10	Bemmel	Damage ($\times 10^6$€)	13.070	14.790	16.590
		Number of fatalities	$125 - 1.135$	$150 - 1.365$	$185 - 1.680$
11	Oosterhout	Damage ($\times 10^6$€)	-	11.305	12.990
		Number of fatalities	-	$95 - 860$	$115 - 1.045$
12	IJzendoorn	Damage ($\times 10^6$€)	7.330	8.600	9.820
		Number of fatalities	$60 - 562$	$75 - 660$	$85 - 790$
14	Tiel-West	Damage ($\times 10^6$€)	8.850	7.990	9.180
		Number of fatalities	$100 - 910$	$110 - 1.005$	$150 - 1.370$
15	Haaften	Damage ($\times 10^6$€)	5.865	8.315	9.424
		Number of fatalities	$50 - 440$	$75 - 685$	$95 - 870$

Table 5.3: Summary of flood-consequences for segments and breaching-locations DR43, after [Rijkswaterstaat VNK Project, 2015]

5.4 Model assumptions case-study

The decision-method, proposed in section 3.3, will be applied to find an alarm-waterlevel to call for evacuation in dikering 43. This alarm-waterlevel will be compared with the criteria for up-scaling (as in the LDHO-protocol), in order to evaluate current emergency-procedures. However, a few differences can be recognized relative to the simplified study:

- Firstly, it was assumed that the strength of the dikering could be described by only one combination of fragility-curves. In reality, multiple homogeneous dike-sections are present, where the same loading- and strength properties hold.
- Thereby, the simplified study contained only one flood-scenario. This scenario was independent of the location of breaching. The report of VNK assessed 15 dike-segments regarding dikering 43. Each of these segments are assumed to result in unique flood-consequences. For every segment, one breaching-location is taken for a detailed flood-analysis. This report only focuses on dike-segments (no segments containing other defence-structures). Therefore, only 13 dike-segments will be studied.
- In reality, waterlevels depend on geometry of the river. This results in a waterlevel-difference at the 13 breaching-locations for the same design-discharge. The relations between discharge and waterlevels (Q/h-relations) must be adapted to obtain realistic results.

Figure 5.8 gives an overview of how dike-sections and dike-segment should be interpreted within a dikering. A dike-section represents the same loading- and strength-parameters, where dike-segments represent equal flood-consequences.

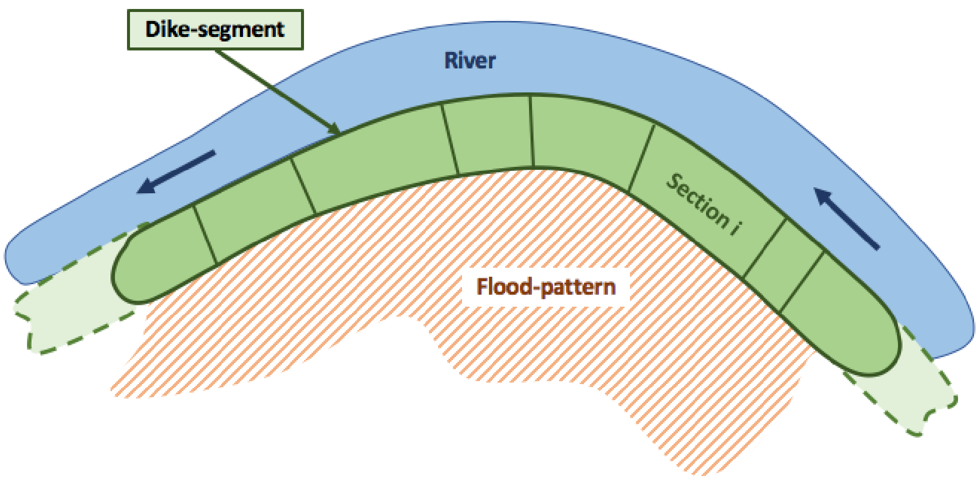


Figure 5.8: Representation of dike-sections and dike-segments within a dikering

Section 5.4.1 treats how the strength of a non-uniform dikering is applied in the model. Section 5.4.2 briefly discusses how a discharges at Lobith are translated to waterlevels at all breaching-locations of interest. Finally, section 5.4.3 moves into remaining interesting assumptions according to the decision-model.

5.4.1 Assumptions related to the strength of a dike-segment

Dike-segments consist of multiple dike-sections. For each of these sections, fragility-curves for relevant failure-mechanisms are present from VNK-studies. To obtain a representative conditional failure-probability of (multiple) dike-segment(s), fragility-curves of dike-sections need to be combined. The following assumptions hold:

- According to the report [Rijkswaterstaat VNK Project, 2015] the fragility-curve of the weakest dike-section is chosen within a dike. The selection is based on the presence of failure-mechanisms piping and overflow/overtopping. By assuming only one representative dike-section, the unique conditions of dike-sections are neglected.
- The length-effect plays a role according to the mechanism piping. Therefore, piping of the weakest dike-section is weighed *proportionally with the number of dike-sections* where piping plays a significant role. In this way: $P_{f,dike} > P_{f,dike-section}$.

5.4.2 Assumptions related to the waterlevel-development over time

Currently, the entire dikering needs to withstand a $1/12,500$ per year waterlevel, based on the exceedance of waterlevel-thresholds. The normative waterlevels related to this scenario, differ per location as a result of the river-geometry. Therefore, the following is applied:

- A design-wave with a peak-discharge of $16,000m^3/s$ is used for this case-study. For every location under study, the corresponding wave-crests are calculated using Q/h-relations.
- The waterlevel-development over time remains the same for every breaching-location. Only the wave-crests are adjusted.
- The waterlevel at Lobith is representative for evacuation-decisions, as in the national emergency-protocols. Again, Q/h-relations are used to calculate these waterlevels.

5.4.3 Other relevant model-assumptions

To find an alarm-waterlevel, cost-indicators need to be conducted to calculate the possible consequences of evacuation. The assumptions related to these cost-indicators are explained in this section.

$C = m \times GDP$:	The costs for economy are in the presented model based on a fraction of the GDP. This fraction m is assumed to be 0.1%, corresponding with 1/20 of the country not contributing to economy for a week.
$M = k \times \text{Damage}$:	The flood damage is related to a normative flood-scenario at corresponding breaching-locations. Theses costs are retrieved from the Dutch national flood-database, which is free for public use (LIWO, Dutch: Landelijk Informatiesysteem Water en Overstromingen). The fraction k saved of this damage by evacuation, is 0.1% (as in the simplified study).
$F3 = b \times I \times V$:	The number of accidents by evacuation is assumed to be proportional with the number of inhabitants within the affected area. This fraction is assumed to be $1/10,000 \times I$.
$F2 = r \times (1-a) \times I \times V$:	The value of loss of life if evacuation is called, depends on several assumptions. The mortality rate is assumed to be 1.7%, according to [Slootjes and Wagenaar, 2016]. The evacuation-percentages as function of the available time, will be used from table 5.2 for a *mean performance*. The number of affected people is again retrieved from LIWO.
$F1 = r \times \times I \times V$:	In the case of "No-evacuation", it is assumed that none of the inhabitants is able to evacuate.

5.5 Evacuation-decision dikering 43

This section uses the decision-method and the assumptions of section 5.4 to find an alarm-waterlevel to call for evacuation for dikering 43. Section 5.5.1 discusses how the alarm-waterlevel is obtained. Second section moves into the main results of these considerations, followed by a sensitivity-analysis and the main conclusions.

5.5.1 Consideration of two separate decisions

It already became clear that the sloping surface of dikering 43 influences the consequences of a possible flood. The number of affected people and damage therefore relate to the location of breaching. For example: if the dike-segment of Angeren breaches (located in the Eastern part), the entire dikering-area becomes flooded. However, if the the breaching occurs in Culemborg (located in the Western part), only a small part of the dikering-area will be affected. Therefore, the study-area is divided in two: the Eastern and Western part (figure 5.9). The Eastern part consists of the seven breaching-locations with the most extreme flood-consequences. The Western part of the remaining six breaching-locations (East and West not necessarily equal in size). Dike-segments are roughly divided over the two areas in the following way:

East: Angeren, Bemmel, Oosterhout, Ijzendoorn, Malburgen, Elden, Heteren;
Inhabitants: 283.000 ; *Damage:* 15,000 €;

West: Kesteren, Eck en Wiel, Ravenswaaij, Culemborg, Tiel-West, Haaften
Inhabitants: 123,000 ; *Damage:* 6,800 €

It is assumed the entire dikering-area needs to be evacuated if breaching occurs in the Eastern part. However, only the Western part needs to evacuated if breaching occurs in the Western part. This section takes a closer look at the call for evacuation for the Eastern and Western part separately. The report [Rijkswaterstaat VNK Project, 2015] calculated the failure-probabilities for all dike-sections. The weakest dike-sections within the dike-reaches under study are assumed to be representative:

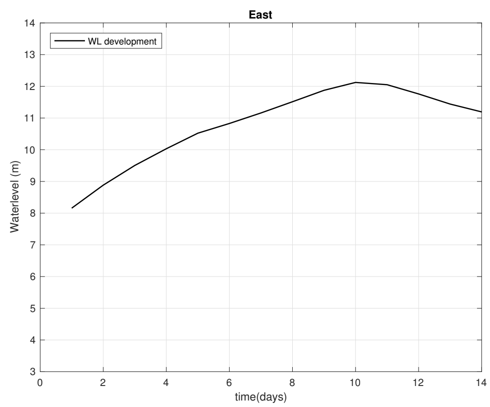
- The weakest dike-section of the *Eastern part* is located in dike-segment *IJzendoorn*. A call for evacuation in the Eastern part is therefore related to this breaching-location.
- The weakest dike-section of the *Western part* is located in dike-segment *Ravenswaaij*. A call for evacuation in the Western part is therefore related to this breaching-location.

