The influence of the crest height of trajectory 225 on the water level at Kampen

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The influence of the crest height of trajectory 225 on the water level at Kampen

Master Thesis

by

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Preface

After eight and a half years of studying, the time has come to write the preface of my master's thesis. The completion of my graduation period means that my period as a student has also come to an end, which feels like a true milestone in my life. To be honest, I did not expect my graduation period to work out the way it did. I wanted to perform my research at a company, which was possible thanks to my former roommate Bart. Unfortunately, I was only able to visit the office for less than a week due to the Covid pandemic. My bedroom became my designated office and the coffee was drunk with my roommates instead of my colleagues. In the first months of my research, I found it hard to keep myself motivated. Nevertheless, I am proud to finish my graduation project and I am curious about what is yet to come.

I would like to explicitly thank several persons whom were closely involved for the duration of this thesis, starting with my graduation committee. Guy, many thanks for your guidance during the past ten months. You were able to provide me with a lot of different views to the problems I have encountered, which I needed to keep focused. Matthijs and Hessel, thank you for the great discussions we have had during my progress meetings and the valuable feedback, which gave me the motivation I needed to proceed. Furthermore, Roy, despite you were not a member of my graduation committee, we had plenty video calls in which you helped me a lot. Especially your help with the sqlite databases saved me a lot of time. Thank you once more!

I would also like to thank all other employees of HKV Lijn in Water for their interest in my graduation project and their willingness to help me.

As this part allows me to reflect on my complete period as a student, I would also like to express my sincere gratitude to my dear parents, sister and girlfriend. Mom and dad, thank you for the support and undoubted love during my entire period as a student. Vivian, even as adults, you are still willing to help your little brother out. Thank you! Judith, thank you for your endless happiness, for motivating me and for the distraction when I needed it.

Enjoy reading!

Stan Vernimmen
Rotterdam, January 2021

Summary

The water levels along the dike of Kampen are mainly affected by the magnitude of the discharge on the river IJssel and the water level set-up caused by the wind characteristics on the IJsselmeer. The Kampereiland has been assigned as a retention area to reduce the water levels near Kampen during a storm. See Figure 1 for their locations. This area should store excess water during a storm at the IJsselmeer of a magnitude corresponding to an annual exceedance probability of 1/500, to prevent this water from flowing in the direction of Kampen. The Kampereiland is protected by dike trajectory 225 and a part of this dike trajectory has been made resistant to the overflow of water. According to new insights, the crest of this dike section seems too high and the Kampereiland inundates less frequently. Furthermore, it is not sure whether the water level at Kampen benefits from the inundation of the Kampereiland and what the possible consequences are for surrounding dike trajectories. The Kamperzeedijk is one of these surrounding dike trajectories and protects the city IJsselmuiden, along with the polder behind.

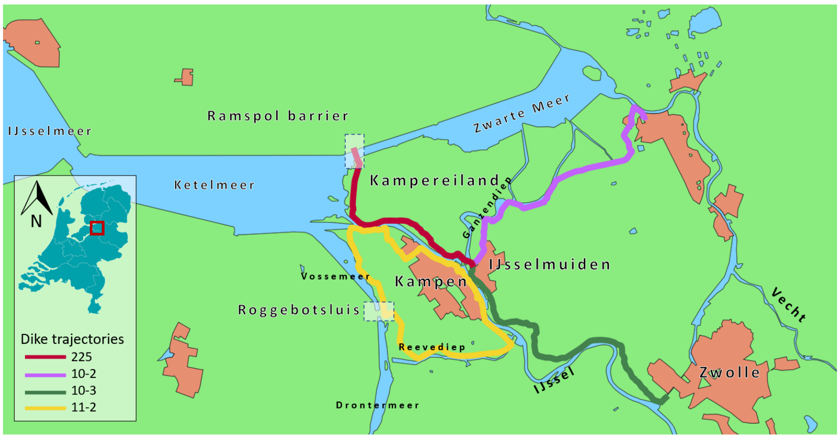

Figure 1: Overview of the area of interest with all cities, areas, water bodies and dike trajectories.

The influence of the crest height of this overflow resistant part on the water levels at Kampen and at IJsselmuiden is investigated in this study. A model is created to derive the water level in front of trajectory 225 and the discharge over the overflow resistant part for various storms. This is done by using existing WAQUA computations as data input. From these data, a storm is simulated to compute the volume of water flowing into the Kampereiland. The most important assumptions are that dikes do not breach and that the water level at Kampen remains constant after water flows into the Kampereiland. The influence on the water levels at Kampen and at the Kamperzeedijk is evaluated for multiple crest heights of the overflow resistant dike section. Eventually, these water levels are processed with a statistical model to compute multiple water level exceedance frequency lines for each location and for various chosen crest heights of trajectory 225.

The results show that higher crest heights of trajectory 225 lead to increased maximum water levels at the Kamperzeedijk and to lower maximum water levels at Kampen. Opposite effects are observed for lower crest heights. The water levels in front of the overflow resistant dike section remain unaffected. The return periods for overflow at Kampen and IJsselmuiden are derived by comparing the water level exceedance frequency lines to their individual crest heights. These are shown in Table 1.

Concluded is that the inundation of the Kampereiland does not immediately lead to a load increase in front of the Kamperzeedijk, but a delay is observed. This delay is the result of the storage capacity of the Kampereiland. As soon as water from the Kampereiland flows into the Ganzendiep, the loads rapidly increase. Furthermore, concluded is that the Kampereiland is capable of reducing the water levels at Kampen.

Based on the results from this research, a crest height of 2.7m +NAP leads to equal return periods for overflow at trajectories 10-2 and 11-2. The reduction of the crest height by ten centimeters increases the return period for overflow at Kampen from 30,000 years to 45,000 years. At the Kamperzeedijk, the return period is reduced from 80,000 years to 45,000 years. In reality, these return periods are also affected by other failure mechanisms. A full dike assessment has to elaborate on this. Furthermore, trajectory 225 is assessed whether it meets its safety standard. It would be more legitimate to assess trajectory 225 by explicitly quantifying its consequences on trajectories 10-2 and 11-2.

Table 1: Exceedance frequency of different dike sections for various crest heights of the overflow resistant part of trajectory 225.

Crest height 225 [m +NAP]	**Kampereiland (225)** [years]	**Kampereiland (Ganzendiep)** [years]	**Kamperzeedijk (10-2)** [years]	**Kampen (11-2)** [years]
2.2	250	1,000	5,000	> 100,000
2.4	500	3,000	10,000	> 100,000
2.6	1,000	10,000	20,000	75,000
2.8	2,000	30,000	80,000	30,000
3.0	4,000	30,000	> 100,000	20,000
3.2	10,000	> 100,000	> 100,000	15,000

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Introduction

The Netherlands has a well known history in terms of vulnerability to floodings. This is the result of the fact that 26% of the Netherlands lies below sea level and many rivers flow through the country [29]. Without dikes protecting against water from the sea, lakes and rivers, 60% of the country would experience regular floodings [29]. Therefore these parts have to be protected by flood defences. The first dikes were built more than a thousand years ago and the Netherlands has experienced multiple floodings since then [15] [22]. Therefore, the Netherlands has a worldwide reputation in flood protection.

1.1. The Vecht- and IJsseldelta

A delta is a system of river branches discharging in a lake or a sea. The Vecht- and IJsseldelta lies in the province Overijssel and is named after the two rivers flowing through: The IJssel and the Vecht. These rivers both flow in western direction and discharge in the Ketelmeer. This lake forms the connection between the two deltas [31]. In these deltas, several cities, areas, water bodies and dike trajectories are present. These are briefly described in this paragraph with multiple overview figures.

The location of the rivers and other water bodies is shown in Figure 1.1. Before the water of the Vecht reaches the IJsselmeer, it flows through the Zwarte Meer and the Ketelmeer. The Ketelmeer is a lake which has an open connection with the IJsselmeer and because of this wide opening between these two lakes, the water level in the Ketelmeer is dependent on the water level and the meteorological situation at the IJsselmeer [30]. The Ketelmeer is also connected to the Zwarte Meer. This lake has a surface of approximately 21 km^2 and at most places the bottom lies higher than one meter below NAP[1] [17].

Before the water of the IJssel reaches the IJsselmeer, it can either flow through the branch between Kampen and the Kampereiland, or through the Reevediep. The locations of Kampen and the Kampereiland can be seen in Figure 1.2. The Reevediep is a branch between the IJssel and the Drontermeer and is only used in a situation with high discharges on the IJssel. This branch makes it easier to discharge the water through the Ketelmeer onto the IJsselmeer, reducing the amount of water flowing along Kampen.

The Ganzendiep is a small branch between the Kampereiland and IJsselmuiden. It has an open connection with the Zwarte Meer and is separated from the IJssel by a sluice. This means that it is supplied with water from the Vecht.

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[1] The NAP (Normaal Amsterdams Peil) is a vertical datum. 0m NAP is approximately equal to the mean water level of the North Sea [21].

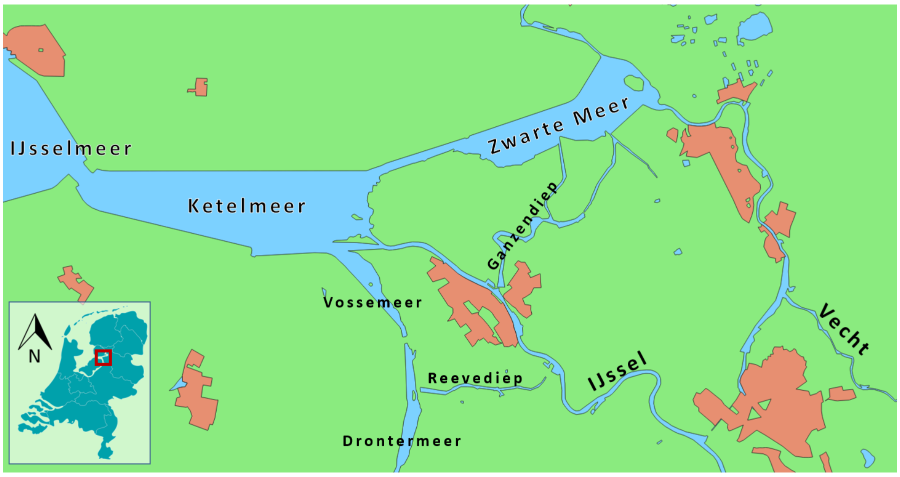


Figure 1.1: Overview of the rivers and lakes in the delta.

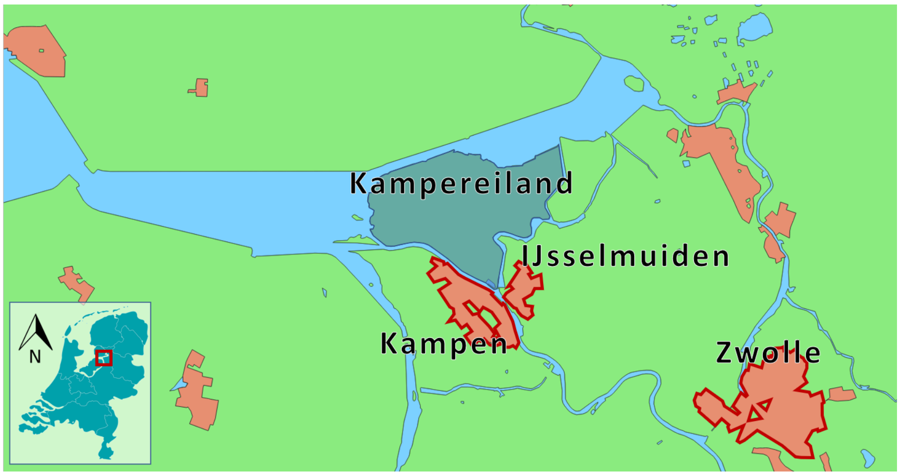


Figure 1.2: The cities in the delta: Kampen, IJsselmuiden and the Kampereiland.

The Ketelmeer and Zwarte Meer are divided by the Ramspol barrier (Figure 1.3), which is an inflatable dam of 240 meters wide. Under normal conditions, water flows in western direction from the Zwarte Meer onto the Ketelmeer. A severe storm on the IJsselmeer can increase the water level at the Ketelmeer, reversing the flow direction. The Ramspol barrier is built to prevent water flowing from the Ketelmeer onto the Zwarte Meer. It is filled with air when the following circumstances arise simultaneously [23]:

- A water level on the Ketelmeer of at least 0.5m +NAP;
- A strong wind from north-western direction;
- A net discharge from the Ketelmeer to the Zwarte Meer.

In a closed situation, the Ramspol barrier is ten meters high. It is part of dike trajectory 225, which protects the western and southern side of the Kampereiland. The sluice between the IJssel and the Ganzendiep is also part of this dike trajectory. Dike trajectory 225 has a total length of 9.4 kilometers and it has three functions [26]:

- Protecting the Vechtdelta;
- Protecting the Kampereiland;
- Reducing the hydraulic loads on Kampen when the Ramspol barrier is closed.

The crest height of this dike varies over the trajectory: the north to south oriented part, which is 2.5 kilometers long, has a lower crest height than the remaining west to east oriented part of the dike. This difference in crest height is made to fulfil its third function: during an extreme storm, the Ramspol barrier closes and water can either flow onto the IJssel in the direction of Kampen, or can flow over this lower part into the Kampereiland. The Roggebotsluis prevents the water from flowing in the direction of the Reevediep and the Drontermeer. When water flows over a dike crest, its strength reduces which can lead to a complete dike failure. To prevent a breach occurring in the overflow resistant part, it has been strengthened so no breach occurs when water flows over [26].

The Kampereiland is protected by dike trajectory 225 to prevent it from flooding, but it should also reduce the hydraulic loads on Kampen. In order to do so, water has to flow onto the Kampereiland instead of in the direction of Kampen. This means that the Kampereiland functions as a retention area and is supposed to inundate during specific circumstances, which leads to a rather ambiguous situation [26]. This retention area is surrounded by other dikes in the north and the east. The dike in the northern part of the Kampereiland separates the area from the Zwarte Meer. In the east, the city IJsselmuiden is located. This city is protected by another dike trajectory: The Kamperzeedijk or trajectory 10-2. The earlier mentioned Ganzendiep is a small branch between the dike in the east of the Kampereiland and the Kamperzeedijk. It is separated from the IJssel with the Ganzensluis and has an open connection with the Zwarte Meer.

Kampen is a city in the delta next to the IJssel and is protected from the IJssel by dike trajectory 11-2. Besides the protection by this dike trajectory, inhabitants of Kampen own small temporary walls, which can be set up in front of their houses in times of threatening high water levels. These walls are 30 centimeters high and act as an additional and movable flood defence [26].

The probability of flooding in this delta is determined by two factors: the characteristics of a storm at the IJsselmeer and the characteristics of the rivers [26]. During a storm on the IJsselmeer in combination with a strong north-western wind, water is blown from the IJsselmeer in the direction of the delta onto the IJssel. This leads to an increase of the water level and to an increased probability of flooding. The other situation resulting in an increased water level is when the rivers have to discharge extreme amounts of water into the IJsselmeer. These different kinds of hydraulic loads in the delta have their own contribution to the total probability of a flooding. The proportion of this contribution differs per location. As a result, some areas are more likely to flood due to a storm situation and other areas due to increased discharge. Consequently, in some areas the probability of flooding is dominated by the characteristics of the storm on the IJsselmeer, while other areas are dominated by the discharge on the IJssel. These specific areas are called the wind dominated area and the discharge dominated area. This does not mean that a wind dominated area cannot flood due to an event with an increased discharge. It means that if it experiences a flooding, it is more likely that this is caused by a storm. Since there is no discrete border between these two areas, a transition area exists in between. The division in contribution to the failure probability and the influence of different hydraulic loads make this delta complex in terms of flood protection. This is further explained in Section 1.2.

A complete overview of all cities, water bodies and dike trajectories can be found in Appendix A.

1.2. Program IJsseldelta

Whether the probability of flooding for a certain area is dominated by either wind or discharge has changed over time. This is the result of changes in the delta, performed within the Program IJsseldelta. This program was initiated as part of the national project Room for the River to protect the hinterlands from river floodings [19].

The Program IJsseldelta focused on the Vecht- and IJsseldelta and aimed to reduce the hydraulic loads by lowering the water levels [11]. Several measures were taken to achieve this goal. During the first phase of this program, the depth of the IJssel has been increased along a section of 7.5 kilometers to increase its discharge capacity. Another important step in this first phase was the introduction of the aforementioned Reevediep. The Reevediep is a branch between the IJssel and the Drontermeer and is only used when the discharges on the IJssel are high. This branch makes it easier to discharge the excess water from the IJssel through the Ketelmeer onto the IJsselmeer, reducing the amount of water flowing along Kampen. Because of this inter-

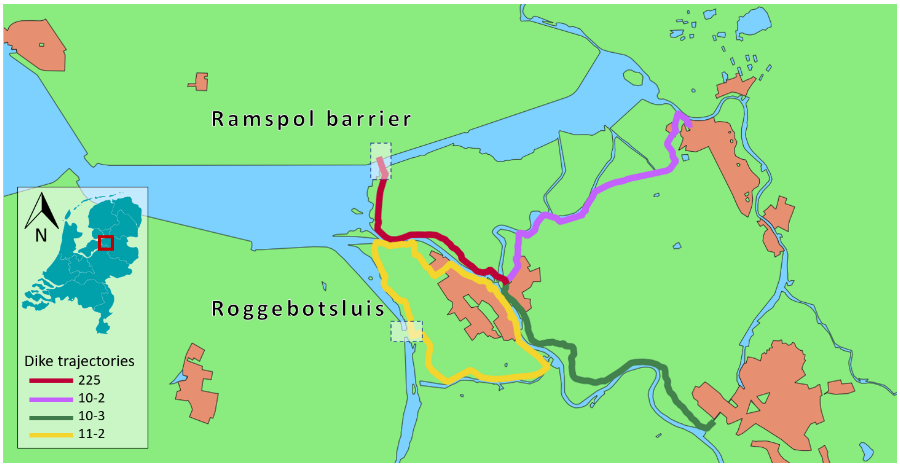
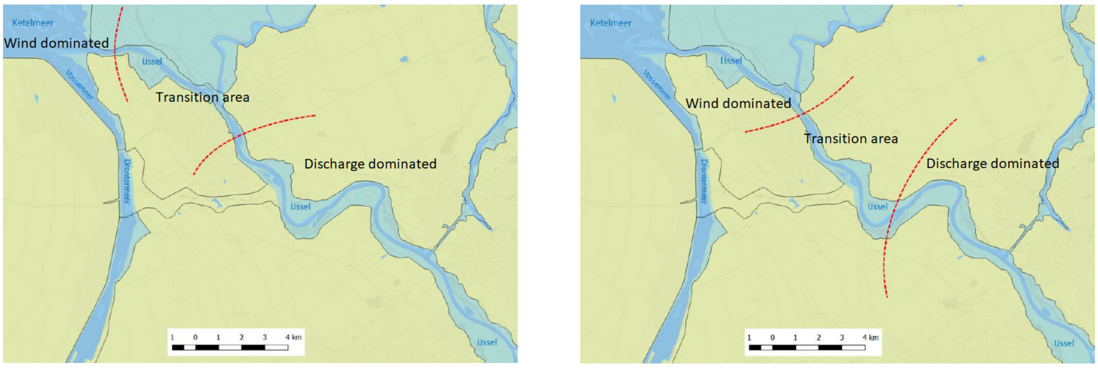


Figure 1.3: Relevant dike trajectories and the Ramspol barrier in the delta.

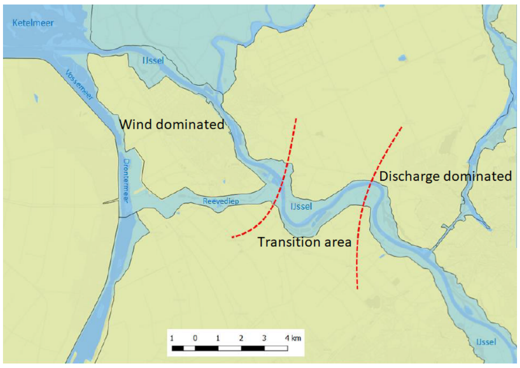
vention, the probability of flooding as a result of high discharge is reduced. The opposite effect of this newly created branch is that water can travel further into the delta during a north-western storm on the IJsselmeer. As a result, the area in which the probability of flooding is dominated by storm is extended in eastern direction [25]. This is visualized in Figures 1.4a and 1.4b [25].

The first phase of Program IJsseldelta was finished in 2019. In the second phase of this program, more measures will be taken to reduce the water levels in the delta. Expected is that, due to these additional measures, the boundaries in the delta are extended even more in eastern direction [25]. The expected boundaries are shown in Figure 1.4c.



(a) The situation before the initiation of Program IJsseldelta, according to the insights in 2006 (HR2006).

(b) After increased depth of the IJssel and before the Reevediep. This overview has been made according to new insights from 2018.



(c) The expected boundaries as a result of the full Program IJsseldelta according to the 2018 regulations.

Figure 1.4: The location of the boundaries in the IJsseldelta for three situations: Before the Program IJsseldelta, after the increased depth of the IJssel, and after the completion of the Program IJsseldelta. Figures obtained from [25].

1.3. Regulations

The Program IJsseldelta is part of the project Room for the River. This project started in 2006 and was created using the Hydraulische Randvoorwaarden (HR2006) as a guideline, which described the regulations in that time. Program IJsseldelta started in 2015 and is not finished yet. Since 2006, much has changed in safety against flooding. During the Room for the River project, the previously mentioned physical measures were taken, but in the same period also some models and methods to assess safety against flooding have been changed [25].

These new models and methods are written down in the Wettelijk Beoordelingsinstrumentarium 2017 (WBI2017). This document consists of three parts: it contains guidelines describing the procedure of assessing dike trajectories, methods to derive hydraulic loads and computation guidelines [36]. Until 2016, a flood defence was assumed to be safe when it was able to retain a certain water level and wave action (hydraulic load). This guideline only focused on the load acting on the flood defence and did not take the strength of a flood defence into account explicitly. Since 2017, flood defences are evaluated on their probability of failure instead of the probability of the load exceeding a certain value. Within these new guidelines, the opportunity has been taken to improve dealing with uncertainties in the assessment of primary flood defences. The concepts of failure probability and uncertainty are explained in Chapter 3.

To summarize: the hydraulic conditions have changed in the delta as a result of the Program IJsseldelta, and the changed regulations have altered the way these conditions are interpreted. This could lead to a situation in which the hydraulic loads rise, but the level of safety, according to the new regulations, remains the same [26]. The effect of these two changes is discussed in Chapter 3.

2
Problem statement

This chapter describes the motivation of this research. It starts with a short introduction, whereafter Section 2.2 describes the research objective. Furthermore, the method description can be found in Section 2.3 and a list of assumptions made regarding this research can be found in Section 2.4. This chapter ends with the thesis outline in Section 2.5.

2.1. Introduction

The Program IJsseldelta was intended to reduce the water levels at locations upstream of the Reevediep entrance during the occurrence of high discharges at the IJssel. This is also supported by calculations made in [25]: in situations with a high discharge on the IJssel, the program achieves a reduction of the water levels. However, by making the Reevediep accessible for excess water, not only high discharges find their way to the Ketelmeer more easily, but storms at the IJsselmeer are able to intrude further into the delta. As a consequence, failure probabilities can increase at locations where the failure probabilities is dominated by storm events [25].

The western part of trajectory 225 is designed to resist the overflow of water and is meant to overflow during a storm of a certain strength. Other parts of this dike are not meant to overflow and therefore have a higher crest height. During a storm situation, the Ramspol barrier closes and water can only flow in the direction of Kampen or into the Kampereiland. When the lower part of trajectory 225 overflows, the Kampereiland inundates and less water flows in the direction of Kampen. According to [26], it is not clear in which situations water starts flowing into the Kampereiland, but it is expected that it happens less frequently than it is supposed to. This uncertainty may lead to a situation in which Kampen is flooded before the Kampereiland is inundated. Another uncertainty is whether inundating the Kampereiland has the desired effect on the water level at Kampen.

Despite the Kampereiland being assigned as a retention area, the inundation of the Kampereiland is not without consequences. When the Kampereiland is completely inundated, water is expected to flow into the Ganzendiep, increasing the water levels at the Kamperzeedijk.

To summarize, an overview of complexities and possible shortcomings is listed [25]:

- During a storm situation, the Ramspol barrier is closed to protect the Vechtdelta, but this increases the hydraulic loads on Kampen, as water can only flow in that direction;
- According to new insights, the crest height of the north-south oriented part of trajectory 225 does not allow water to overflow in the intended situation, but less frequent;
- During a situation in which trajectory 225 overflows as it is intended to do, it is unclear whether the Kampereiland is capable of retaining enough water to significantly lower the hydraulic loads on Kampen;
- The consequences of an inundated Kampereiland for water levels in front of the Kamperzeedijk are uncertain.

2.2. Research objective

The main objective of this research is to solve these complexities by quantifying the consequences of the crest height of the overflow resistant part of trajectory 225 for the water levels at Kampen and at the Kamperzeedijk. To find the answer on the proposed problem, the following questions are answered. The main research question is:

How does the crest height of the overflow resistant part of trajectory 225 influence the water levels at Kampen and at the Kamperzeedijk during a storm at the IJsselmeer?

The answer on this main question is built on several sub-questions:

1. **How does the current system function from a physical point of view?**
   Goal: Getting a better understanding of how the system works and to determine whether Kampen is more vulnerable to a storm on the IJsselmeer. Therefore it is important to gain insight in the return periods of important parameters (discharge, wind speed). Next, the hydraulic loads and crest heights in the area are quantified and sketches of possible inundation scenarios are made.

2. **What is the exact role of trajectory 225 and the Kampereiland in the dike system?**
   Goal: Determining to what extent the Kampereiland is capable of reducing the hydraulic loads at Kampen. To answer this question, it is important to know with which objective trajectory 225 has been designed. A hydraulic model is created to reproduce the water levels based on known physical parameters.

3. **What are the consequences of an inundated Kampereiland for the Kamperzeedijk?**
   Goal: The prevailing water levels in front of the Kamperzeedijk are observed, to check what the impact of several crest heights is on the Kamperzeedijk.

2.3. Method

To answer this research question, a python model is created which derives the water levels at three locations: in front of trajectory 225, the Kamperzeedijk and Kampen. The derivation of the water levels is done by inter- and extrapolating between computed water levels from existing WAQUA computations. WAQUA is a computational model and is used to simulate water levels and water movements in two dimensions [35]. It uses discrete input parameters and computes the resulting water level. The input parameters are:

- Wind direction;
- Wind speed;
- Discharge at the IJssel;
- Lake level at the IJsselmeer;
- Closing situation of the Ramspol barrier.

In the ideal situation, the overflow resistant part of trajectory 225 is able to reduce the water level at Kampen during a storm situation, without critically increasing the water level at the Kamperzeedijk. To determine the best crest height for trajectory 225, the water levels at three locations are computed and compared for various crest heights: In front of trajectory 225, at Kampen and at the Kamperzeedijk. Eventually, the effect of the crest height of trajectory 225 on the water level at Kampen and at the Kamperzeedijk is described and an optimal height is defined.

The requirements of the model are:

- It has to quantify the water levels at Kampen and in front of the Kamperzeedijk;
- It should take the effect of an inundated Kampereiland on the water levels into account;
- It has to take all relevant uncertainties into account.

To achieve these requirements, a method framework is worked out, consisting of the following components:

1. **Data input**
   The data input for this research consists of various determined heights for the overflow resistant part of trajectory 225, along with a number of stochastic variables. The current crest height of the overflow resistant part is 2.8m +NAP and several lower and higher heights are evaluated to quantify the effect on the water levels. The stochastic variables are used to simulate a probabilistic scenario, consisting of a wind speed, wind direction, a discharge of the IJssel and a lake level on the IJsselmeer.
2. **Computations**
   The computational part consists of three parts: the hydrodynamic part, the processing of data and the probabilistic part. The next paragraph comprises a more extensive elaboration upon these parts.
3. **Output**
   The results of the probabilistic calculations form the output and consists of water level exceedance frequencies. The output is dependent on the crest height of the overflow resistant part of trajectory 225 and the location. Eighteen unique outputs are generated, as three locations and six crest heights are observed.
4. **Visualization**
   A water level exceedance frequency line is generated for every unique combination of crest height and location.

The method framework is visualized in Figure 2.1. The hydrodynamic and probabilistic method are further explained in the following paragraphs.

2.3.1. Hydrodynamic modelling

The water levels for various locations are obtained from detailed WAQUA computations. These WAQUA computations consist of discrete input parameters. However, a storm develops from a mild wind speed to its maximum wind speed in continuous steps. In the hydrodynamic part, this continuous relationship is created by linear interpolation over the discrete input parameters. For every obtained water level in front of trajectory 225, the discharge over the dike has to be calculated. This discharge rate leads to the water level inside the Kampereiland.

As a storm is observed, the main wind direction of interest are those around the WNW direction. This area is defined as the range of 45° on both sides of the WNW direction, see Figure 2.2 [39]. This range is chosen by comparing the maximum resulting water levels for different wind directions. The maximum water levels for wind directions outside this range are mostly lower than the crest height of trajectory 225. However, some computed water levels exceed the crest height, but these water levels only lead to a small volume flowing into the Kampereiland. Decided is to take the described range of wind directions into account, as the inclusion of more wind directions leads to a higher computation time.

2.3.2. Probabilistic approach

With WAQUA it is possible to compute a water level based on several input parameters, but it does not indicate how frequent this water level occurs. To place the hydrodynamic results into perspective, a probabilistic analysis is performed. The current WAQUA computations have been processed by a probabilistic model which is called HydraNL. This model calculates the statistics of hydraulic loads, such as water levels and wave characteristics, and is used to assess flood defences in the Netherlands [10]. These probabilistic calculations have given insight in how often a certain water level is observed.