Figure 5.9: Overview Eastern part of the dikering (red) and Western part of the dikering (blue)

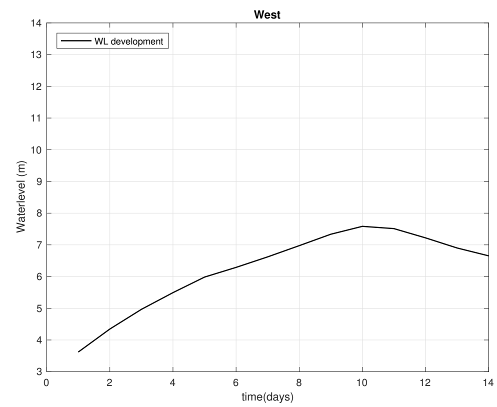
Appendix B provides an analysis for all dike-segments according to [Rijkswaterstaat VNK Project, 2015] individually, by using the same approach. This information provides insights in the dike-strength of these dike-segments. However, the results are not further treated in this report.

5.5.2 Results case-study

To find an alarm-waterlevel for both parts of the dikering-area, the assumed waterlevel-development over time from chapter 3 is used. The peak of this wave corresponds with a discharge of $16,000m^3/s$. Figure 5.10 shows how the peak-discharge of this wave is adjusted for the chosen breaching-locations of the Eastern and Western part. The wave-crest of IJzendoorn reaches **12,10 meters**, versus **7,65 meters** at Ravenswaaij.



(a) East: Waterlevel-development over time at IJzendoorn

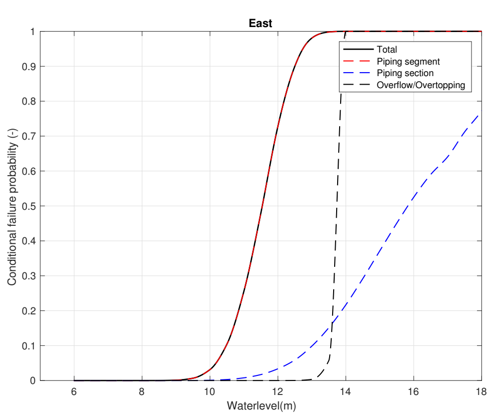


(b) West: Waterlevel-development over time at Ravenswaaij

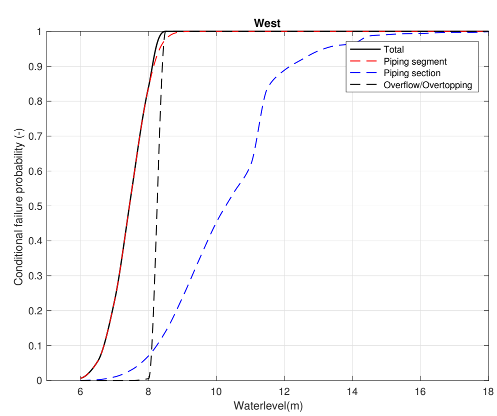
Figure 5.10: Development of waterlevel over time for both breaching-locations.

Secondly, fragility-curves for both dike-reaches are conducted, presented in figure 5.11. The curves relate to the entire dike-reaches under study. They contain the overflow/overtopping-contribution of the weakest dike-section and its piping-curve. The total contribution of piping is proportionally weighed with the number of dike-sections within the dike-reach, relatively sensible to this failure-mechanism.

The curves clearly show the influence of the weakest dike-section on the total conditional failure-probability: The blue dashed line in the fragility-curves presents piping of only the weakest dike-section. The red curve is obtained if this piping-curve is proportionally weighed with the number of piping-sections within the studied dike-reach (East or West). The conditional failure-probability has reached almost 100% for a waterlevel of **13,50** meters at IJzendoorn and nearly **9,00 meters** at Ravenswaaij.



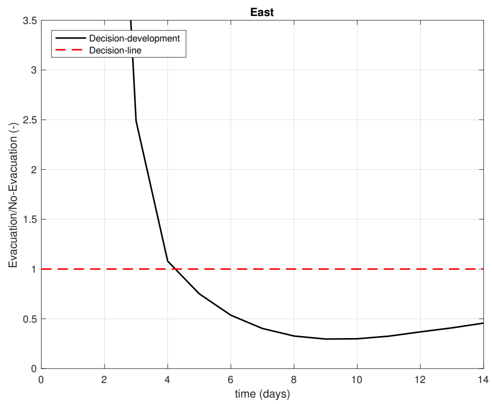
(a) East: Fragility curve entire dike-reach



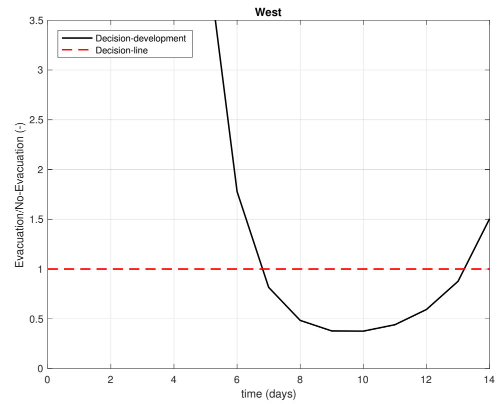
(b) West: Fragility-curve entire dike-reach

Figure 5.11: Fragility-curves for both dike-reaches

The waterlevel-development over time and the fragility-curves are used to obtain the development of the evacuation-decisions over time. Figure 5.12 presents the development of the Eastern and Western part. The large contribution of piping in the Eastern part results in relatively high failure-probabilities for lower waterlevels. The evacuation-decision therefore becomes worthwhile in an early stage of the assumed waterlevel-development over time.



(a) East: Development of decision (Scenario *tp*)



(b) West: Development of decision (Scenario *tp*)

Figure 5.12: Development of evacuation-decisions over time for Eastern and Western part of dikering-area

The following information is retrieved from these diagrams, related to the threshold for the decision *evacuation*. The start of evacuation correspond with the first day the evacuation-decision became worthwhile (i.e. ration evacuation / no evacuation smaller than one).

	Eastern part	**Western part**
Conditional failure-probability:	0.1106	0.0838 (-)
Start evacuation:	Day 5	Day 7
Corresponding waterlevel:	10.52 m	6.62 m
Waterlevel at Lobith:	16.41 m	16.90 m

The evacuation-decision *East* can be considered normative for the entire dikering-area. This conclusion follows from the assumption that the entire dikering-area will be evacuated after a dike-breach in the Eastern-part. Evacuation of the entire dikering-area therefore needs to start for a waterlevel of 16.40 meters at Lobith, with an expected waterlevel-increase the next 24 hours. As is explained in the literature, time is needed for decision-making, warning and response (figure 5.13. Therefore, evacuation must be considered 24 hours prior to an expected waterlevel of 16.40 meters at Lobith. This suggests to *start considering evacuation* for a waterlevel of 10,05 meters at IJzendoorn, corresponding with **15,82 meters** at Lobith.

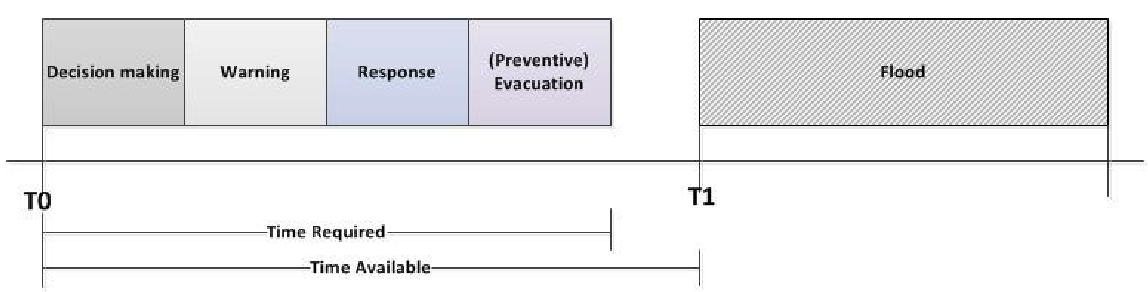


Figure 5.13: Representation of the time required and available for evacuation, after [Barendregt and van Noortwijk, 2004] (see Chapter 2)

5.5.3 Sensitivity-analysis of case-study results

This section gives an overview of the range of possible alarm-waterlevels to call for evacuation for dikering 43. Previous section already showed that the decision *evacuation* for the entire dikering-area is determined by breaching in the Eastern part. This resulted in the following waterlevels at Lobith:

Start considering evacuation	15,82 meters
Start evacuation	16,41 meters

These results where obtained by several model-assumptions. This section takes a closer look into three of these assumptions, to be known:

- **The performance of evacuation:** Table 5.2 on page 45 presented the results of evacuation-studies in the Netherlands from [Kolen et al., 2013]. Scenario studies and expert judgment were used to develop estimates of evacuation-percentages for areas in the Netherlands. The results are based on a minimum, mean and maximum performance of evacuation. The results of the case-study are conducted by considering an mean performance. The sensitivity-analysis uses the maximum performance as a best-case and the minimum performance as a worst-case scenario.