Using WAQUA, water levels have been computed for a discrete set of input parameters. These water levels are linked to their probability of occurrence, which are calculated using HydraNL. To quantify the influence of different crest heights of the overflow resistant part of trajectory 225, a new hydraulic model is created. Using this newly adapted hydraulic model, water levels are computed for the same discrete set of input parameters and these results are linked to a probability using HydraNL. The outcomes of these calculations are

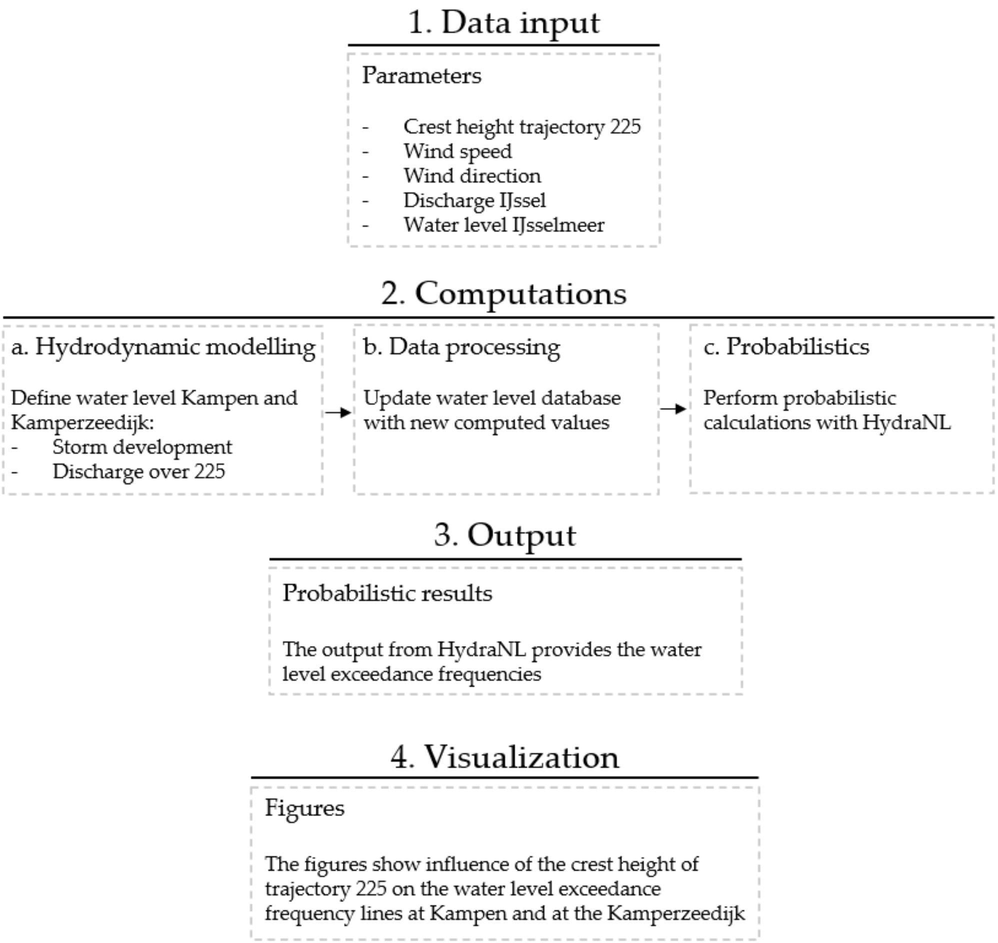


Figure 2.1: Schematic overview of the method framework.

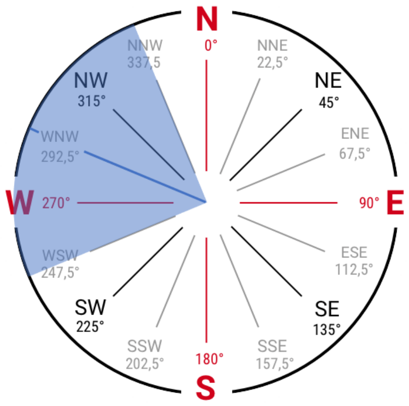


Figure 2.2: Wind directions used for modelling indicated by the blue are in the wind rose. This is an area of 90° with its center at WNW direction. Figure obtained from [39].

used to generate a water level frequency line for various crest heights of the overflow resistant part of trajectory 225. This line shows the water level against its corresponding return period. Every crest height leads to a new water level frequency line, which makes it possible to compare the effect of various crest heights. Based on this comparison, the optimal crest height of the overflow resistant part of trajectory 225 is determined.

2.4. Assumptions

Various assumptions have been made to perform this research. These assumptions are described in this section.

Hydraulic loads

The situation in the delta is very complex due to the different kinds of hydraulic loads. A simplified situation is observed to answer the research question. This research focuses on the situation with a storm on the IJsselmeer and does not evaluate the probability of flooding as a result of increased discharge from the IJssel. This means that the only consequences for the Kamperzeedijk result from a storm.

Failure mechanisms

In the real world situation, dikes can fail as a result of many different failure mechanisms. A full probabilistic analysis requires that dikes are assessed for all possible failure mechanisms, but this lies outside the scope of this research as no dike assessment is performed. Therefore, assumed is that dikes do not breach and that overflow is the the only failure mechanism. This also means that the wave height is not incorporated in the model. The contribution of wind waves to the discharge over a dike is expected to be low compared to the contribution of overflow. However, overtopping waves can have a significant contribution to the probability of other failure mechanisms. Since overflow is the only mechanism which is taken into account, the impact of wind waves is less relevant for the situation.

Water level Kampen

When the water level at the Ketelmeer exceeds the crest height of trajectory 225, water can flow either in the direction of Kampen or it can flow into the Kampereiland. The overflow resistant part of trajectory 225 has a length of 2,500 meters and the IJssel entrance is 200 meters wide. Because of this large difference, assumed is that all the water flows into the Kampereiland when the water level exceeds this crest height and that the water level at Kampen remains the same.

Crest height Kamperzeedijk

In the WAQUA computations for the Kamperzeedijk is assumed that the crest height is infinitely high and that no water flows over the crest. As a result, unrealistic water levels can be found at this location.

Correlation discharge IJssel and Vecht

The information regarding the correlation between the discharge of the IJssel and the Vecht was mainly obtained from [9]. This report describes the hydraulic boundary conditions of the Vecht- and IJsseldelta, containing statistics of the lake level at the IJsselmeer and the discharges of the rivers.

The data for the model input are obtained from WAQUA calculations. Within WAQUA, the situation at Kampen and at trajectory 225 is dependent on the discharge of the IJssel. However, the water level at the Kamperzeedijk is dependent on the discharge of the Vecht. It is assumed that these discharges are correlated and that the maximum discharge on the IJssel coincides with the maximum discharge on the Vecht. [9] describes that locations along the IJssel are barely affected by the magnitude of the discharge of the Vecht and two explanations are given. The magnitude of the discharge of the Vecht is small compared to the discharge of the IJssel. Furthermore, the Ketelmeer forms the only connection between these two rivers. The Ketelmeer is downstream of the IJssel and therefore changes in the relatively small discharge of the Vecht lead to marginal water level fluctuations along the IJssel.

This does not hold for locations along the Vecht, according to [9], as the discharge of the IJssel is relatively large to the discharge of the Vecht. It states that high discharges on the IJssel will affect the water levels near the Ramspol barrier. Eventually, [9] concludes that the presented relation between the discharges is justified for the purpose of the WAQUA computations.

2.5. Thesis outline

At the end of this research, a model is delivered to compute the water levels at various locations in the delta, based on the input of stochastic physical parameters. The results show the effect of the crest height of the overflow resistant part of trajectory 225 on the water levels at Kampen and at the Kamperzeedijk.

- **Chapter 1 – Introduction**
  An overview of the area of interest is given, indicating the relevant cities, water bodies and dike trajectories.

- **Chapter 2 – Problem statement**
  This chapter describes the motivation for this research. The actual problem is summarized, together with the research questions and method. Furthermore, the limitations and assumptions are listed.

- **Chapter 3 – Literature review**
  An introduction to some basic principles is given and important definitions used in this research are explained. Furthermore, a brief summary of previously performed research is given.

- **Chapter 4 – Current system**
  To gain insight in how the current system in the Vecht- and IJsseldelta behaves from a physical and probabilistic point of view, an extensive description of the area in terms of statistical parameters is given. Parameters influencing the water levels are described based on their return periods. This is compared with the crest heights of important dike trajectories.

- **Chapter 5 – Model set-up**
  The exact lay-out and the validation of the model are described in this chapter. The processes of hydrodynamic modelling and performing the probabilistic calculations are elaborated upon.

- **Chapter 6 – Results**
  The outcomes of the model are presented and described. There is not yet evaluated what these results mean as this is left out for the conclusion.

- **Chapter 7 – Discussion**
  The possible influence of the assumptions and limitations on the model results are discussed.

- **Chapter 8 – Conclusion**
  The conclusions are formed by the interpretation of the results and by answering the research questions.

3

Literature review

In Section 3.1 the necessary principles are explained to help understand this research. Research has already been performed regarding the situation in the delta. The relevant outcomes and recommendations are described in Section 3.2.

3.1. Terminology

In this section, the concepts are introduced which are of importance to this research.

Flood defences

Flood defences are created to protect the country from the sea, lakes and rivers. [27] describes a number of flood defences:

- A **dike** is a water retaining structure made of soil;
- A **dam** divides two water bodies;
- A **dune** is a sandy structure along the coast, which is usually formed by natural processes;
- A **storm surge barrier** is a partly movable flood defence in a river or an estuary;
- A **hydraulic structure** is a structure which can be part of a flood protection system. They can have additional functions besides flood defence.

In the Netherlands it is common to distinguish flood defences based on two criteria:

- Primary and secondary flood defences;
- Front and rear flood defences.

These two criteria require further explanation. Primary flood defences directly or indirectly protect a low-lying area from flooding from large water bodies of which the water levels cannot be controlled, such as the sea or rivers [27]. There are three types of primary defences, shown in Figure 3.1. The first type directly protects the area from flooding. The second type connects two dike rings and has water on both sides. The main goal of this type is to prevent high water in the water bodies behind the defence. The third and last type is not directly in touch with water, but has a function when other sections fail. In addition to these primary defences, there are secondary flood defences, which are situated along canals and other regional waterways [27]. These do not protect areas from large water bodies, but from small water bodies such as canals.

The second distinction regarding categorizing flood defences is the difference between front and rear defences. A front defence stands in direct contact with a water body and constantly retains the water (type A and B in Figure 3.1 [6]). It is possible that behind this front defence, another dike trajectory is present, which is not in direct contact with the water body. This secondary defence only fulfills a water retaining function in case of failure of the front defence (type C in Figure 3.1 [6]).

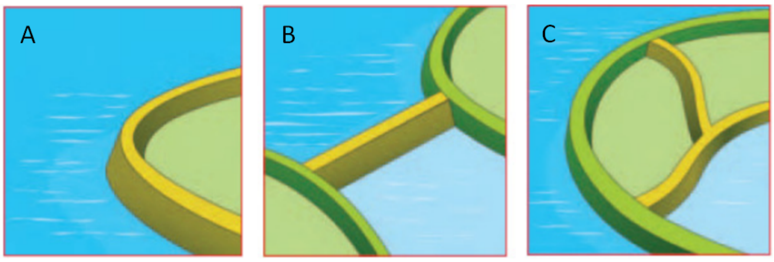


Figure 3.1: Types of primary flood defences. Figure obtained from [6].
A) Directly retaining high water; B) Connecting two dike rings; C) Not directly retaining high water

Failure mechanisms
A flooding occurs when an uncontrollable amount of water from a lake, river or sea flows onto the land. A possible cause of flooding is the failure of a flood defence. Subsequently, there are several ways for a flood defence to fail, called failure mechanisms. Before these mechanisms are discussed, it is important to define what failure actually is:

"A flood defence fails when it loses its water retaining function" [27]

In Figure 3.2 several failure mechanisms are shown [32]. Each of these mechanisms can cause a flood defence to fail. Every mechanism has a certain probability of occurring. Some of the probabilities are harder to define than others. It is clear that when the water level exceeds the height of the dike, this dike will overflow (mechanism A in Figure 3.2). On the other hand, piping (mechanism G) is for example dependent on the soil characteristics which can differ along the dike, since the soil is not completely homogeneous.

Dike systems can be multiple kilometers long and there only has to be one weak spot for a complete dike trajectory to fail. To asses a dike trajectory for its safety, it is divided in multiple dike sections (denoted as elements in Figure 3.3 [27]). Each section fails when one of the failure mechanisms occurs. This means that the total failure probability of a section is equal to the probability of either one of these mechanisms occurring. Subsequently, failure of the dike trajectory is equal to the probability that one or multiple dike sections fail.

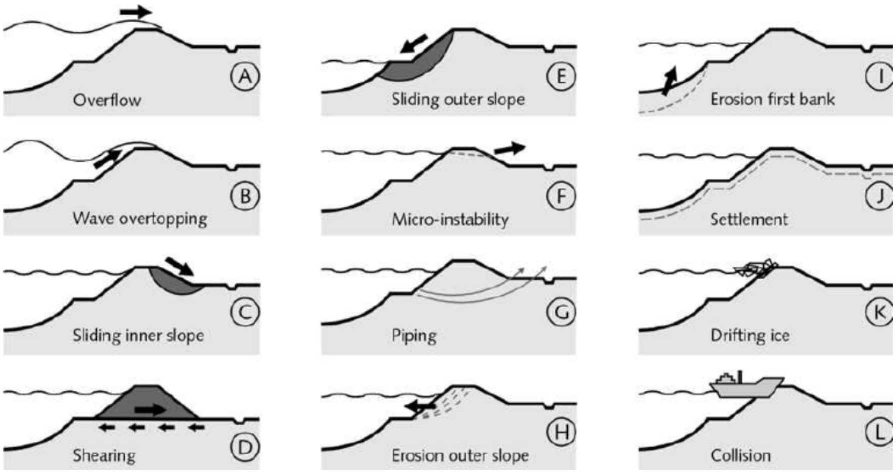


Figure 3.2: Schematic overview of the most relevant failure mechanisms of flood defences. Figure obtained from [32].

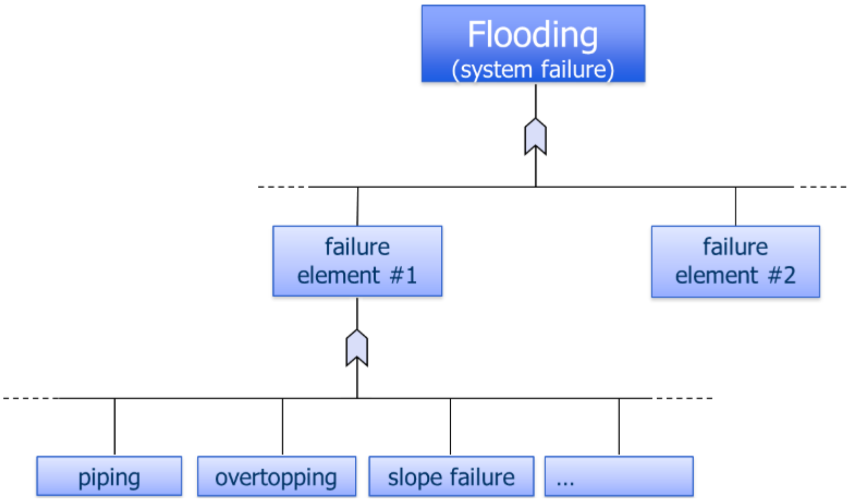


Figure 3.3: Schematic fault tree for a flood defence system. In the lowest layer the different failure mechanisms are shown. The occurrence of one or multiple of these mechanisms cause an element to fail, and one or more failed elements cause the complete system to fail. Figure obtained from [27].

Flood risk

The water safety policy in the Netherlands aims to reduce the flood risk to an acceptable level. Depending on the area, a flood event has consequences for human health, the environment and economical activities. The term risk is defined as:

> *"Risk is the probability of an undesired event multiplied by the consequences"* [13]

The same amount of risk can therefore consist of a high probability combined with a small consequence or a small chance combined with a high consequence [18]. The unit of risk is dependent on the units of the probability and the consequences. Probability is usually defined as a probability per unit time (for example: probability per year), while the consequences can be expressed in various different units, such as ecological damages and fatalities. However, in engineering practices, they are often expressed as a monetary value. The unit of risk then becomes [€ / year] [13]. The expected damages are described by the following formula:

$$E(d) = \sum_{i=1}^{n} P_i \cdot d_i \tag{3.1}$$

with:

E(d) = Expected damages [€/year];
P_i = Probability of scenario i [1/year];
d_i = Damages of scenario i [€].

The expected damages do not indicate the actual probability or damage per scenario. It is possible that there are multiple events with low damages, or there can be a single event with a large damage as result. To gain more insight in these values, a risk curve is often used. This curve shows the probability of a certain magnitude of consequences. In Figure 3.4 a FN-curve is shown, which visualizes the risk curve. It relates the number of fatalities (N) to the probability. Another widely used risk curve is the FD-curve, which shows the exceedance probability of a certain damage [27].

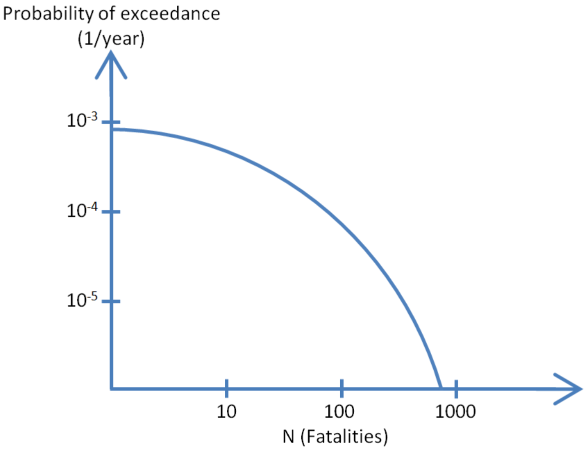


Figure 3.4: The FN-curve relates the number of fatalities to the probability with a logarithmic scale on both the x-axis and the y-axis.

Flood risk is defined as a set of flood scenarios, with each scenario having its own probability and consequence. Different kinds of risks are used to quantify risk. Usually, the following types are distinguished: economical risk, individual risk and societal risk. These three types are described in the following paragraphs.

First of all, economical risk is the way of quantifying flood risk scenarios as the expected economical damages and is defined by the combination of failure probability and the damages caused by an eventual flooding. Formula 3.1 can be used for this quantification. When assessing all possible consequences with their corresponding probabilities, this formula leads to the expected annual damages. This value is equal to the area under the FD-curve. This FD-curve is similar to the FN-curve (Figure 3.4) [7].

Economic risk deals with expected annual damages as monetary value. However, when an area is flooded, there is danger for loss of life as well. This can be quantified in individual risk and societal risk. The individual risk describes the probability of the death of one individual person at a certain location due to an accident, taking into account the possibilities for evacuation [7]. This risk is quantified by Formula 3.2. In the Netherlands, the acceptable risk of a fatality as result of a flooding is set to 1/100,000 per year [18].

$$IR(x,y) = \sum_{i}^{n} P_i F_{D,i}(x,y)\left(1 - F_{E,i}\right) \tag{3.2}$$

with:

$IR(x,y)$ = Individual risk at location (x,y);
P_i = Probability of scenario i [1/year];
$F_{D,i}(x,y)$ = Mortality at location (x,y) for scenario i;
$F_{E,i}$ = Evacuation fraction for scenario i.

Lastly, societal risk describes the probability of a disaster with multiple fatalities. This is usually visualized with a FN-curve, since this gives insight in the probability of exceedance of events with certain numbers of fatalities. The individual risk is independent on the amount of people living in a certain area, but societal risk does take this into account. There are guidelines to determine whether the risk is acceptable using a limit line:

$$1 - F_N(n) \le C/n^{\alpha} \tag{3.3}$$

with:

C = Constant that determines the vertical position of the limit line;
α = Coefficient that determines the steepness of the limit line.

If the FN-curve exceeds the limit line, the situation is not acceptable. For a higher value of α, the limit line is steeper. This means that for an event with ten times more fatalities, the probability is hundred times smaller. This is called *risk averse*, since people have aversion to large number of fatalities.

Failure probability and return period

A flood defence fails when it loses its water retaining function. Every failure mechanism has a certain strength (also called: resistance) and the water exerts a certain load on the flood defence. For the failure mechanism overflow (type A in Figure 3.2), the height of the flood defence is the resistance parameter and the water level is the load parameter. When the load exceeds the resistance (the water level is higher than the height of the flood defence), failure occurs. This can be expressed in the so-called limit state function:

$$Z = R–S \tag{3.4}$$

With R denoting the resistance and S the load. When S > R, the limit state function reaches a negative value, which implies failure. The probability of failure is computed as following:

$$P_f = P(Z < 0) = \int_0^\infty f_H(h) \cdot F_R(h) dh \tag{3.5}$$

with:

P_f = Failure probability;
$f_H(h)$ = Probability density function;
$F_R(h)$ = Cumulative distribution of resistance given a certain hydraulic load level.

The failure probability P_f is usually expressed in a probability per unit time. A specific dike section could for example be allowed to fail with a probability of 1/1,000 per year. This means that every year, there is a chance of 0.1% that this section fails.

A failure probability of 1/1,000 per year does not mean that a certain event only happens once in a thousand years or that it takes a thousand years before it happens again. It means that on average, a certain event happens once every thousand years. There is also a probability that this event happens in two consecutive years. To calculate the probability of a failure in *n* years, the following formula is used:

$$P_n = 1 - ((1 - P_f)^n) \tag{3.6}$$

with:

P_n = Probability of failure in *n* years;
P_f = Failure probability per year;
n = Period.

If a flood defence has a failure probability of 1/1,000, the probability it will flood in 1,000 years is, according to Formula 3.6, equal to:

$$P_n = 1 - ((1 - P_f)^n)$$
$$P_{1000} = 1 - \left((1 - 1/1000)^{1000}\right)$$
$$P_{1000} = 0.632$$

This means that there is an actual probability of 63.2% that a flood defence with a safety standard of 1/1,000 fails in 1,000 years. This is also called the *return period.* The return period gives insight in how often a certain situation can happen. Load parameters, such as wind speed, water level or wave height, are often described by their return period. The return period is defined as:

$$\text{Return Period} = \frac{1}{P(X > x)} \tag{3.7}$$

Uncertainties

To assess the failure probabilities of dike sections, often numerical models are used. A model uses mathematical and numerical terms to create a simplified representation of the real world. As a result of this simplification, model outcomes are involved with errors and uncertainties. When performing a dike assessment according to the WBI2017, two uncertainties have to be taken into account:

- Statistical uncertainty
- Model uncertainty

Statistical uncertainty is related to estimations for large return periods when only limited data are available. In the Netherlands, roughly 100 years of measured data are available [20]. Based on these measured data, it is possible to determine which wind speed or discharge is most likely to have a return period of somewhere between 1 and 100 years. To compute the value of the wind speed which has a return period of for example 10,000 years, statistical models are used. The outcomes of these models cannot be verified as there are not enough data. This induces a statistical uncertainty [1].

Model uncertainty is associated to specific models and occurs due to the fact that models show a simplified physical representation. A representation is based on mathematical equations, probability distributions and deterministic parameters [12].

Safety standards

Every dike in the Netherlands has a certain safety standard which is dependent on the possible consequences. Until 2016, these safety standards were based on the probability of exceeding a certain load acting on the defences and the main failure mechanisms observed were overtopping and overflow. It denotes which hydraulic load a flood defence has to withstand. The hydraulic load represents the level of the dike which is, given the current circumstances, equal to the sum of the water level and wave overtopping height [8]. The height of the dike corresponding to a certain allowable overtopping rate, contributes to the hydraulic load of the dike section. According to new regulations, the method of assessing dikes has changed and the safety standards are now based on the actual failure probability. This is a different standard and indicates the probability for which a certain area is allowed to be flooded. The probability of every failure mechanism contributes to the overall probability of flooding. Therefore, the new safety standards represent a different observation than the old safety standards and cannot be compared.

A dike fails when at least one of the possible failure mechanisms occurs. This total probability is less than the sum of each individual failure probability, since many of them are correlated. The safety standard of a dike trajectory consists of the failure probability of each individual mechanism. Standard values for the failure probability contribution are written down in the Dutch dike assessment regulations, see Figure 3.5. For a dike trajectory with a safety standard of 1:1,000 (or failure probability of 10^{-3} per year), this means it should be resistant to overtopping and overflow characterized by a probability of $2.4 \cdot 10^{-4}$ (and a return period of 4167 years):

$$P_{\mathrm{req,i}} = \omega_{\mathrm{i}} \cdot P_{\mathrm{req}} \tag{3.8}$$

$$P_{\mathrm{req,i}} = 0.24 \cdot 10^{-3} = 2.4 \cdot 10^{-4} \tag{3.9}$$

with:

$P_{\mathrm{req,i}}$ = Required annual failure probability for failure mechanism i;

ω_{i} = Maximum contribution of failure mechanism i to the system failure probability (Figure 3.5);

P_{req} = Required annual failure probability for the dike trajectory.

The target failure probabilities for individual failure mechanisms in a dike trajectory with a safety standard of 1:1,000 are shown in Table 3.1.

To determine to required level of protection, there are two criteria for dikes: a safety standard and a signal value. In the Netherlands, both values are stated in the Dutch Law. These values are expressed in a allowable probability of failure per year. The safety standard declares the maximum allowable failure probability of the section. Since the failure probability can change over time, for example due to changing conditions or strength decay, a signal value is introduced to guarantee the dike meets this safety standard. The signal value is also expressed as a failure probability and has a more strict value. When the actual failure probability exceeds this signal value, this should be reported to the Dutch Ministry of Infrastructure and Environment. Passing this signal value means the start of improving the trajectory. Doing this, the actual failure probability can never become lower than the safety standard. This process can be seen in Figure 3.6 [38] [18] [25].

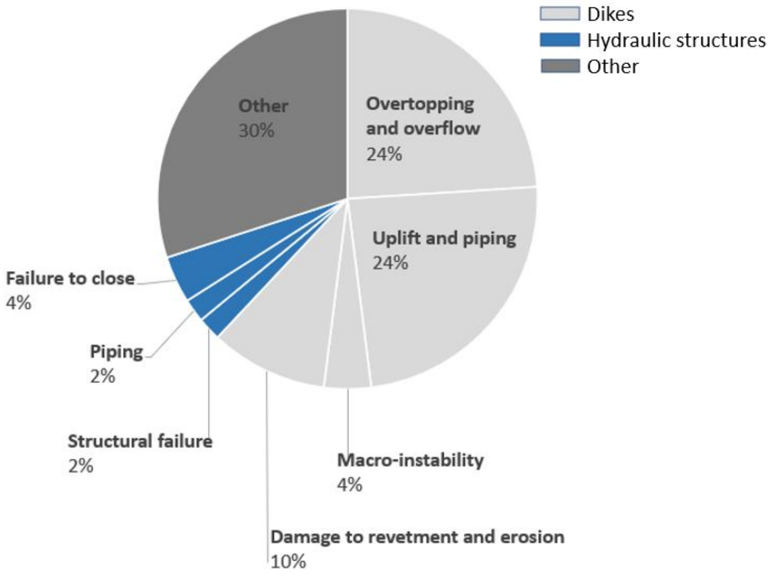


Figure 3.5: A failure probability budget to determine the required failure probability for every failure mechanism. Data obtained from [37].

Table 3.1: Acceptable failure probabilities for each failure mechanism contributing to a safety standard of 1:1,000. Contribution percentages obtained from [37].

Failure mechanism	**Contribution**	**Probability**[1]	**Return period**[2]
Overtopping and overflow	24%	0.00024	4,166.7
Uplift and piping	24%	0.00024	4,166.7
Macro-instability	4%	0.00004	25,000
Damage to revetment and erosion	10%	0.0001	10,000
Structural failure	2%	0.00002	50,000
Piping	2%	0.00002	50,000
Failure to close	4%	0.00004	25,000
Other	30%	0.0003	3,333.3
Total	100%	0.001	1,000

[1] Contribution · 1/1,000

[2] 1/P(f)

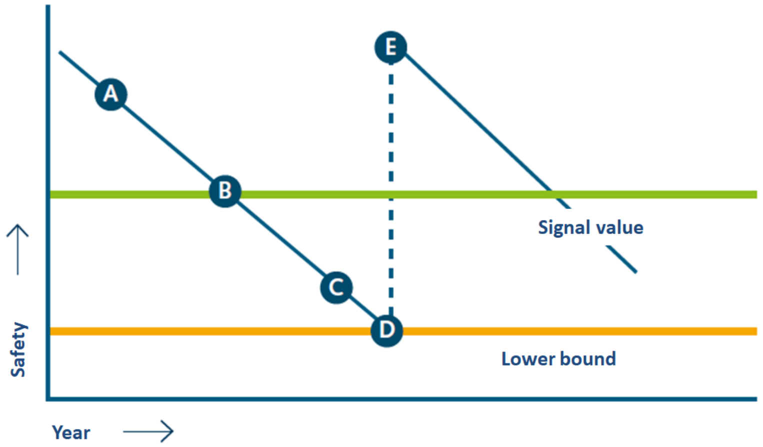


Figure 3.6: The process of reaching the signal value and the start of the improvement. Figure obtained from [18].
A. Safety reduces due to increasing loads or due to strength decay; *B.* Preparations start for improvement; *C.* Start improvement of flood defence; *D.* Lower bound is reached; *E.* Safety right after improvement.

Hydraulic load interdependencies
As discussed in the previous section, every dike in the Netherlands has a safety standard and signal value. These values are calculated by carrying out a flood risk analysis based on the possible hydraulic loads acting on the dike section. However, within these flood risk analyses, potential flood defence failures caused by an upstream failure are not assessed [14]. Load interdependence is the effect upstream flood defences can have on downstream flood defences and this can either be a positive or a negative effect. An example of both positive and negative interdependency is shown in Figure 3.7 [14]. Due to a dike breach upstream, the discharge in the left two branches is reduced with ΔQ and this also reduces the hydraulic loads and thus the failure probability of the downstream sections. This phenomena is called positive interdependency. For the branch flowing to the upside direction, the discharge increases with ΔQ. This is an example of negative interdependency.

Positive interdependency can also be achieved by means of a detention area. This area is able to store large amounts of water and prevents this water flowing downstream.

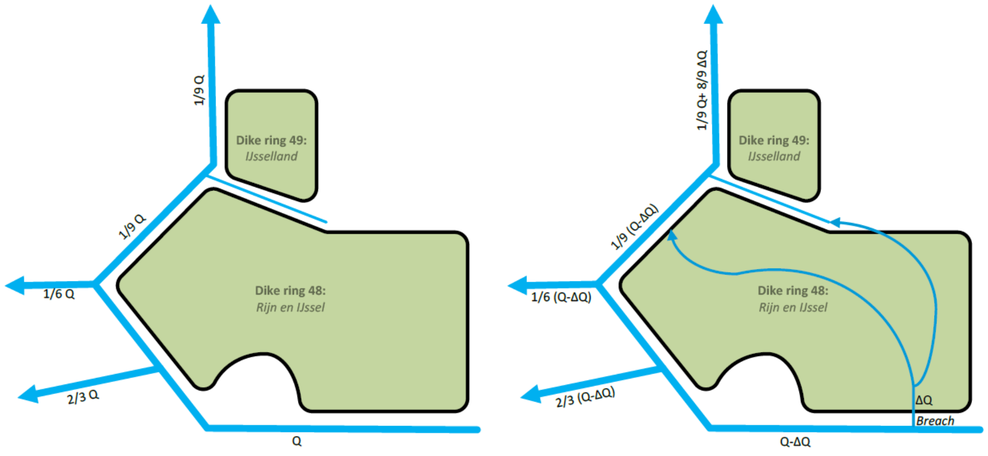


Figure 3.7: The effect of an upstream breach on the discharge through a channel and showing the hydraulic load interdependencies [14].