- **The costs for business interruption (B.I.):** As in the simplified dikering-study, the costs for business interruption are roughly estimated by a fraction of the GDP. Again, a worst- $(2 \times C)$and best-case $(0,50 \times C)$ are provided to represent the range of results.

- **The number of piping-sections:** This study focuses on a fictive situation where the number of piping-sections within the studied dike-reach is reduced. These results support the understanding of dike-strengthening on the justified alarm-waterlevel to call for evacuation. Two situations are treated where first 50% of the piping-sections are remained. Secondly, only 30% are remained within the Eastern dike-reach.

Figure 5.14 gives an overview of the model-changes, relative to the reference situation. The bars represent the adjusted waterlevels where evacuation should start. If benefits of evacuation increase by an improved evacuation-process, the threshold to decide for preventive evacuation decreases. The same conclusion holds if costs for business interruption reduce. The understanding of these behaviours is extensively treated in the sensitivity-analysis of the simplified study, chapter 4. This will therefore not be treated in more detail.

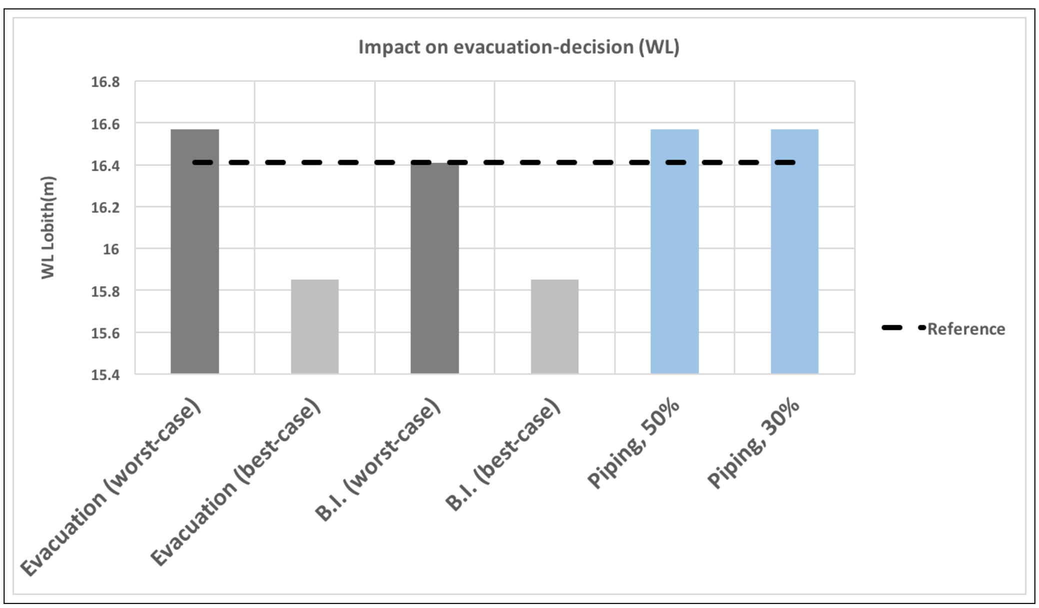


Figure 5.14: Sensitivities of case-study results: WL at Lobith

It must be noticed that a moment to decide for evacuation corresponds with the first day the decision is worthwhile. A best-case evacuation performance and a best-case business interruption therefore lead to the same alarm-waterlevel, since the same waterlevel-development over time is used.

5.6 Conclusions

The decision-method enables to support an evacuation-decision for dikering-areas in the Netherlands. The method is based on a cost-benefit study, where a monetary value is assigned to a (prevented) fatality. This approach is in accordance with the new risk-approach in the Netherlands. Accordingly, the method uses dike-strength information, to account for all sorts of failure-mechanisms explicitly. The case-study only focused on the influence of piping and overflow/overtopping on the alarm-waterlevel to call for evacuation.

According to dikering 43, the consequences of a possible flood are determined by its breaching-location, due to its sloping surface. Therefore, evacuation is considered for the Eastern and Western part of the dikering separately. This analysis showed that evacuation should be considered first in the Eastern-part. Since in that case the entire dikering should be evacuated, this decision is assumed to be normative. An alarm-waterlevel is obtained, which is translated to a waterlevel at Lobith using Q/h-relations. To account for time needed for decision-making, warning and response, one should start considering evacuation 24 hours prior to the expected waterlevel. The following results are obtained as waterlevels at Lobith:

	Lower limit	Reference	Upper limit
Start considering evacuation	15,47 m	15,82 m	16,41 m
Start evacuation	15,82 m	16,41 m	16,57 m

The reference waterlevels correspond with the most likely situation. Upper and lower limits are obtained by a sensitivity-study. Parameters and cost-indicators are estimated using literature of [Kolen, 2013], [Kolen et al., 2013], [Slootjes and Wagenaar, 2016] and information from the Dutch national flood-database (LIWO). Sensitivities of parameter-choices result in upper and lower limits, as presented in figure 5.14. To illustrate the reference-situation, the representative waterlevel-development with a peak-discharge of $16,000 m^3/s$ is presented at Lobith. Figure 5.15 shows the evacuation-considerations in this waterlevel-development over time, relative to the up-scaling criteria of current emergency-protocols. The figure presents the five known up-scaling criteria of waterboard *Rivierenland* and the phases according to the protocol LDHO. The blue dashed line indicates when evacuation should be considered. This provides enough time for decision-making, warning and response. The green-dashed line represents the moment of evacuation if a further increase of the waterlevel is expected.

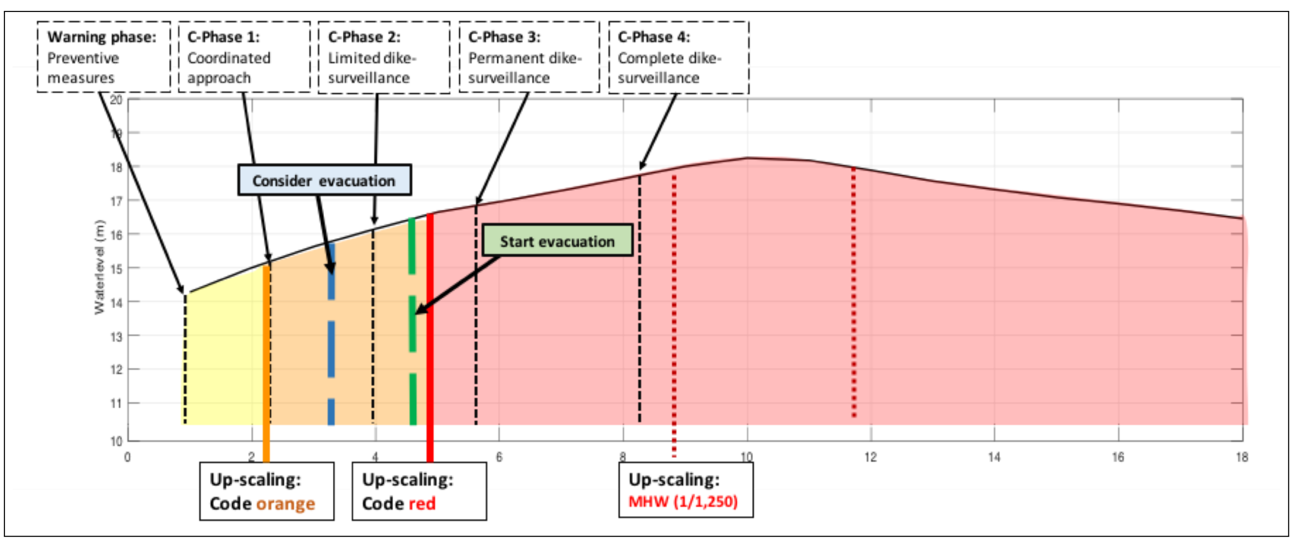


Figure 5.15: Optimal evacuation decision relative to current up-scaling criteria dikering 43

The information of figure 5.15 is again presented in table 5.4. The results of the case-study make clear that evacuation can be considered in an earlier stage than previously expected. The method suggests for waterboard *Rivierenland* to start consider evacuation between coordination-phases 1 and 2. Usually, only flood-prevention measures are considered in this stage of a flood-threat. If the waterlevel reaches a point of 16,41 metres and a further increase of the waterlevel is expected, the decision *evacuation* is advised.

Phase	**Description**	**Protocol**	**Expected WL at Lobith, within 24h**
Warning phase	Preventive measures	Rivierenland	14,00 m
Coordination-phase 1	Coordinated approach	Rivierenland	15,00 m
Code orange		LDHO	15,00 m
Consider evacuation		**Decision-method**	**15,82** m
Coordination-phase 2	Limited dike-surveillance	Rivierenland	16,15 m
Start evacuation		**Decision-method**	**16,41 m**
Code red		LDHO	16,50 m
Coordination-phase 3	Permanent dike-surveillance	Rivierenland	16,90 m
Coordination-phase 4	Complete dike-survaillance	Rivierenland	17,65 m
MHW		LDHO	18,00 m

Table 5.4: Evaluation of optimal decision with current emergency-protocols

Lastly, the sensitivity-analysis (section 5.5.3) showed the influence of evacuation-performance, business interruption and the amount of piping-sections on the alarm-waterlevels. This analysis showed that increasing expected benefits of evacuation (i.e. an improved evacuation-process), results in an earlier evacuation-decision. The measure *evacuation* becomes in that sense more attractive, relative to *no evacuation*. The same conclusion follows for decreased costs for business interruption. Accordingly, when the number of piping-sections is reduced, uncertainty of dike-failure decreases. The moment to call for evacuation therefore can be postponed, which increases the alarm-waterlevel to call for evacuation.