3.2. Previously performed research

The Reevediep has been constructed as part of the Program IJsseldelta. This program aims to reduce the hydraulic loads in the area downstream of the IJssel and upstream of the Reevediep. The effects of this program are discussed in [26]. These effects are subdivided in three parts:

- The quantification of safety against flooding;
- How often the movable flood defences at Kampen have to be used;
- The remaining lifetime of the flood defences.

The remaining lifetime indicates the time until a flood defence cannot resist external loads due to for example climate change (point D in Figure 3.6). In [26] is focused on the effect on the prevailing water levels and the influences of waves. Other failure mechanisms, such as piping and stability, are not evaluated.

Research shows that the hydraulic loads upstream of Kampen and IJsselmuiden are decreased as a result of the taken measures. Downstream of Kampen and IJsselmuiden the hydraulic loads are increased by a few centimeters. For the left riverside of the IJssel (dike trajectory 11-2), this increase of hydraulic loads does not result in a lower level of safety against flooding. From the analyses it follows that the right riverside (dike trajectory 225) possibly does not meet the lower bound.

One of the measures in Program IJsseldelta is the demolition of the Roggebotsluis. Currently, this sluice separates the Vossemeer from the Drontermeer and prevents water from flowing from the Ketelmeer onto the Reevediep during a storm situation on the IJsselmeer. This demolition creates an extra connection between the IJssel and the Ketelmeer [25].

As described in Chapter 1, the water levels in the delta are mainly influenced by the discharge of the IJssel and the wind speed and direction on the IJsselmeer. Depending on the location in the delta, the probability of flooding is either mainly determined by the discharge characteristics or by the storm characteristics. By making the Reevediep accessible, water from the IJssel is discharged more easily to the Ketelmeer, but water can also reach much further into the delta during a storm situation. The consequences of the Program IJsseldelta, including the demolition of the Roggebotsluis, are calculated with WAQUA.

In [26] is concluded that no safety issue arises due to the increased hydraulic loads. However, the remaining lifetime of the flood defences decreases. Moreover it turns out that, as a result of the Program IJsseldelta, the movable barriers in Kampen only have to be used once every thirteen years instead of once every eight years [26].

According to [25], the hydraulic loads are reduced along most parts of the IJssel. Small increases are found downstream of Kampen and IJsselmuiden, but these increases do not lead to a lower level of safety.

Ramspol barrier

The construction of the Ramspol barrier was finished in 2002 [23]. Before the start of the construction, an Environmental Impact Assessment (EIA) was made, evaluating the hydraulic boundary conditions [30]. The EIA describes that the water level at the Ketelmeer was expected to increase during a storm situation after the Ramspol barrier was completed. This could be prevented by reducing the crest height of trajectory to a height which should overflow with a probability of 1/500 per year instead of 1/2,000 per year.

The situation in which a storm surge barrier fails to close, is incorporated in the flood safety assessment. For the Ramspol barrier, this failure probability is set to 0.01 per closing situation [38]. In the case the crest height of trajectory 225 is set to the 1/2,000 standard, the failure of closing of the Ramspol barrier has large consequences for the water level at the Ketelmeer, according to [30]. In the case of an overflow resistant part of trajectory 225, the failure of closing of the Ramspol barrier has much less influence on the water level at the Ketelmeer. The water level at the Zwarte Meer is hardly affected by a failing Ramspol barrier [30].

In [30] is concluded that the height of trajectory 225 does not influence the safety against flooding at Zwolle, which is more upstream of the IJssel. This is a result of the governing situation at this location, which is described by a high discharge and a lower water level at the Ketelmeer. This lower water level at the Ketelmeer makes the crest height of trajectory 225 at the Ketelmeer irrelevant regarding the flood risk at Zwolle.

Trajectory 225 was designed to resist a 1/2,000 per year situation to reduce the hydraulic loads at the Zwarte Meer. In [30] is concluded that the effect of a higher crest height of trajectory 225 on the Zwarte Meer is negligible. Furthermore, higher crest heights would increase the water levels at the Ketelmeer. Also the effect of the crest height of trajectory 225 on the maximum inundation depth of the Kampereiland is investigated in [30]. When the maximum inundation depth is lower than 1.30m, the effect of waves on the southern part of trajectory 225 and on the Kamperzeedijk is heavily reduced. This maximum inundation depth increases for lower crest heights of trajectory 225, since more water can flows into the area. It becomes clear that both a higher and a lower crest height have positive and negative consequences for different areas. All consequences were considered in [30] and it was decided to make the overflow resistant part of trajectory 225 as it is now, to guarantee the same level of safety to all surrounding areas.

4

Current system

This chapter gives a more explicit description of the Vecht- and IJsseldelta in terms of statistics and probabilistics. In the first section, the characteristics of the governing wind speed, wind direction, discharge and water level at the IJsselmeer are given. These parameters are used within pre-existing WAQUA computations to compute the water levels in the delta. Section 4.2 provides a sensitivity analysis on the important parameters. Furthermore, the safety standards of the relevant dike trajectories and the development of a storm situation are described are described in Section 4.3 and 4.4, respectively. This chapter ends with a conclusion, found in Section 4.5.

4.1. Important parameters

The water levels at different locations inside the delta are dependent on multiple variables. As described in Chapter 1, the probability of a flood event occurring is mainly determined by either storm characteristics or by discharge characteristics. The proportion of the influence of the discharge increases as the location is further upstream. A certain scenario leads to a water level at a given location in the delta. These scenarios are described by the following parameters:

- Wind speed;
- Wind direction;
- Water level IJsselmeer;
- Discharge IJssel;
- Closing situation Ramspolbarrier.

First of all, wind causes two different effects in the hydraulic system. The first effect is the wind induced water level set-up. This water level rise is the result of the shear stress between the wind and the water surface, which makes the surface tilt into the wind direction. The second effect caused by wind is that wind waves are formed. Both effects are proportional to the wind speed. The unit of wind speed is meters per second and it is often categorized in the Beaufort wind scale in Table 4.1 [24].

A high wind speed by itself does not necessarily result in a high water level in the delta. This only happens when the wind is blowing from specific directions. As described in Chapter 1, the Ramspol barrier closes when a strong wind blows from a WNW direction to prevent large amounts of water ending up in the Zwarte Meer. An opposite wind direction can lead to large amounts of water being blown out of the delta and can result in lower water levels. Therefore, the magnitude of a storm and its possible danger is also dependent on the wind direction. Furthermore, waves have a much higher possible impact when approaching dikes from a perpendicular direction. This means that the wind direction has substantial consequences for the possible wave impact on the dikes.

The water level at the Ketelmeer is dependent on the water level at the IJsselmeer because of the wide opening in between. Under normal circumstances, water from the IJsselmeer is discharged through the Afsluitdijk in the Waddenzee. When the water level outside the Afsluitdijk is higher than at the IJsselmeer, the discharge is not possible. When a strong wind is blowing from north-western direction, a wind induced water level set-up causes a rise of the water level outside the Afsluitdijk and a water level reduction at the IJsselmeer at the location of the Afsluitdijk. The water level at the IJsselmeer is also affected by the discharges of the IJssel and the Vecht.

Table 4.1: Wind speed intervals according to Beaufort scale. Table reproduced from [24].

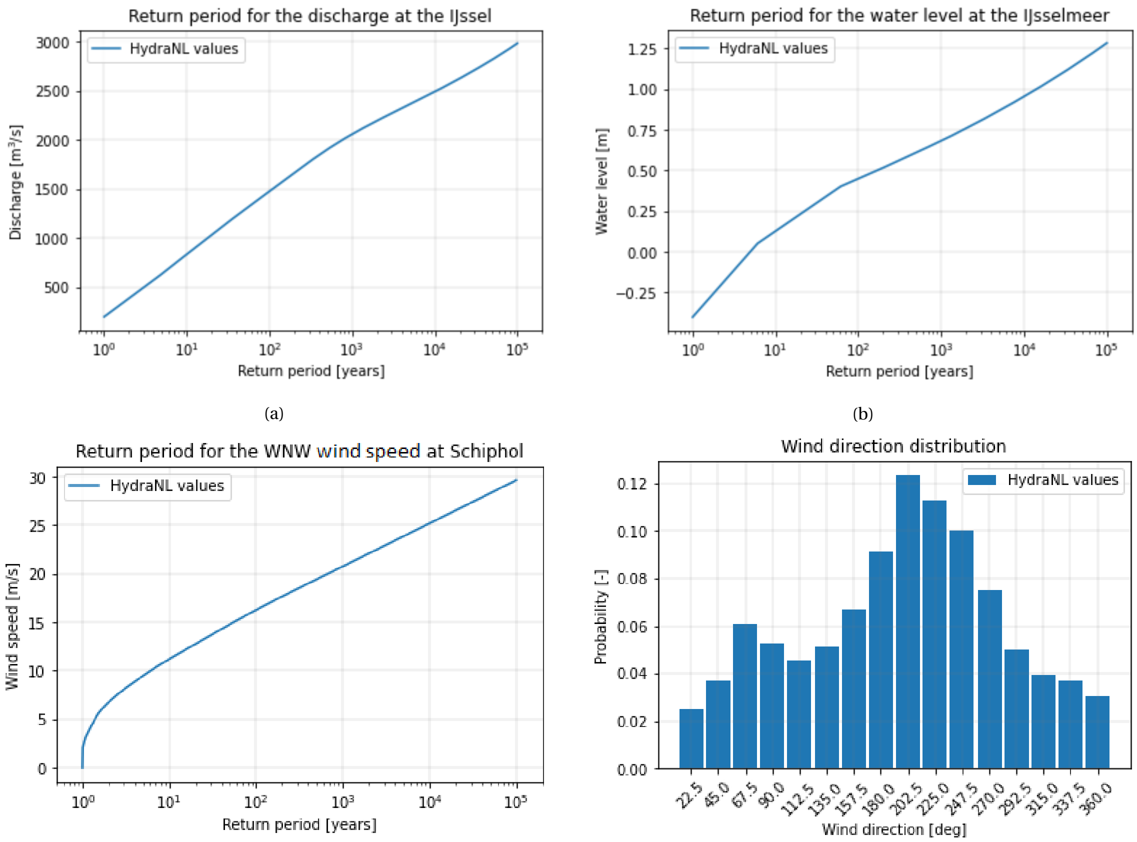
Beaufort no.	**Wind speed** [m/s]	**Description**
0	0 - 0.2	Calm
1	0.3 - 1.5	Light air
2	1.6 - 3.3	Light breeze
3	3.4 - 5.4	Gentle breeze
4	5.5 - 7.9	Moderate breeze
5	8.0 - 10.7	Fresh breeze
6	10.8 13.8	Strong breeze
7	13.9 - 17.1	Moderate gale
8	17.2 - 20.7	Fresh gale
9	20.8 - 24.4	Strong gale
10	24.5 - 28.4	Storm
11	28.5 - 32.6	Violent storm
12	≥ 32.7	Hurricane

As described in Chapter 3, parameters can be quantified by their return periods. The exceeding probabilities for the maximum values of these parameters are available in a database containing hydraulic boundary conditions. HydraNL uses these databases for performing probabilistic calculations. HydraNL is a probabilistic model and is used to compute the statistics of hydraulic loads, such as water level and wave conditions. In the graphs in Figure 4.1, the return periods of the previously listed parameters are shown. Each set of parameters has a certain probability of occurring and results in a water level. This is visualized in Figure 4.2. WAQUA uses discrete input variables, but in reality these values are continuous. There is possibly an infinite amount of continuous combinations and it is likely that multiple combinations lead to the same water level. A relatively high discharge in combination with a low wind speed could for example lead to the same water level as a low discharge with a higher wind speed. The combined probability of all these events leads to the probability of a certain water level. This can be seen in Figure 4.3. Note that each individual scenario has a lower corresponding probability than the combined probability leading to that water level. The combination with the highest contribution to this combined probability is the most likely situation leading to that water level and is therefore the leading combination.

HydraNL provides two leading combinations which are distinguished by one parameter: the closing situation of the Ramspol barrier. As this barrier is closed during storm events, this situation indicates a storm driven event. The barrier remains open in the situation with extreme discharges, which implies a discharge driven event. For five different locations, one HydraNL calculation is performed. These results are shown in Table 4.2. For every calculation, two leading combinations are shown, distinguished by the closing situation of the Ramspol barrier. This table shows that for the first five locations the contribution to the exceedance frequency is dominated by the situation with a closed Ramspol barrier, indicating that the failure probability at these locations is dominated by a storm situation. For Zwolle, which lies much more upstream, the exceedance frequency is mainly determined by the situation with the open Ramspol barrier.

4.2. Sensitivity analysis

The water levels in the delta are determined by the parameters listed in the previous paragraph. However, some of these parameters may have more influence on the water level than other parameters. This influence can be quantified by plotting the water levels computed with WAQUA for different sets of these variables. These plots are shown in Figure 4.4. The influence of the discharge on the IJssel and the wind speed at Schiphol Airport is shown in Figure 4.4a. From this figure it can be observed that there is a difference in the water level for different values for the discharge on the IJssel at lower wind speeds. For wind speeds exceeding 25 m/s, the difference between different values for the discharge becomes smaller.



(a) (b)

(c) (d)

Figure 4.1: Empirical return periods for the most important parameters determining the water level in the delta. Data obtained from HydraNL.

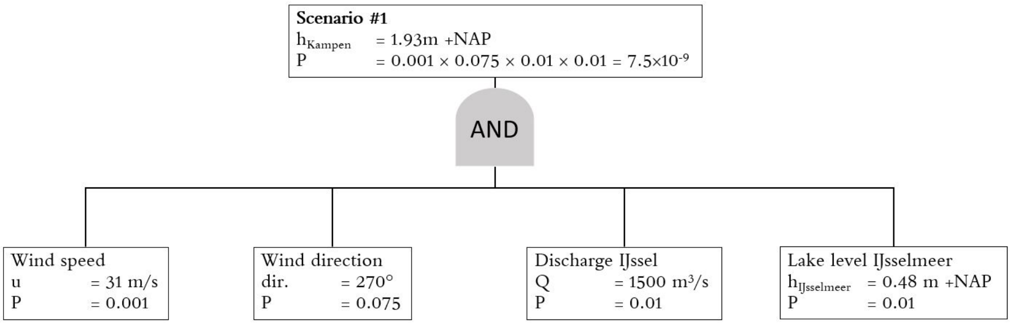


Figure 4.2: A scenario consisting of random values for the parameters of influence leads to one specific water level with a probability of occurring. In this simplified overview, the product of the individual probabilities leads to the scenario probability. In HydraNL, dependency between stochastic parameters is also incorporated. Note that these are just indicative values.