Context of conclusions To give an impression of the implications of the above stated alarm-waterlevels, a comparison with the evacuation of 1995 in the same dikering-area will be provided. The following presents an overview of this event:

25 January:	Within one day, a waterlevel-increase of two metres is measured at Lobith;
27 January:	Roads are closed for all sorts of traffic. The waterlevel at Lobith has reached NAP +15.02 metres;
28 January:	Waterlevel at Lobith further increased towards NAP +15.42 metres;
31 January:	The Queen's Commissioner, Jan Terlouw, called for evacuation in *het Rivierengebied*. A waterlevel of NAP +16.63 metres was measured at Lobith;
1 February:	Date of the highest observed waterlevel at Lobith (+16.68 metres).

Related to the proposed alarm-waterlevel of table 5.4, it can be concluded that evacuation in 1995 could have been considered in an earlier stage. However, the dikes of dikering 43 remained firm within these extreme conditions. The measure therefore only incurred costs. Since a flood-event is uncertain, no clear conclusions can be drawn with respect to the number of prevented fatalities. However, when failure-probabilities start to become significant, the call for evacuation is economically satisfied.

Chapter 6

Conclusions and discussion

This chapter presents the most important conclusions of this thesis. Second, a discussion will be provided to explain the central results and the potential implications of the study. The research question holds:

How can, in the case of a flood threat, an alarm-waterlevel for evacuation be developed if the new flood risk-approach is applied?

A main goal of this study is defined, related to this research-question. This goal is the development of a decision-method to find an alarm-waterlevel to call for evacuation in the case of a flood-threat, for dikering-areas in the Netherlands.

6.1 Conclusions

Four objectives were defined to accomplish the main goal of this study. This section treats these objectives and their conclusions separately.

Objective 1: Investigation of the implications of the new risk approach regarding the design of flood-defences and its impact on evacuation-considerations.

The Dutch Water Act formerly defined norm-values for flood-defences as exceeding-probabilities of a design-waterlevel. Influence of all sorts of failure-mechanisms on dike-failure was not taken into account. The legal implementation of the new risk-approach therefore proposed to explicitly include knowledge of failure-mechanisms, to better guarantee safety against flooding. The approach therefore uses three indicators of risk: economic-, individual- and societal risk.

The fundamentals of these risk metrics are derived from a combination of flooding-probabilities and consequences in terms of damage and fatalities. Defence-structures are required to lower the probability of flooding. A safe levee-system therefore accounts for all sorts of failure-mechanisms. Failure-budgetting is a method, where the contribution of every failure-mechanism contributes to the final standard. The total budget determines the shape of the construction. Secondly, implementation of the length-effect accounts for uncertainty related to the location of breaching.

Evacuation is a measure to reduce the possible consequences of a flood. The performance of this measure relates to the available time until the uncertain critical event, and the required time to take measures. Decision-makers and crisis-managers accordingly, are in need for support to shorten the decision-making process. Currently, design-waterlevels function as up-scaling criteria within the national emergency-protocol. These waterlevels only represent indicators for risk, and do not define concrete actions. [Kolen, 2013] therefore conducted an evacuation-decision diagram, based on the number of loss of life prevented by evacuation. The diagram supports a decision-maker in the case of a flood-threat, and tells whether the call for evacuation is satisfied. However, the diagram only implicitly takes into account the influence of required time for taking measures, as well as the uncertain time until the critical event. The decision-method of this report therefore needs to account for these aspects and dike-strength explicitly. Accordingly, an alarm-waterlevel needs to be the result, serving as a clear indicator for decision-makers.

Objective 2: Investigation and development of a simplified model to obtain an alarm-waterlevel to call for evacuation in the case of a flood-threat.

The decision-method is proposed in section 3.3. The method is based on the same risk-management approach as used to define the new safety standards, and conducted for dikering-areas in the Netherlands. Accordingly, it requires three important aspects to find an alarm-waterlevel to call for evacuation:

1. **The costs and benefits of the measure evacuation:** Evacuation has the opportunity to save loss of life, but is costly as well. The evacuation-decision is always a consideration between costs and possible benefits. Therefore, a social cost-benefit analysis is used where a value is addressed to a (prevented) fatality after [Bockarjova et al., 2010, Bockarjova et al., 2012]. Costs are related to economy (GDP) if inhabitants are requested to leave the threatened area. Besides, some fatalities will occur because of evacuation itself due to a chaotic response. Benefits are defined by the prevented loss of life and the value of moved goods, saved by evacuation. These aspects rely on the uncertain flood-event.

2. **Forecasts of high-waterlevels:** Expected high waterlevels are used as indicator for evacuation. Forecasts are made every day, for time-frames of four days ahead. To mimic waterlevel-forecasting, a representative waterlevel-development over time is used. Every day along the design-wave, forecasts are mimicked, where uncertainty of forecasts increases for longer time-frames.

3. **Conditional dike-strength information:** Fragility-curves represent the conditional probability of failure, as a function of a waterlevel, per failure-mechanism. These curves are required to express the likeliness of failure for expected high-waterlevels. This study only focused on failure-mechanisms piping and overflow/overtopping.

If evacuation is called, one is uncertain about *when* and *if* a flood hits. However, the decision cannot be reversed. If one decided for *no evacuation* and no flood occurred, a new decision with updated information can be made the next day. To support these decisions, the method assesses a moment where the decision is economically satisfied, relative to a representative waterlevel-development over time. This moment is based on a threshold, described by the first time the expected costs for *evacuation* are smaller than the expected costs for *no evacuation*. This moment corresponds with the alarm-waterlevel to start evacuation. One should start considering this measure 24 hours in advance, to ensure there is enough time for decision-making, warning and response.

Objective 3: Analysis of implications of a decision-model for evacuation based on a social cost-benefit analysis and probabilistic forecasting.
The decision-model is based on cost-indicators, a representative waterlevel-development over time and uses conditional dike-strength to calculate failure-probabilities. The two most important implications of the decision-method on the alarm-waterlevel to call for evacuation will be presented:

- **The effect of evacuation-performance:** The performance of evacuation is described by the percentage of affected people who are able to evacuate within a certain amount of time. If the performance is improved, more people are able to evacuate within the same amount of time. Possible benefits of an evacuation therefore increase. This puts more favour to the decision *evacuation* compared to the decision *no evacuation*, for the same loading-and strength-conditions. As a result of an improved evacuation-process, the evacuation-decision is satisfied for lower waterlevels.

- **The effect of dike-strength:** This report focused on a situation where the conditional failure-probability of a dikering is only determined by failure-mechanisms overflow/overtopping and piping. The mechanism piping contributes significantly to the failure-probability for lower waterlevels. The mechanism overtopping/overflow is mainly determined by the crest height of the levee. If the conditional failure-probability is increased due to presence piping, the dike-strength is decreased for the same loading conditions. As a result, the evacuation-decision is worthwhile for lower waterlevels. Concluding, the analysis shows that the evacuation-decision relates to the strength of a dike. A stronger dike relates to a higher waterlevel where a call for evacuation is satisfied.

Objective 4: Application of the decision-method on a dikering-area in the Netherlands, to evaluate current emergency-procedures with an alarm-waterlevel to call for evacuation.

This study used the proposed decision-method to find an alarm-waterlevel to call for evacuation for dikering 43 in the Netherlands. The model uses estimates of cost-parameters, an evacuation-performance study of [Kolen et al., 2013], information of dike-strength from [Rijkswaterstaat VNK Project, 2015] and a representative waterlevel-development over time with a peak-discharge of $16,000m^3/s$ as input.

VNK-studies of dikering 43 made clear that consequences of a possible flood are influenced by its breaching-location, due to a sloping surface. An evacuation-decision is therefore composed for the Eastern and Western part of the dikering-area, using the following assumptions:

- If breaching in the Eastern part occurs, the entire dikering needs to be evacuated.
- If breaching in the Western part occurs, only the Western part needs to be evacuated.

The analysis showed that evacuation is considered first in the Eastern part of the dikering. Since in that case the entire area needs to be evacuated, this decision is stated to be normative. Concluding, evacuation is currently considered in the most extreme scale of a threatening event (code red of the national emergency-protocol). However, the decision-method shows that evacuation is worthwhile for a significantly lower design-waterlevel. This is mainly due to the presence of failure-mechanism piping, which brings a significant contribution to the conditional failure-probability for lower waterlevels. A sensitivity-analysis showed, if the contribution of piping is reduced, the failure-probability for lower waterlevels decrease. As a result, the evacuation-decision can be postponed.

6.2 Discussion

This section explains the central results and potential implications of the study. First, section 6.2.1 moves into research-evaluation. Second, some recommendations will be made for future research in section 6.2.2.

6.2.1 Research-evaluation

The research developed a method to decide for evacuation in the case of a flood-threat, for dikering-areas in the Netherlands. The method is based on the same risk-management approach as used to define the new safety-standards. A theoretical example is based on a simplified dikering to explain its general use. Finally, dikering-area 43 in the Netherlands served as case-study, to compare current emergency-procedures with an alarm-waterlevel to call for evacuation. This section evaluates the decision-model, scrutinizes the results of the case-study and discusses methodological biases.