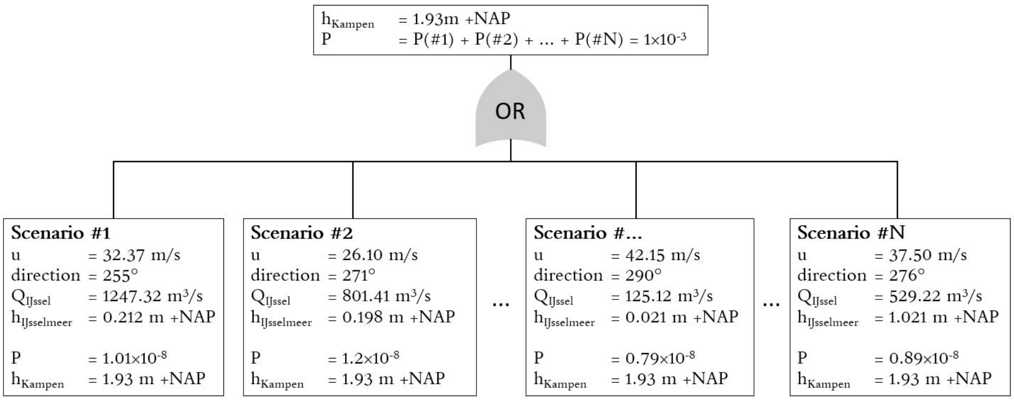


Figure 4.3: There is possibly an infinite amount of scenarios leading to one specific water level. The probability corresponding to the water level is equal to the sum of the probabilities of each of these mutually exclusive scenarios. For that reason, a wind speed with a return period of 10,000 years can lead to a water level with a return period of 1,000 years. Note that these are just indicative values.

Table 4.2: Most likely combination of parameters for a 1:3,000 water level computed with HydraNL. The contribution to the exceedance frequency is applicable to the closing situation of the Ramspol barrier. This means that for the the IJssel mouth, all situations with a closed barrier combined contribute for 99.7% to the total exceedance probability.

Location	**Ramspol Barrier**	**Water level IJsselmeer** [m]	**Discharge IJssel** [m^3/s]	**Wind direction** [-]	**Wind speed** [m/s]	**Resulting water level** [m]	**Contr. to exceedance freq.** [-]
IJssel mouth	Open	-0.22	350	WNW	35.4	2.75	0.003
	Closed	-0.1	420	WNW	32.3	2.75	0.997
Roggebotsluis	Open	-0.22	350	WNW	35.2	2.99	0.004
	Closed	-0.1	420	WNW	32.4	2.99	0.996
Reevediep (halfway)	Open	-0.22	350	WNW	35.2	3.1	0.004
	Closed	-0.1	420	WNW	32.4	3.1	0.996
Reevediep (entrance)	Open	2.05	2882	WNW	10.2	3.13	0.005
	Closed	-0.1	420	WNW	32.4	3.13	0.995
Kampen	Open	-0.22	350	WNW	35.1	2.94	0.004
	Closed	-0.1	420	WNW	32.4	2.94	0.996
Zwolle	Open	0.85	2426	SW	9	3.96	0.845
	Closed	-0.1	450	WNW	38.3	3.96	0.155

Table 4.3: Safety standards and signal values for relevant dike trajectories. Data obtained from [38].

Trajectory	Protecting	Safety standard	Signal value
10-2	IJsselmuiden	1:1,000	1:3,000
11-2	Kampen	1:1,000	1:3,000
225	Kampereiland	1:10,000	1:30,000

The relationship between the wind speed and the water level at the IJsselmeer (Figure 4.4b) is comparable to the relationship between the discharge and the wind speed. For lower wind speeds, the water level at the IJsselmeer has a relatively large impact on the water level at trajectory 225. This difference between the various water levels reduces for higher values for the wind speed.

A linear relationship between the discharge of the IJssel and the water level of the IJsselmeer can be seen in Figure 4.4c. However, for higher water levels at the IJsselmeer, the lines are more closely to each other. The influence of the closing situation of the Ramspol barrier is shown in Figure 4.4d.

From these graphs can be concluded that the influence of both the discharge and the water level at the IJsselmeer reduces for higher wind speeds and that the wind speed is the parameter with the highest influence on the water level. Also, the influence of the discharge reduces when the water level at the IJsselmeer increases. When the Ramspol barrier closes when it should, it results in higher water levels due to the fact that more water flows along trajectory 225 onto the IJssel.

4.3. Safety standards

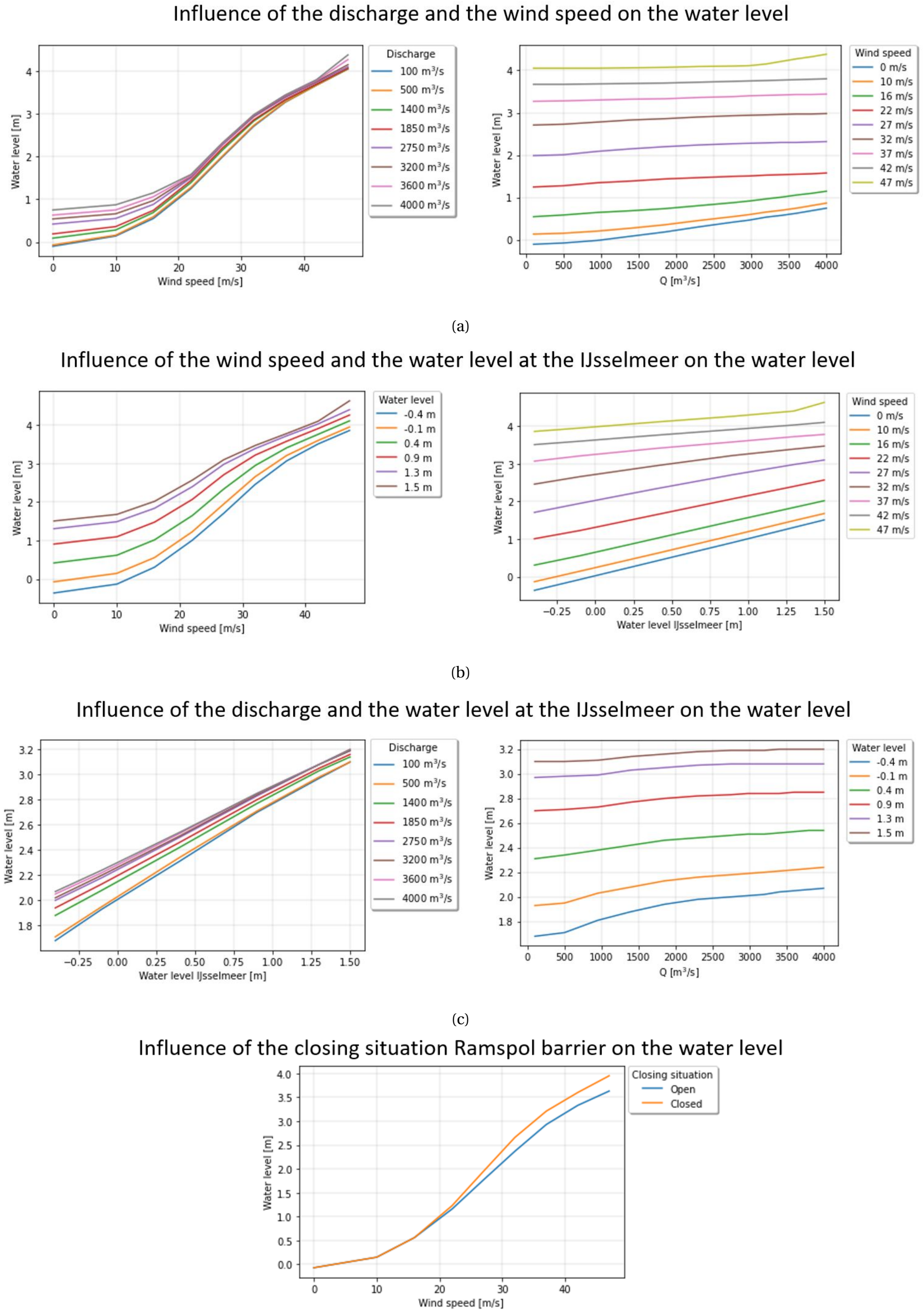
Kampen, IJsselmuiden and the Kampereiland are protected by two types flood defences: several dikes and the Ramspol barrier. Each flood defence has its individual safety standard, which are shown in Table 4.3. The Ramspol barrier is part of trajectory 225 and therefore has the same safety standard of 1:10,000. The pictures referenced to in this section can be found in Appendix in A.

According to new regulations in the dike assessment procedure of the Nieuwe Waterwet 2017, safety standards are now expressed in terms of failure probabilities instead of exceeding probabilities. The safety standard of trajectory 225 was increased from an exceeding probability of 1:2,000 to a failure probability of 1:10,000 [26]. At the same time, the north-south oriented part was made resistant to overflow for water levels corresponding to an exceeding probability of 1:500 [34]. This is achieved by reducing the crest height of trajectory 225 in this part. The crest heights along trajectory 225 can be seen in Figure A.2. It can be seen that the crest height along the IJssel varies between 2.9 and 3.3 m +NAP and that the north-south oriented part is approximately 2.8m +NAP.

The crest heights of dike trajectories 10-2 and 11-2 are obtained from [4]. This online database consists of multiple hectometer posts, which are shown in Figure A.3. For a number of these posts, longitudinal profiles are available. The crest heights of these profiles at these hectometer posts are plotted in Figure A.4. Note that the hectometer posts for trajectory 11-2 increase in western direction, while those of 225 increase in eastern direction. It can be seen that at every location, the crest height of trajectory 11-2 exceeds the height of 225.

4.4. Storm situation

To be able to determine the influence of the crest height of trajectory 225, it is important to analyze the different possible events in a storm situation. In case of a strong wind from WNW direction, water is blown into the delta. Dependent on the exact storm characteristics, various situations might occur. An important factor in each situation is whether the Ramspol barrier is closed or not. As described in the previous paragraph, this storm surge barrier has a safety standard of 1:10,000 and in closed situation it prevents large amounts



(a)

(b)

(c)

(d)

Figure 4.4: The water levels at trajectory 225 for different combinations of parameters.

of water flow from the Ketelmeer into the Zwarte Meer. This means that it is usually closed when the water level at the Ketelmeer is 0.5m +NAP in combination with strong NW wind. Due to the closure of the barrier, water flows into the IJsseldelta. In the current situation, the Roggebotsluis prevents the water from flowing in the direction of the Drontermeer and the Reevediep. This means there are only two directions for the water to flow to: either along the IJssel in the direction of Kampen, or exceed the overflow resistant part of trajectory 225 into the Kampereiland. Both situations and their consequences are described in more detail in the following sections. As a part of the Program IJsseldelta, the Roggebotsluis is planned to be demolished in the near future. When this has been done, the Reevediep is accessible and water can more easily flow into the delta. In the current situation, this is only possible when the Roggebotsluis fails to retain the water. This process is visualized in Figure 4.5.

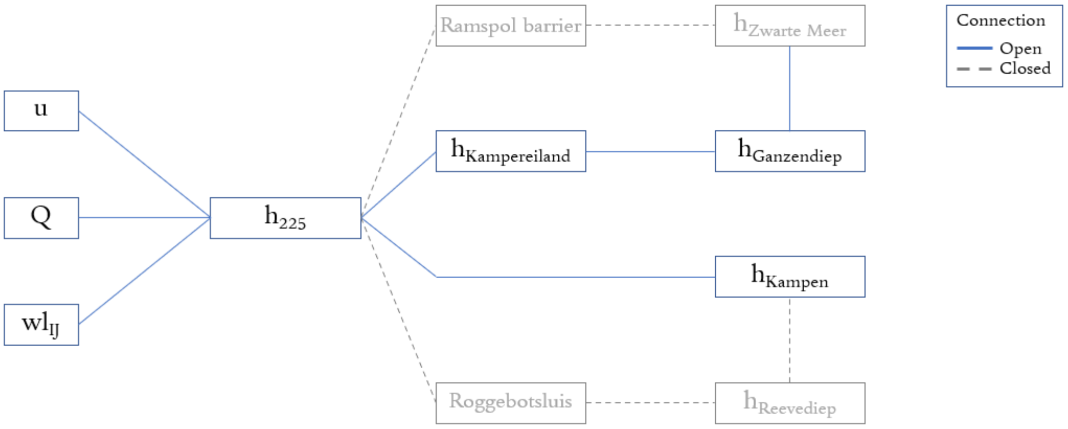


Figure 4.5: Schematic view of the hydraulic interdependencies in the Vecht- and IJsseldelta. The dashed lines indicate connections blocked by for example a flood defence.

In the current situation, large amounts of water flow along the IJssel into the IJsseldelta. For this situation, the part of the IJssel from the Reevediep until the Ketelmeer are relevant. The hinterland is protected on both the left and the right sides of the IJssel. Observing the IJssel from a downstream flow direction, Kampen is situated on the left side of the IJssel and the Kampereiland on the right side. Kampen is protected by dike trajectory 11-2, which has a safety standard of 1:1,000. As described in Chapter 1, the inhabitants of Kampen have small movable barriers as an additional protection against flooding.

The Kampereiland is surrounded by trajectory 225 in the south and in the west. The crest height of the overflow resistant part of trajectory 225 is equal to 2.8m +NAP and this crest has a width of 2,500 meters. The remaining part of trajectory 225 has a crest height varying from 2.9m +NAP to 3.3m +NAP. The dike in the north and the east of the Kampereiland have a crest height of respectively 2.0m +NAP and 1.6m +NAP and the average ground level of the Kampereiland is 0.35m +NAP. The maximum inundation depth of the Kampereiland is limited by the lowest surrounding dike trajectory. This means that when the Kampereiland is completely inundated and water level reaches 1.6m +NAP, water starts flowing over this part and end up in the Ganzendiep and in front of the Kamperzeedijk. Depending on various factors, such as the discharge capacity of the Ganzendiep and the wind characteristics, water either flows through the Ganzendiep into the Zwarte Meer or it reaches the Kamperzeedijk.

There are multiple small dikes inside the Kampereiland, dividing the area in multiple compartments. These boxes get filled up consecutively when water flows into the area. In fact, the overflow resistant part of trajectory 225 can be seen as a wide weir. When water flows into an empty area, the discharge is described by the clear overflow equation. As soon as water starts flowing over the dike, the water level inside the area rises. From that moment on, the discharge over the dike is characterized as submerged overflow. The water level in the first box rises faster compared to the situation without boxes, since the area is smaller. As a result, water flowing over the dike is reduced by the water level inside. The dikes surrounding the Kampereiland have to withstand large hydraulic forces when the Kampereiland is completely inundated. In case one of these dikes fails, the compartments prevent all the water in the Kampereiland from flowing through the breach.

Figure 4.6: Crest heights of the two main compartments inside the Kampereiland. Heights obtained from [16].

Table 4.4: The maximum storage capacity of the individual compartments of the Kampereiland and the Kampereiland as a whole. Keep in mind that the average ground level of the Kampereiland is equal to 0.35m +NAP.

Area	**Number**	**Surface** [10^6 m^2]	**Crest height** [m +NAP]	**Storage height** [m]	**Maximum capacity** [10^6 m^3]
Left	I	6.25	1.2	0.85	5.3
Right	II	14.25	1.2	0.85	12.1
Left + right	I + II + III	20.5	1.6	1.25	25.6

To compute the maximum storage capacity of the Kampereiland, the surface of the individual compartments is estimated and multiplied with the lowest surrounding crest height. These crest heights can be seen in Figure 4.6 and the maximum storage capacities are shown in Table 4.4. The visualization of the compartments is shown in Figure 4.7.

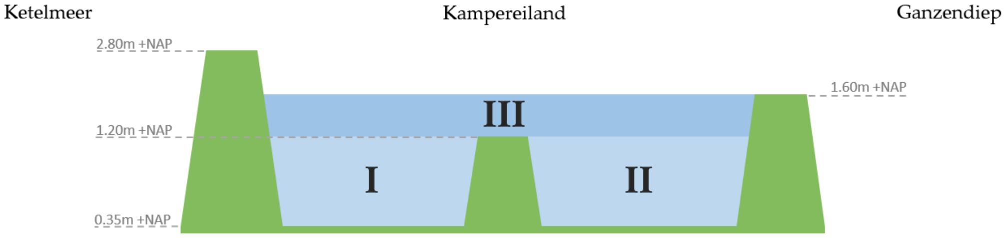


Figure 4.7: Visualization of the storage areas of the Kampereiland.

4.5. Conclusion

This chapter described how the system in the delta works and insight is given in the return periods of the important parameters. The individual influence of the important parameters on the water levels inside the delta is shown in Figures 4.4a and 4.4b. It can be seen that the lines converge for higher wind speeds, which means that the relative influence of both the discharge and the lake level at the IJsselmeer reduces and the influence of the wind speed increases. In Figure 4.4c can be seen that the lines are straight and that they are closer to each other for higher lake levels and for higher discharges. This means that the relative influence of an increasing discharge and lake level remains the same. Therefore, it can be concluded that the wind speed is the parameter with the most influence on the water levels.

Observed from the crest heights obtained from [4] is that the crest height of trajectory 11-2 exceeds the crest height of trajectory 225 along the IJssel. The resistance of a dike trajectory is not determined by the crest height by itself, but it gives an indication of the level of protection. It seems unlikely that Kampen is flooded at an earlier stage than the Kampereiland. This is rather remarkable, as the safety standard of trajectory 225 is higher than the safety standard of trajectory 11-2 at Kampen. However, no full probabilistic analysis has been performed, which is necessary to prove this statement.

In case the water level at the Ketelmeer exceeds the crest height of the overflow resistant part of trajectory 225, water can flow into the Kampereiland. There are two reasons why most of the water will flow over the crest: the width of the flow paths and the downstream water level. The overflow resistant part has a width of 2,500 meters and the IJssel is only 200 meters wide. Due to this wider opening, a higher discharge can be reached over the crest, compared to the flow path onto the IJssel. Furthermore, the surrounding dike trajectory of the Kampereiland is only 1.6m +NAP high. Therefore, the water level inside the Kampereiland cannot exceed this level. If water flows onto the IJssel, its water level rises and becoming higher than the water level inside the Kampereiland. In case the water level at the IJssel is higher than the crest of the overflow resistant part, no more water flows onto the IJssel and the water level remains the same.

Furthermore, the Kampereiland consists of multiple compartments. If a breach occurs in one of the surrounding dikes, only the volume of one compartment flows through the breach. However, assumed is that no dike breaches occur. If the Kampereiland is completely inundated, it is expected that the water flows out over the dike in the east since this is the lowest surrounding dike. The water will end up in the Ganzendiep, which is the branch between this eastern dike and the Kamperzeedijk.

5

Model set-up

This chapter describes how the model is created to produce the results. Section 2.3 described that the model outline consists of four parts: the data input, the computational part, the output and the visualization. This chapter focuses on the computational part, consisting of the three subparts, shown in Figure 5.1: hydrodynamic modelling, data processing and probabilistic calculations. This chapter comprises these three parts including the corresponding assumptions.

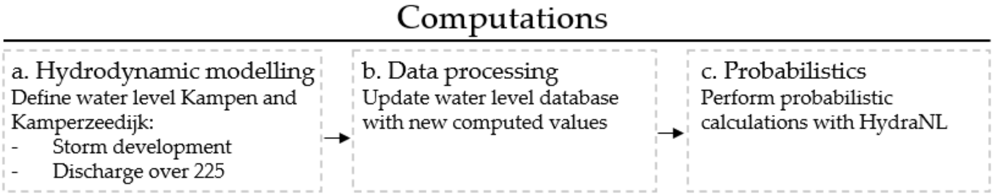


Figure 5.1: The components of the computational part of the model outline.

5.1. Assumptions in computations

The specific assumptions for the computations in this thesis, apart from the assumptions listed in Section 2.4, are noted below.

- **Water level Kampen**
  Assumed is that as soon as water starts flowing onto the Kampereiland, a negligible amount of water flows onto the IJssel to Kampen. The overflow resistant part of trajectory 225 has a width of 2.5 kilometers and the width of the IJssel is only 200 meters. Therefore it is much easier for the water to flow into the Kampereiland. Furthermore, the water level difference between Kampen and the Ketelmeer decreases when the water level at Kampen rises. This reduces the possible flow of water onto the IJssel. This does not hold for the situation at the Kampereiland, as the water level difference remains.
- **Discharge and lake level variation during a storm**
  The influence of the discharge variations and lake level variations on the water level during a storm are assumed to be negligible. These assumptions are elaborated upon in Section 5.2.
- **Evaluated wind speeds**
  The wind speeds of 0 m/s and 10 m/s are not evaluated in the hydrodynamic modelling part for two reasons. The first reason is that the resulting water levels from these wind speeds are much lower than the crest height and do not lead to the inundation of the Kampereiland. Therefore, the water levels do not vary from the WAQUA computations. The second reason is a more factual one, as these wind speeds do not fall under storm conditions. This is elaborated upon in Section 5.3.

5.2. Hydrodynamic modelling

For the model input, the WAQUA computations for three locations are used. These locations, indicated in Figure 5.2, are:

1. In front of the overflow resistant part of trajectory 225;
2. At the left riverside of the IJssel at Kampen;

3. In front of the Kamperzeedijk, near IJsselmuiden.

Multiple WAQUA computations are available, e.g. the WBI2017 and RD2018 databases. The WBI database has an official status, but the presence of the Reevediep and the demolition of the Roggebotsluis have not yet been incorporated in these computations. Therefore, the Reevediep 2018 (RD2018) database is used. These data have been verified and are confirmed to be reliable according to [26].

The location of trajectory 225 has been chosen somewhere in the middle of the overflow resistant part. The water level along the trajectory is dependent on multiple stochastic variables. For a given moment, the water levels can differ along trajectory 225. The water level exceedance frequency lines for three different locations along the overflow resistant part are shown in Figure 5.3. It can be seen that these lines coincide and therefore expected is that the results are not affected by the choice of the location.

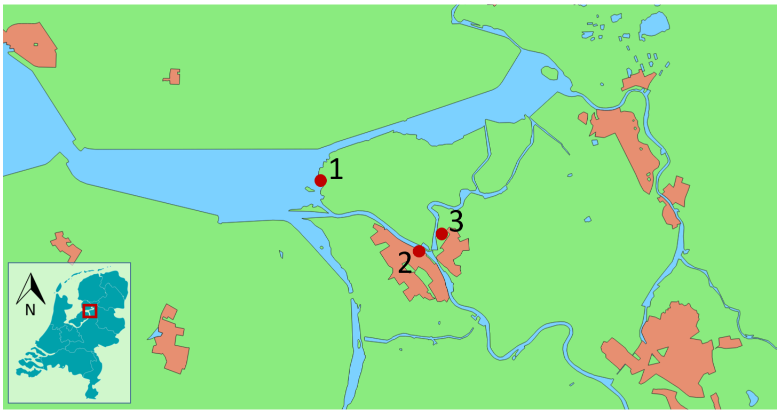
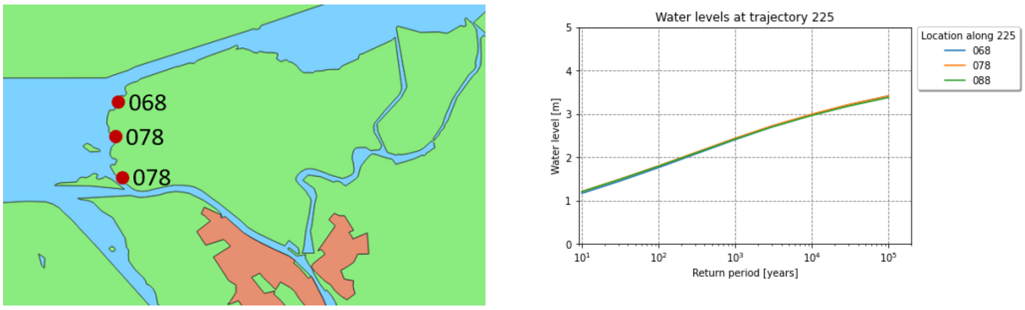


Figure 5.2: Indication of the exact locations for the WAQUA results.



(a) Indication of the three observed locations along the overflow resistant part of trajectory 225.

(b) The water level exceedance frequency lines corresponding to the three locations. The lines are generated with HydraNL with data from WAQUA computations.

Figure 5.3: Sensitivity analysis for the chosen location along trajectory 225. The locations are named after the WAQUA files.

The hydrodynamic part of the model describes the water movements in the area. The first step to describe these water movements is to define storm development. As described in Section 4.5, wind characteristics are the most important parameters in determining the resulting water level. The water level halfway trajectory 225 is retrieved from the WAQUA computations for every time step in the storm. When this water level exceeds the crest height, water starts flowing into the area. When this area is completely inundated, water leaves the area and flows into the Ganzendiep. The water level at the Kamperzeedijk is partly determined by this discharge. All these steps are described in this section and this process is visualized in Figure 5.4.

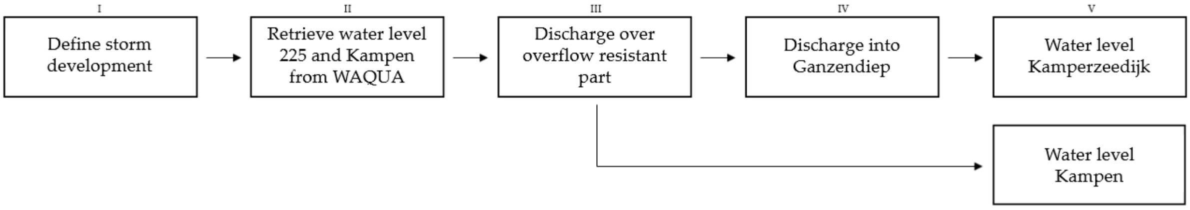


Figure 5.4: The outline of the hydrodynamic modelling part.

Storm development

During a storm, the wind speed increases and decreases as a function over time. Every storm has a certain way of development, described by its wind speed at the beginning, storm growth rate, peak wind speed and peak duration. There is no conventional storm profile, but there are guidelines that are based on storm statistics. These regulations deal with peak statistics and duration. A memo, written by Deltares, describes the following guidelines regarding a storm simulation [5]:

- The storm duration is defined as the duration that the wind speeds exceeds 10m/s;
- The storm duration is independent of the maximum wind speed.

In [5] is focused on a single peak storm event and estimated is that 40 hours is a realistic duration for storm surge.[1] The proposed storm development is fitted on actual storm data from storms at Hoek van Holland, which were obtained from the KNMI. As the higher wind speeds are more relevant for applications in flood risk analysis, the fitted trapezium should be a good fit compared to the highest 30% of the values. In order to retrieve a good fit for simulating storms, [5] advises a storm duration of 51 hours with a top duration of one hour. This is shown in Figure 5.5.

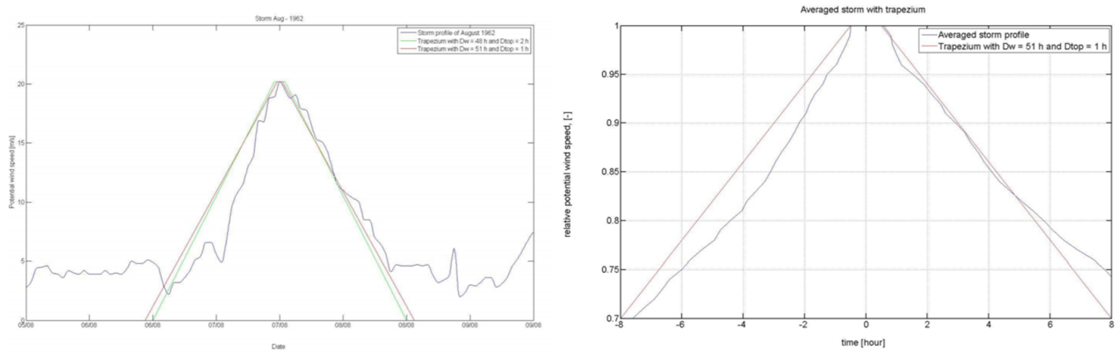


Figure 5.5: Visualization of the trapezoid storm development with a duration of 51 hours and a top duration of one hour. Figures obtained from [5].

To retrieve the water level for a certain location, WAQUA computations are used. In this database, the water level is computed as a function of wind speed, wind direction, discharge at the IJssel, the water level at the IJsselmeer and the closing situation of the Ramspol barrier. As mentioned before, the results of the WAQUA computations are discretized. The wind speed is for example discretized in nine values between 0 m/s and 42 m/s. These discrete values are shown in Table 5.1. With these values, 22,464 unique combinations of parameters can be generated. Only the combinations which lead to a different water level due to the overflow of trajectory 225 are used in the model. Therefore, only 2,170 combinations are evaluated in the hydrodynamic model. In the next paragraphs, the selection of these combinations is elaborated upon.

As described earlier, a storm is defined as the time that the wind speed exceeds 10 m/s. Therefore, the wind speeds of 0 m/s and 10 m/s are of no relevance and do not have to be computed. Furthermore, several wind directions can be neglected as a storm is observed. A storm in this area is defined as a strong wind from WNW

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[1] Note that storm duration and storm surge duration are strongly linked, but they are not the same [5].

Table 5.1: Applied discretization of the input parameters for the WAQUA computations.
The total amount of results becomes $9 \cdot 13 \cdot 6 \cdot 16 \cdot 2 = 22{,}464$

	Wind speed [m/s]	**Discharge** [m^3/s]	**Water level IJsselmeer** [m]	**Wind direction** [deg]	**Closing situation Ramspol barrier** [-]	
	0	100	-0.4	22.5	Open	
	10	500	-0.1	45	Closed	
	16	950	0.4	67.5		
	22	1400	0.9	90 [E]		
	27	1850	1.3	112.5		
	32	2300	1.5	135		
	37	2750		157.5		
	42	2975		180 [S]		
	47	3200		202.5		
		3400		225		
		3600		247.5		
		3800		270 [W]		
		4000		292.5		
				315		
				337.5		
				360 [N]		
						+
Total:	9	13	6	16	2	

direction (272.5°). Expected is that high wind speeds from slightly different directions can contribute to the hydraulic loads as well and therefore a total of five wind directions are observed: from 247.5° to 337.5°. Lastly, the situation in which the Ramspol barrier fails to close is not evaluated in the model. When this barrier fails to close, water can flow onto the Zwarte Meer which leads to a lower water level in front of trajectory 225 and at Kampen, see Figure 5.6. Expected is that less water flows over the crest and that this situation does not change for lower or higher crest heights.

By reducing the number of parameters, the number of combinations is reduced by 88% from 22,464 combinations to 2,730.

Since a storm profile is generated, the discretization of the wind speed within WAQUA becomes a problem, as the wind speed in a storm increases continuously. Therefore, a linear interpolation is used which has to be applied in three directions: wind speed, discharge and the IJsselmeer water level. The closing situation of the Ramspol barrier and the wind direction are not discretized. This is because the closing situation is in fact a discrete phenomenon in the real world. Either the barrier works the way it should, or it fails. The wind direction is discretized in sixteen bins of 22.5°, which is assumed to be accurate enough for this model.

The number of input variables for interpolation over x variables is equal to 2^x. As this interpolation is performed over three variables, a number of eight input variables is needed. The output of this triple linear interpolation is the continuous water level in front of trajectory 225. The results of these individual interpolations are shown in Figure 5.7. For values that lie outside the set of discretized values, an extrapolation is applied based on the last two discrete values.