- **Method - a social cost-benefit analysis to support an evacuation-decision:** The social cost-benefit analysis considers the implicated costs and benefits for an evacuation decision. The method addresses a value to a (prevented) fatality to decide for evacuation rationally.
  - The method needs to be interpreted as a supportive tool, to make decisions for emergency-measures more rationally. The study therefore expresses fatalities in monetary units after [Bockarjova et al., 2010, Bockarjova et al., 2012]. Accordingly, it is stated that costs are involved with an evacuation-decision. People are requested to leave the threatened area, and are therefore not able to produce goods or provide services during that period. Accordingly, decision-makers will always weigh the costs against potential benefits.
  - Currently, the model used simplified cost-indicators to assess the involved costs and benefits. The values of these costs and benefits are roughly estimated. Sensitivities of the most important cost-indicators show how the variability of these cost-indicators affect the development of the evacuation-decision (section 4.2). It is advised to include better estimations of costs and benefits of evacuation, in order to inform the public by a well-considered alarm-waterlevel.

- **Method - The implications of the decision-tree:** An evacuation-decision is composed by an evaluation of the expected costs of *evacuation* against the expected costs of *no evacuation*. The method however, is limited:
  - It is assumed an evacuation-decision is composed every 24 hours. Every day, forecasts of waterlevels are made with a maximum lead-time of four days. In reality, an evacuation-decision can be composed more frequently.
  - Every day in the design-wave, an evacuation-decision is based on the current and expected situation. Loading of previous days is implicitly neglected in this way. The failure-mechanism piping relies on the duration of loading, which is therefore not taken into account.
- **Case - Determination of strength of dike-segments by considering weakest dike-section:** The results of the evacuation-decision rely on the strength of the considered dike. The fragility-curve of the weakest dike-section is used to represent the strength of a dike. Three aspects of this simplification will be discussed.
  - First, the use of the weakest dike-section results in an underestimation of the actual strength of the dike. The calculated evacuation-decisions for dikering 43 can therefore be interpreted as lower boundary if only piping and overflow/overtopping are considered.
  - Second, the method only focused on failure-mechanisms overflow/overtopping and piping. Although these mechanisms are the main contributors to the probability of dike-failure (according to [Rijkswaterstaat VNK Project, 2015], the inclusion of other failure-mechanisms will give a better insight in the current state of the dike.
  - Third, the length-effect is mimicked by counting the number of dike-sections where piping plays a significant role within the study-area. This method results in an increased contribution of piping, but neglects the *length* of dike-sections. Inclusion of length influences the alarm-waterlevel, since dike-sections differ in length. If the weakest dike-section is relatively large, compared to other dike-sections, the presence of piping within a dike will be overestimated with this approach. If this dike-section is relatively small, dike-strength is somewhat underestimated. Therefore, a better inclusion of the conditional failure-probability due to piping could be obtained if length of dike-sections is properly included.
- **Case - Application of model for other dikering-areas in the Netherlands:** The objective was to develop a decision-method for dikering-areas in the Netherlands. The research included a case-study of dikering 43. It must be noticed that every dikering needs its own attention. Most important aspect is the predictability of waterlevels. Since river-discharges are easy to predict, forecasting of flood-threats is relatively accurate for dikering 43. Other dikering-areas need to consider tidal influences, and the effect of wind. These considerations will effect the design-wave to be able to draw conclusions.

6.2.2 Recommendations for future research

This research bridges knowledge regarding the strength of defence-structures and emergency-procedures. To do so, a decision-method is developed which includes these aspects. It is recommended for future-research to refine some aspects. Only considerations which might lead to a significant change of the output will be considered.

- **Include dependence of failure with waterlevel-development:** It is advised to take a closer look in the mathematical assumptions of the decision-tree regarding dike-failure. By neglecting information of the past, the probability of failure is underestimated.
- **Properly apply dike-strength to an evacuation-decision:** As concluded in this report, dike-strength is an important parameter regarding the evacuation-decision. The case-study used a simplification of the actual strength by considering the weakest dike-section as representative. It is advised to think about ways to include the strength of dike-sections more precisely.

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Appendix A

Explanation of an evacuation-decision diagram

This analysis treats an example of how an evacuation-decision diagram can be conducted, as presented in [Kolen and Wegman, 2016]. To do so, a decision-tree is used in figure A.1, to present the decision-dilemma. The figure gives an overview of possible decisions and consequences in the case of a flood-threat. The result of this approach is a threshold based on the conditional flooding probability P, given an acting load. Table A.1 presents the different cost-indicators, involved with the four scenarios. They present:

- Loss of life (in monetary units) by F1 and F2. The first indicator relates to loss of life in the case of a flood if no evacuation is called. The second indicator relates to loss of life if evacuation is called. Indicator F3 relates to fatalities by the evacuation-process itself (car accidents, people from hospitals).
- The costs for business interruption (C), since people are in the case of evacuation not able to contribute to economy.
- The value of movable goods (M), saved by evacuation.

Costs-indicators related to evacuation-decisions				
	Evacuation	Flood	Fatalities [€]	Business interruption [€]
Scenario 1	Yes	Yes	$F2 + F3$	$C - M$
Scenario 2	Yes	No	$F3$	C
Scenario 3	No	Yes	$F1$	0
Scenario 4	No	No	0	0

Table A.1: Cost-indicators involved with evacuation, given a flood/no-flood, after [Kolen, 2013]

The decision-maker chooses the objective to strive for. Based on his or her perception of risk, a call for evacuation will be made. It sounds reasonable to minimise the expected loss of life. However, this objective relates to a no regret solution. In that case, one will always decide for evacuation, wich is certainly not the case since evacuation is costly and can affect the reputation of the decision-maker [Wojciechowska, 2015]. The social cost-benefit analysis will be used to optimize the decision in terms of the expected costs. Therefore, a monetary value is addressed to a victim, which is politically accepted in Dutch context.

Figure A.1 shows a basic concept of an evacuation-decision in case of a flood threat. A combination of a decision ("evacuation" or "no evacuation") and an event ("flood" or "no flood") will lead to one of the four cost-scenarios as presented in table A.1.

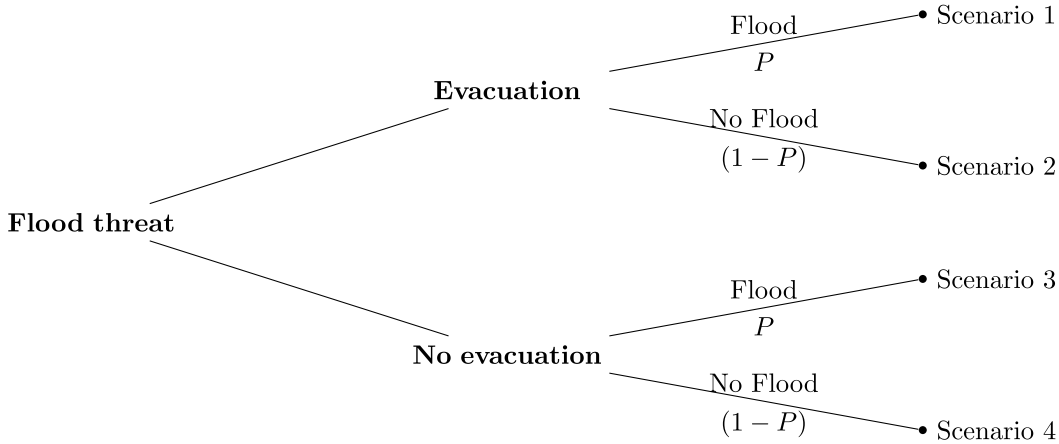

Figure A.1: Decision tree simplified approach. Derivation of decision-threshold.

The expected costs of both decisions can be conducted by a combination of costs and probabilities:

- Expected costs **Evacuation** $= P \times (F2 + F3 + C - M) + (1 - P) \times (F3 + C)$
- Expected costs **No evacuation** $= P \times F1$

Only if the expected costs of preventive evacuation are smaller than the expected costs of no preventive evacuation, the measure is economically worthwhile [Wojciechowska, 2015]. Based on this consideration, a call for evacuation will be satisfactory. Using the parameters from table A.1:

$$P \times (F2 - M) + F3 + C \quad < \quad P \times F1 \tag{A.1}$$

Rewriting equation A.1 finally leads to equation A.2. The statement above the quotation mark can be seen as costs involved with evacuation. The parameters below the quotation mark are the benefits. The part $(F1 - F2)$ can be considered as the loss of life prevented by evacuation.

$$\text{Evacuate when} \quad 1 > P \geq \frac{F3 + C}{(F1 - F2) + M}, \qquad \text{do not otherwise} \tag{A.2}$$

A.1 A numerical example

A numerical example will be provided to give more insight in the role of different parameters, related to the evacuation-decision diagram. All parameters are applied in Dutch context.

$V = 6.7M€$: This is known as the economic value of a victim based on recent literature [Bockarjova et al., 2010] and [Bockarjova et al., 2012].

$C = m \times GDP$: The costs for economy are in the presented model based on a fraction of the GDP. This fraction m is assumed to be 0.25%, corresponding with 15% of the country not contributing to economy for a week. In an optimistic scenario, it is assumed that costs will decrease by a factor 2. The pessimistic scenario assumes a cost-increase of 100%.

$M = k \times$ Damage : The value of movable goods, saved by evacuation is assumed to be a fraction of the flood damage. The fraction k saved of this damage by evacuation, is 0.1%. [Rijkswaterstaat, 2015] shows that a breach in the Western part of the Netherlands already may lead to 12.5 Billion € damage. The optimistic scenario assumes that 10% can be saved, where the pessimistic assumption uses $k = 0.01\%$.

$F3 = b \times I \times V$: The report of [Kolen, 2013] suggests that in the order of 25 persons will die because of evacuation itself. This number is recognized to be an optimistic assumption. The value of F3 will in the simplified study be expressed as $F3 = 25 \times V$.

The optimistic and pessimistic scenarios will lead to decision-thresholds in a worst- and best-case situation. Conducting such scenarios will support decision-makers during a flood-threat. In this case only the prevented damage by evacuation and the impact on economy are considered as variable inputs for certain event classes. Referring to [Kolen, 2013] an optimistic scenario lies within a small event class, and a pessimistic scenario within an extreme event class. Classes for impact, where the available time to take measures is the most important factor, is not yet considered. The result of this study is presented in figure A.2. The figure shows the evacuation-decision as a function of the loss of life prevented by evacuation ($F1 - F2$). The more people can be saved, the lower conditional failure probability is required to make evacuation worthwhile. The blue and red lines present the optimistic and pessimistic scenarios respectively.

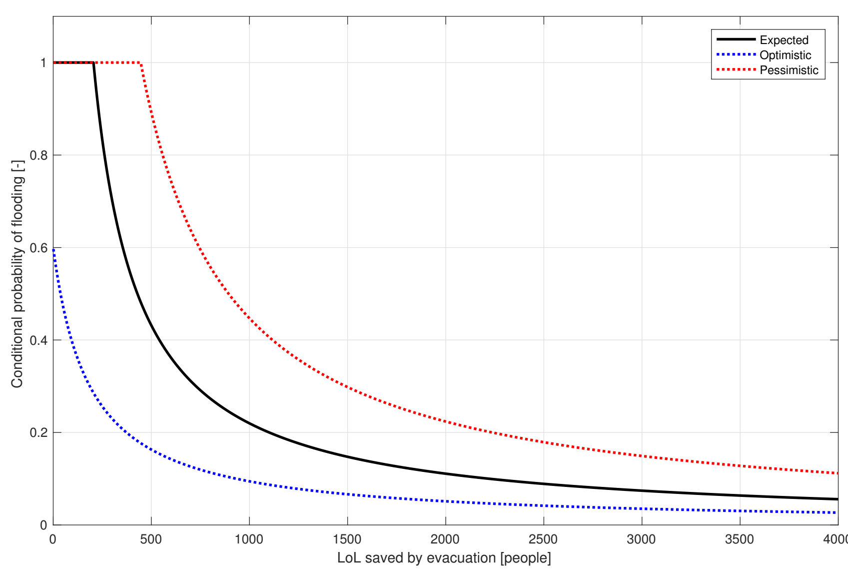

Figure A.2: Evacuation decision-diagram for the simplified study

Appendix B

Results evacuation-decisions per dike-segment

This appendix moves into evacuation-decisions of 13 dike-segments of dikering 43. The main objective of this study was to evaluate the influence of the new risk approach on emergency measures. To do so, it is relevant to get a better understanding of the strength of each dike-segment individually. First, a short summary of the most important results is presented. The following sections will move further into the evacuation-decisions at specific breaching-locations.

Two design-waves are studied in this appendix: waves of $16,000m^3/s$ and $17,000m^3/s$. Both design-waves are combined with flood-scenarios, representing the number of affected people and the value of expected damage. For every dike-segment it is checked when the expected costs for evacuation are smaller than the expected costs for no evacuation. For every segment, a representative dike-section is used. These are the weakest dike-sections according to [Rijkswaterstaat VNK Project, 2015]. The results are listed in table B.1.

Results at moment of decision-making								
	Scenario: tp, $Q = 16,000m^3/s$				Scenario: $(tp + 1d)$, $Q = 17,000m^3/s$			
Segment	P_f (-)	Day	WL (m)	Lobith (m)	P_f (-)	Day	WL (m)	Lobith (m)
Angeren	0.0634	9	14.65	17.66	0.0636	9	14.67	17.66
Bemmel	0.0632	7	14.32	17.35	0.0738	6	14.41	17.45
IJzendoorn	0.1167	7	11.51	17.66	0.1232	7	11.55	17.66
Malburgen	-	-	-	-	-	-	-	-
Elden	-	-	-	-	-	-	-	-
Heteren	0.0592	9	11.67	17.89	0.0618	9	11.68	17.89
Kesteren	-	-	-	-	-	-	-	-
Eck en Wiel	-	-	-	-	-	-	-	-
Ravenswaaij	0.1087	9	7.34	17.81	0.1152	9	7.37	17.81
Oosterhout	0.0565	9	13.31	17.96	0.0596	8	13.34	17.96
Haaften	-	-	-	-	0.1039	9	8.63	18.41
Tiel-West	-	-	-	-	-	-	-	-
Culemborg	-	-	-	-	-	-	-	-

Table B.1: Summary of evacuation-decisions at breaching-locations

The results show that evacuation already becomes worthwhile if the conditional probability of failure of dike-segments is relatively low. However, it can be noticed that evacuation will not be considered for the segments of Malbugen, Elden, Kesteren, Eck en Wiel, Haaften, Tiel-West and Culemborg. The following sections will discuss how evacuation-decisions are obtained by a combination of dike-strength and flood-consequences.

B.1 Results segment Angeren

The dike-segment with breaching-location Angeren results in one of the most extreme flood-scenarios. Almost the entire hinterland of dikering 43 will be flooded if breaching occurs. The relevant information at the optimal moment of decision-making is presented in the table B.2.

	Scenario: tp	**Scenario:** $tp + 1d$
Inhabitants:	271,226	278,998
Damage:	12,422 M €	14,177 M €
Conditional failure-probability:	0.0634 (-)	0.0636 (-)
Moment of decision-making:	Day 9	Day 9
Waterlevel (Angeren):	14.65 m	14.67 m
Waterlevel (Lobith):	17.66 m	17.66 m

Table B.2: Angeren: summary of information at optimal-decision

Figure B.1 presents the fragility-curve of the dike-segment under study. The mechanism piping has a relatively little impact on the total conditional failure-probability. The blue line shows the influence of piping for the weakest dike-section. The red line relates to piping for the entire segment. It is obtained by a proportional increase with the number of dike-sections sensible for the mechanism piping.

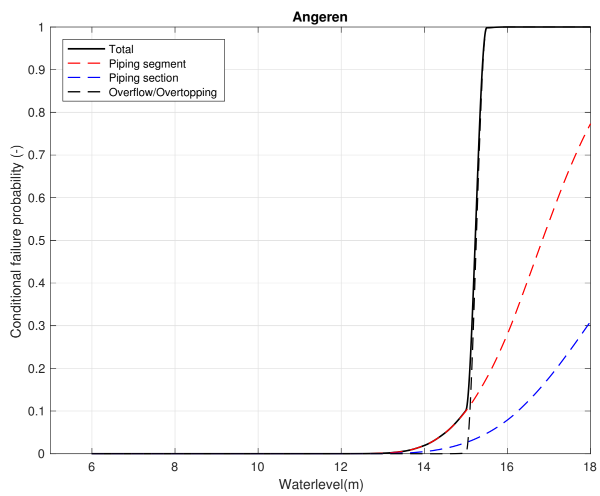

Figure B.1: Angeren: Fragility-curve for segment. Blue: piping weakest dike-section, Red: piping entire segment

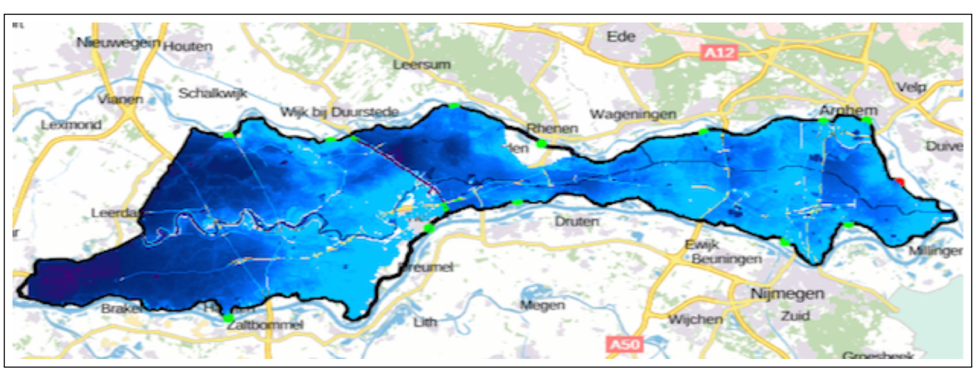

Figure B.2: Angeren: representation of flood-consequences (normative scenario)

B.2 Results segment Bemmel

The consequences of breaching at segment Bemmel are of the same order as segment Angeren. In the case of a possible dike-breach within this segment, the entire dikering needs to be evacuated. A summary of the information at the moment of decision-making is presented in table B.3.

	Scenario: tp	**Scenario:** $tp + 1d$
Inhabitants:	282,673	289,389
Damage:	14,946 M €	16,770 M €
Conditional failure-probability:	0.0632 (-)	0.0738 (-)
Moment of decision-making:	Day 7	Day 6
Waterlevel (Bemmel):	14.32 m	14.41 m
Waterlevel (Lobith):	17.35 m	17.45 m

Table B.3: Bemmel: summary of information at optimal-decision

Figure B.3 shows that failure-mechanism piping plays an important role in this segment. The number of sensible dike-segments for piping give a strong weight to the total failure-probability. As a result, it is allowed to make a relatively early call for evacuation.

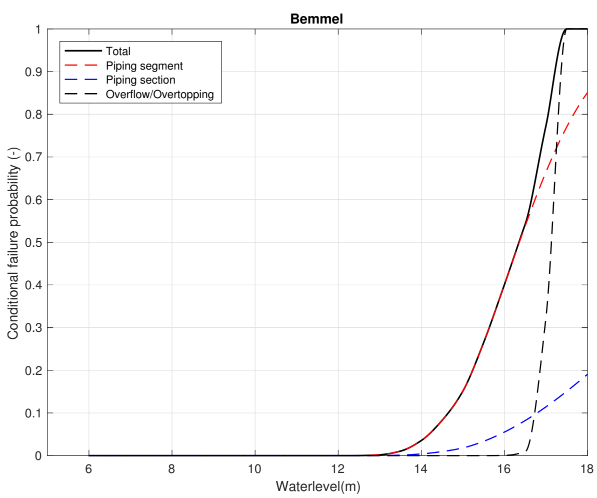

Figure B.3: Bemmel: Fragility-curve for segment. Blue: piping weakest dike-section, Red: piping entire segment

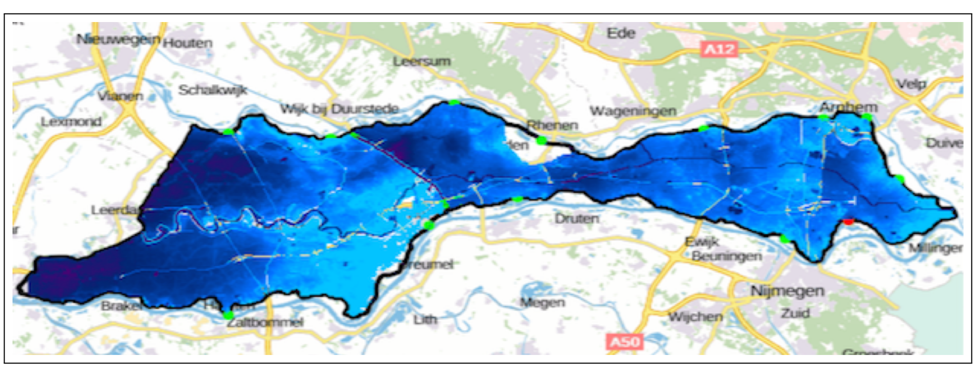

Figure B.4: Bemmel: representation of flood-consequences (normative scenario)

B.3 Results segment IJzendoorn

IJzendoorn is located in the Southern part of the dikering. A breach within this segment will lead to a scenario where almost 50% of the dikering-area gets flooded. Table B.4 presents the information at the optimal moment of decision-making.

	Scenario: tp	**Scenario:** $tp + 1d$
Inhabitants:	140,987	149,718
Damage:	8,676 M €	9,907 M €
Conditional failure-probability:	0.1167 (-)	0.1232 (-)
Moment of decision-making:	Day 7	Day 7
Waterlevel (IJzendoorn):	11.51 m	11.55 m
Waterlevel (Lobith):	17.66 m	17.66 m

Table B.4: IJzendoorn: summary of information at optimal-decision

It can be concluded that this segment contains many segments where the failure-mechanism piping plays a significant role. The total conditional failure-probability is mainly determined by the piping-curve. Although, the contribution of piping is relatively large, the conditional probability of failure at the moment of decision-making is over 10%. This is mainly due to the gradient of the fragility-curve.

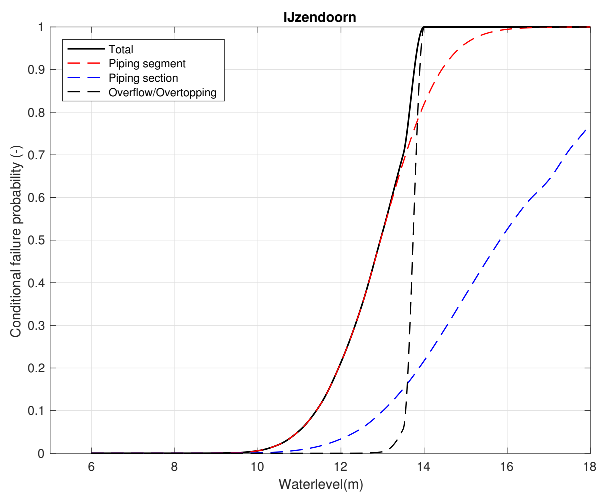

Figure B.5: IJzendoorn: Fragility-curve for segment. Blue: piping weakest dike-section, Red: piping entire segment

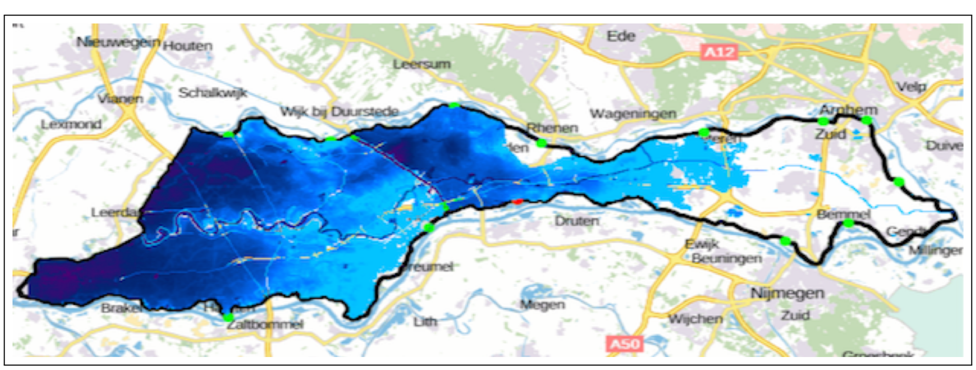

Figure B.6: IJzendoorn: representation of flood-consequences (normative scenario)

B.4 Results segment Heteren

A flood within the segment of Heteren leads to flooding of the Western part of the dikering-area. The moment of decision-making is relatively late, compared with other dike-segments. Other relevant information regarding the evacuation-decision can be found in table B.5.

	Scenario: tp	**Scenario:** $tp + 1d$
Inhabitants:	99,248	121,040
Damage:	4,360 M €	6,040 M €
Conditional failure-probability:	0.0592 (-)	0.0618 (-)
Moment of decision-making:	Day 9	Day 9
Waterlevel (Heteren):	11.67 m	11.68 m
Waterlevel (Lobith):	17.89 m	17.89 m

Table B.5: Heteren: summary of information at optimal-decision

The fragility-curve is steep, which corresponds with a relatively small piping-contribution. Thus, the conditional failure-probability at the moment of decision-making is smaller than 6%. However, future waterlevel forecasts predict a strong increase of this failure-probability due to the steep gradient of the fragility-curve.

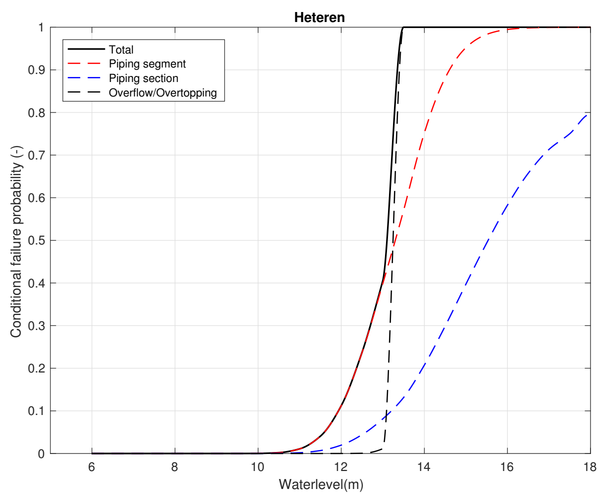

Figure B.7: Heteren: Fragility-curve for segment. Blue: piping weakest dike-section, Red: piping entire segment

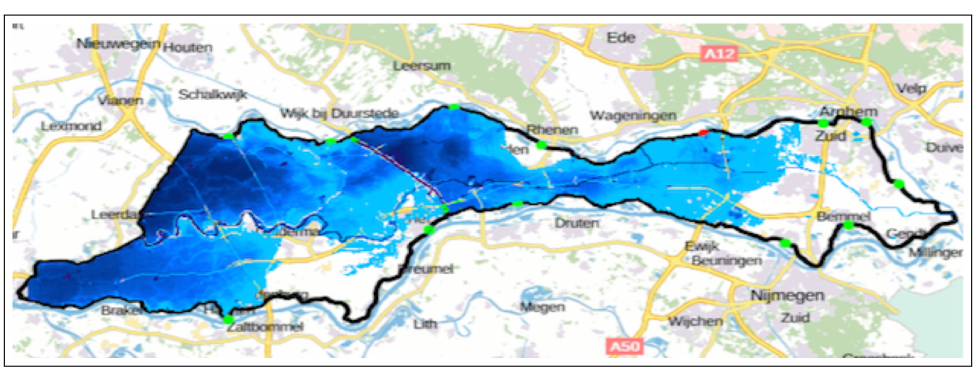

Figure B.8: Heteren: representation of flood-consequences (normative scenario)

B.5 Results segment Ravenswaaij

The evacuation-decision of Ravenswaaij can be compared with the decision of Heteren. A flood-scenario only will affect the Western-part of the dikering-area. From day 9 in the design-wave, the evacuation-decision will become worthwhile for both flood-scenarios. Table B.6 gives an overview of all relevant information on the moment of decision-making.

	Scenario: tp	**Scenario:** $tp + 1d$
Inhabitants:	82,794	87,551
Damage:	5,346 M €	5,920 M €
Conditional failure-probability:	0.1087 (-)	0.1152 (-)
Moment of decision-making:	Day 9	Day 9
Waterlevel (Ravenswaaij):	7.34 m	7.37 m
Waterlevel (Lobith):	17.81 m	17.81 m

Table B.6: Ravenswaaij: summary of information at optimal-decision

Again, the fragility-curve shows a relatively steep gradient. The failure-mechanism piping is only dominant for low waterlevels.

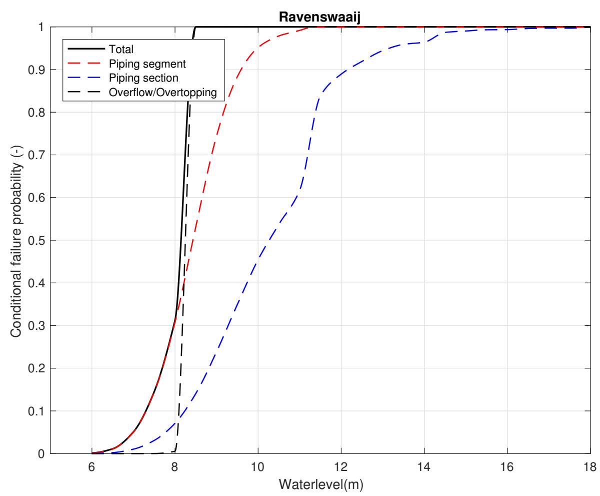

Figure B.9: Ravenswaaij: Fragility-curve for segment. Blue: piping weakest dike-section, Red: piping entire segment

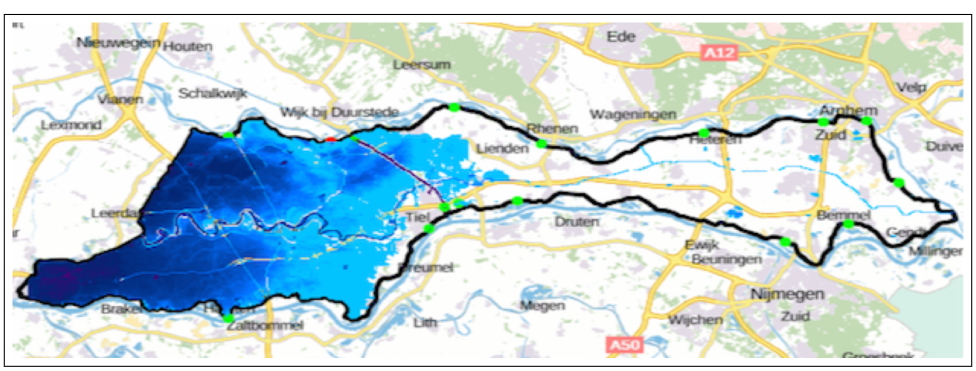

Figure B.10: Ravenswaaij: representation of flood-consequences (normative scenario)

B.6 Results segment Oosterhout

The dike-segment of Oosterhout is an important segment, since it protects almost the entire dikering against flooding. Scenarios tp and $tp + 1d$ show a difference for the moment of decision-making, but the waterlevel to decide for evacuation remains nearly constant. Table B.7 presents this information clearly.

	Scenario: tp	**Scenario:** $tp + 1d$
Inhabitants:	234,233	251,233
Damage:	11,404 M €	13,108 M €
Conditional failure-probability:	0.0565 (-)	0.0596 (-)
Moment of decision-making:	Day 9	Day 8
Waterlevel (Oosterhout):	13.31 m	13.34 m
Waterlevel (Lobith):	17.96 m	17.96

Table B.7: Oosterhout: summary of information at optimal-decision

According to this dike-segment, piping plays only a dominant role for lower waterlevels. If the waterlevel in the river further increases from 14 meters, the fragility-curve will show a steep gradient.

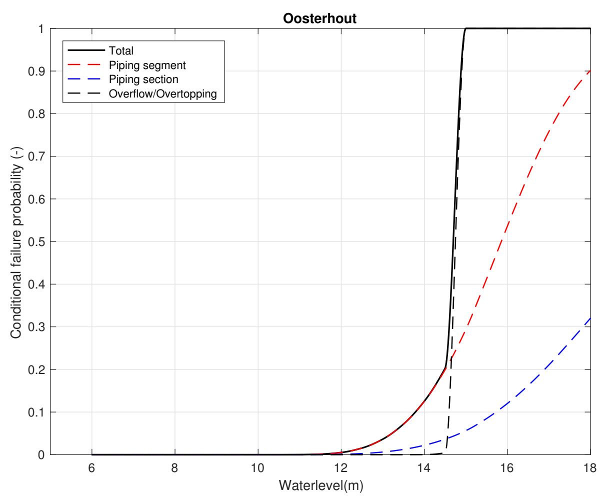

Figure B.11: Oosterhout: Fragility-curve for segment. Blue: piping weakest dike-section, Red: piping entire segment

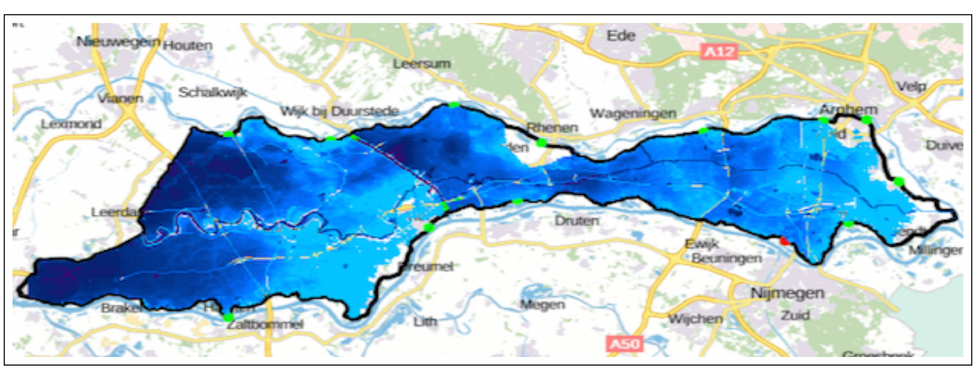

Figure B.12: Oosterhout: representation of flood-consequences (normative scenario)

B.7 Results segment Haaften

Haaften is the final segment which will be treated. The segment is located in the Western part of the dikering. The VNK-reports only calculated consequences for a normative flood, which is in this case used for both scenarios (tp and $tp + 1d$). In the case of a design-wave of $16,000 m^3/s$, the expected costs for evacuation will not become smaller than the expected costs for no evacuation.

	Scenario: tp	**Scenario:** $tp + 1d$
Inhabitants:	100,838	-
Damage:	8,435 M €	-
Conditional failure-probability:	-	0.1039 (-)
Moment of decision-making:	-	Day 9
Waterlevel (Haaften):	-	8.63 m
Waterlevel (Lobith):	-	18.41 m

Table B.8: Haaften: summary of information at optimal-decision

Within the segment of Haaften, only a few dike-segments are likely to fail as a consequence of the failure-mechanism piping.

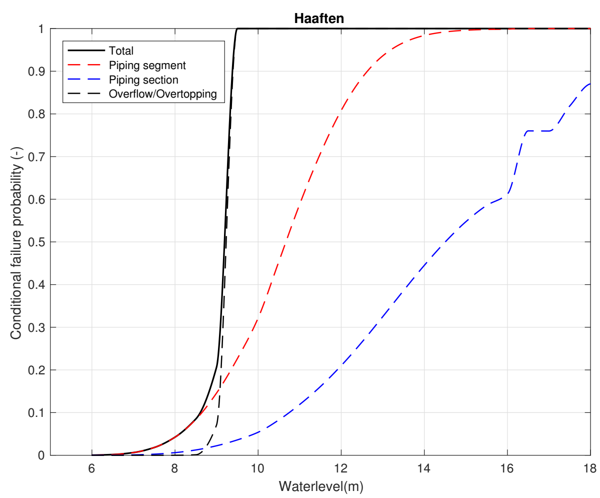

Figure B.13: Haaften: Fragility-curve for segment. Blue: piping weakest dike-section, Red: piping entire segment

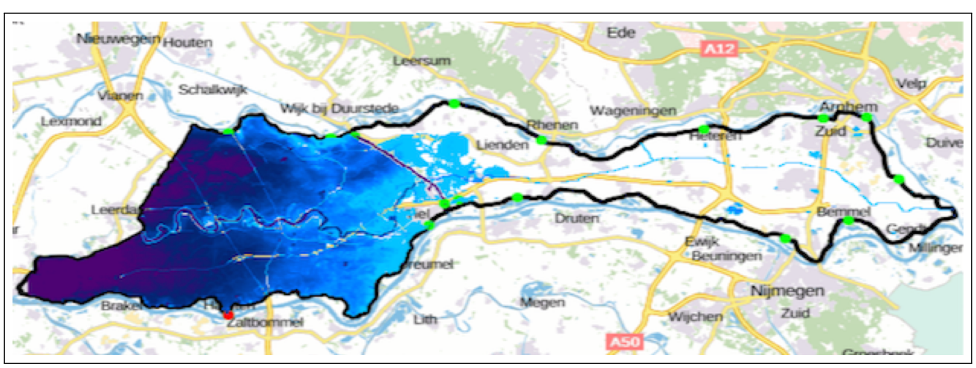

Figure B.14: Haaften: representation of flood-consequences (normative scenario)