Discharge into the Kampereiland

The water levels are retrieved from the WAQUA database for every time step. When the water level in front of trajectory 225 exceeds the crest height, water starts flowing into the Kampereiland. The crest of the overflow resistant part can be seen as a weir. The discharge over a weir is described by the formulas for clear overflow (Eq. 5.1) and submerged overflow (Eq. 5.2) [3]. These formulas differ from each other in the last term, where the down stream water level is incorporated. When the water level on the downstream side of the flow direction exceeds the crest height, this downstream water level decelerates the water flowing over it. This is shown in Figures 5.8a and 5.8b. The situation of submerged flow can only arise when the water level inside the Kampereiland exceeds the crest height of the overflow resistant part. This is not possible in the current layout

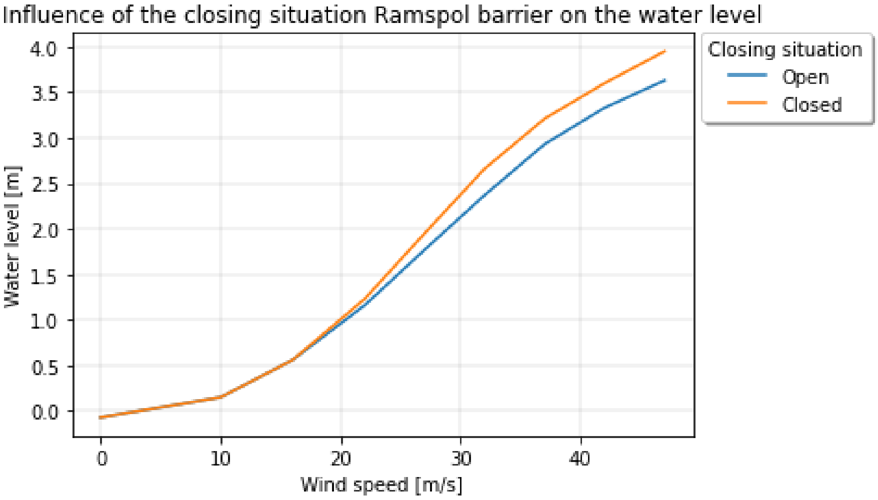
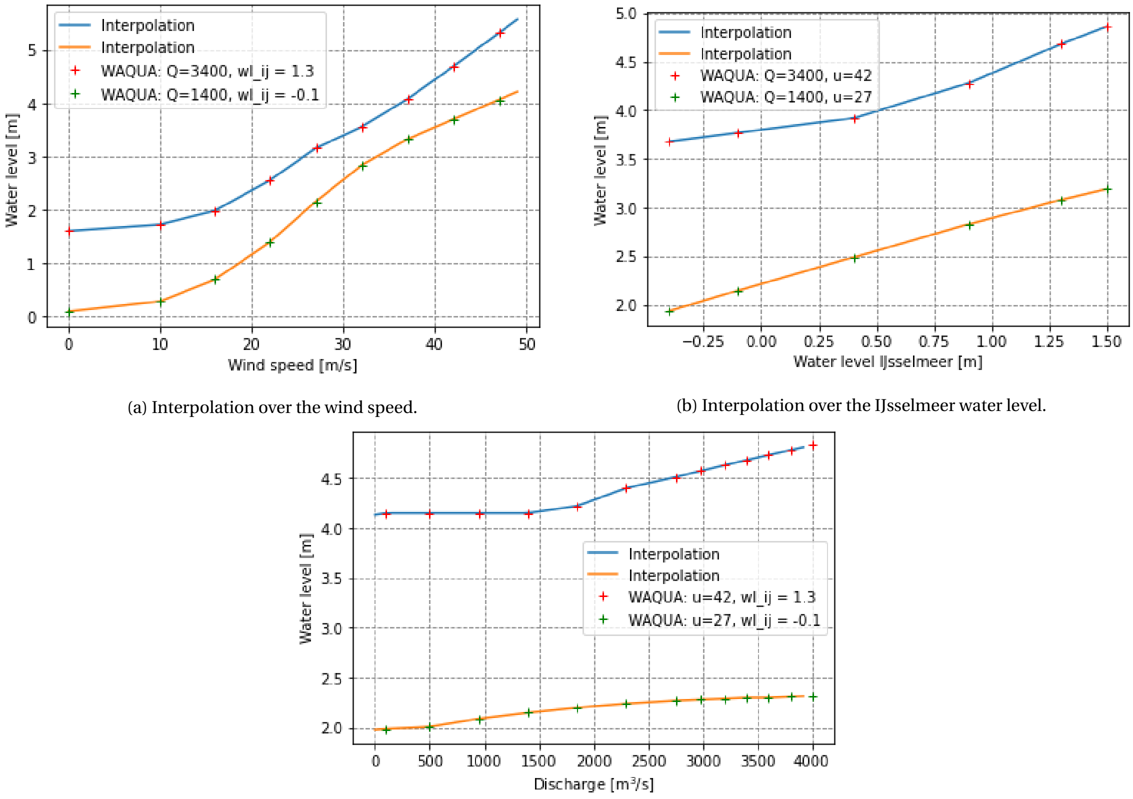


Figure 5.6: The influence of a failure of the Ramspol barrier on the water level at Kampen. This figure shows a situation with WNW wind, a moderate discharge and lake level on the IJsselmeer.

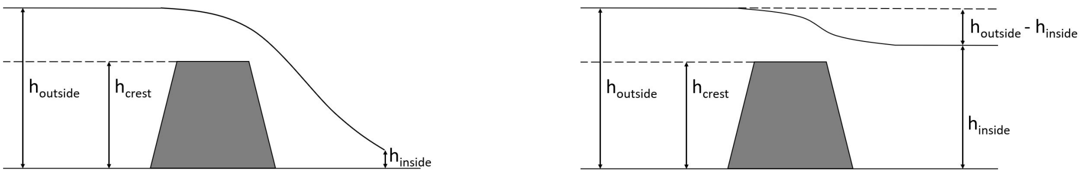


(a) Interpolation over the wind speed.

(b) Interpolation over the IJsselmeer water level.

(c) Interpolation over discharge.

Figure 5.7: Linear interpolation for all variables of influence. The lines represent the continuous outcome of the interpolation, while the crosses represent the exact discrete WAQUA results. These graphs prove the interpolation is accurate.



(a) Free flow (Eq. 5.1). The inside water level is lower than the crest height.

(b) Submerged flow (Eq. 5.2). The inside water level exceeds the crest height.

Figure 5.8: Difference between free flow and submerged flow.

of the Kampereiland, since the surrounding dike trajectories are lower than the crest height of the overflow resistant part. However, this situation might occur when evaluating different crest heights.

$$Q = m \cdot B \cdot (h_{\text{outside}} - h_{\text{crest}}) \cdot \sqrt{2g\,(h_{\text{outside}} - h_{\text{crest}})} \tag{5.1}$$

$$Q = m \cdot B \cdot (h_{\text{outside}} - h_{\text{crest}}) \cdot \sqrt{2g\,(h_{\text{outside}} - h_{\text{inside}})} \tag{5.2}$$

with:
Q = Discharge [m^3/s];
m = Discharge coefficient [$\sqrt{m}/s$];
B = Width of the overflow resistant part of trajectory 225 [m];
$h_{outside}$ = Water level at the Ketelmeer [m +NAP];
h_{crest} = Crest height of the overflow resistant part of trajectory 225 [m +NAP];
h_{inside} = Water level inside the Kampereiland [m +NAP].

The first assumption listed in Section 5.1 was that a negligible amount of water flows onto the IJssel in the direction of Kampen as soon as the water starts flowing onto the Kampereiland. This assumption makes it possible to model the effect of water flowing into the Kampereiland on Kampen. However, this does not mean that the water level at Kampen does not change anymore. After the storm reaches a certain wind speed, it takes some time for the water level to increase and for the wind to travel. Due to this phase lag, the water levels at different places do not rise simultaneously. The water levels during a storm event for different locations are shown in Figure 5.9. The numbers represent different section lines, as can be seen in Figure A.5. During a storm, the water level increase at the Ketelmeer (section line 1005) takes place before the water level increase at the beginning of Kampen (section line 1000) and the entrance of the Ganzendiep (section line 996). This phase difference is approximately 45 minutes. This means that as soon as the Kampereiland starts to inundate, the water level at Kampen can still rise for 45 minutes, whereafter it becomes stable.

Discharge IJssel and lake level IJsselmeer

Not only the wind speed changes over time but also the discharge of the IJssel and the water level at the IJsselmeer. Although the wind speed was characterized as the most influential parameter, the discharge and water level also contribute to the increase of the water levels. The rate of change of these parameters is important to estimate the probability that two or more peak values coincide. In [33], wind speed is characterized as a fast stochastic variable. As described in the storm development, the duration of a storm is equal to approximately 50 hours. River discharge and the water level at the IJsselmeer are, on the other hand, slow stochastic variables, which vary slowly over time. The next paragraph examines whether this change in discharge and lake level has to be incorporated in the model.

In [33], the duration of a river discharge wave is set to 30 days with a peak duration of one day. This means that it takes 14.5 days for the discharge to increase from its lowest to its highest point. To make a basic calculation for an extreme discharge of 2,500 m^3/s with a return period of 10^4 years (Figure 4.1a), this means that the discharge increases from 100 m^3/s to 2,500 m^3/s in 14.5 days (Figure 5.10a). It takes approximately one day for the storm to develop from its starting point to its peak and in the same time span the discharge can increase with 165 m^3/s. For wind speeds higher than 20 m/s, the increase of 165 m^3/s results in a negligible increase

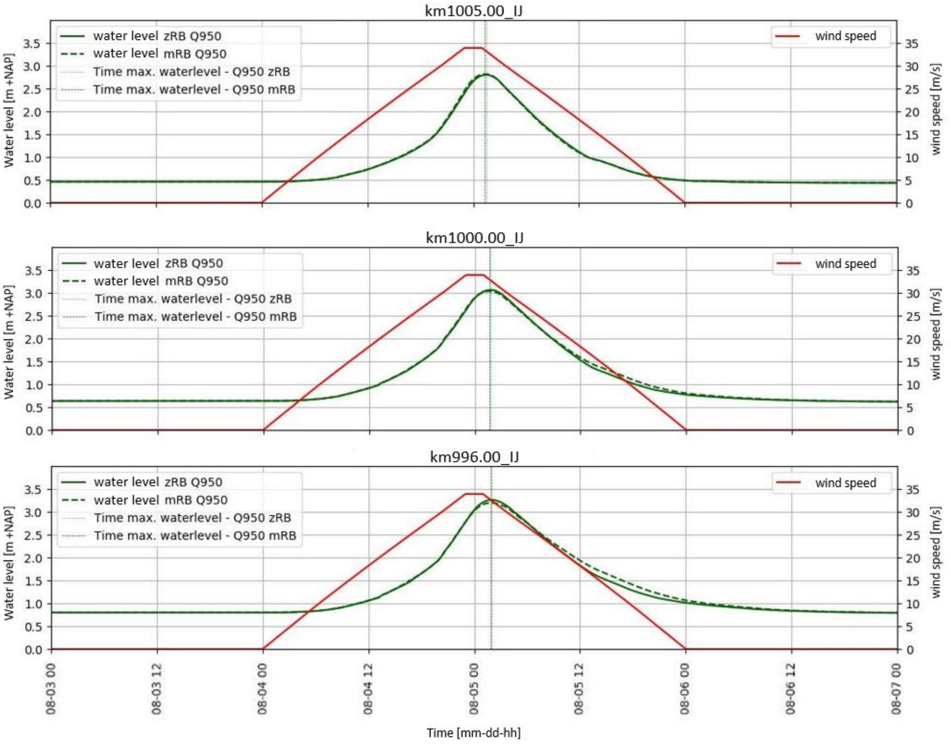


Figure 5.9: Water level increase during a storm situation as a function of time for three different locations: At the Ketelmeer (1005), at the beginning of Kampen (1000) and at the entrance of the Ganzendiep (996). The grid lines on the x-axis show intervals of twelve hours. The exact locations of these section lines are shown in Figure A.5. The water level at section line 996 increases a little later compared to section line 1005.

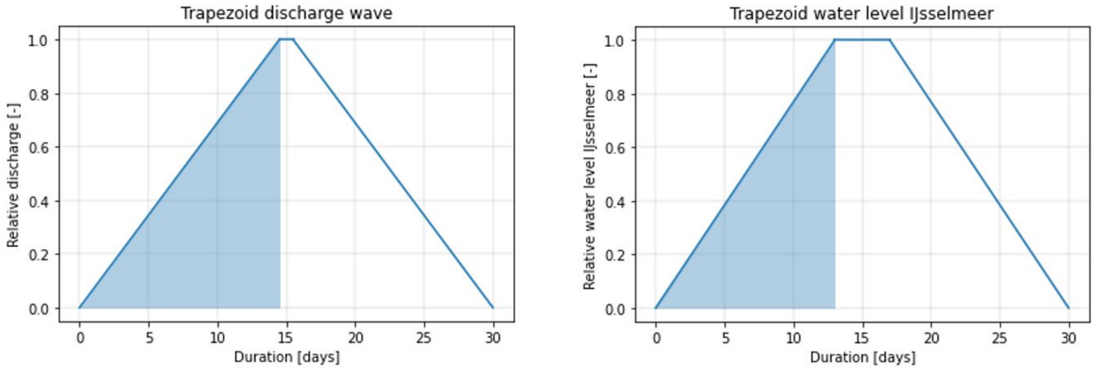
of the water level, as shown in Figure 4.4a. Therefore, the influence on the water level as a result of the rate of change of the discharge during a storm situation is assumed to be very low and is therefore neglected.

The water level fluctuation at the IJsselmeer also has a period of 30 days, but with a peak duration of four hours, according to [33]. In case of an extreme water level at the IJsselmeer of 1.0m +NAP (return period of 10^4 years, Figure 4.1b), the water level increases from -0.25m +NAP to 1.0m +NAP in thirteen days (Figure 5.10b). This is equal to a water level increase or decrease of 0.09m from the beginning of the storm until its peak. For wind speeds higher than 20 m/s, the increase of the water level is in the order of ten centimeters.

This rise of ten centimeters is an estimated maximum. To observe this increase, both an extreme lake level and an extreme storm have to occur simultaneously. Also, the phase of the lake level development has to coincide with the phase of the storm development. Only when they occur simultaneously, this maximum increase can be observed. Little is known about the correlation between the lake level and the storm characteristics, which makes it possible that this effect is incorrectly incorporated. Consequently, it is uncertain whether the incorporation of this effect leads to a more realistic view of the situation. The choice is made to ignore the water level fluctuation of the IJsselmeer.

Water level Kamperzeedijk

The last part of the hydrodynamic model is to compute the water levels in front of the Kamperzeedijk. Assumed is that this water level heavily depends on the amount of water leaving the Kampereiland into the Ganzendiep. To find a relation between the discharge and the water level, data from two different WAQUA computations have to be combined: trajectory 225 and 10-2. The amount of water leaving the Kampereiland can be calculated from the WAQUA computations in front of trajectory 225. Water flows into the Kampereiland until its maximum capacity is reached. When this capacity is reached, all excess water leaves the Kampereiland into the Ganzendiep. Therefore, the volume ending up in the Ganzendiep is equal to the volume flowing from the Ketelmeer into the Kampereiland, minus the storage capacity of the Kampereiland:



(a) A discharge wave with a duration of 30 days and a peak duration of one day, according to [33]. It takes 14.5 days to increase from the lowest to the highest value for the discharge.

(b) The water level rise at the IJsselmeer with a duration of 30 days and a peak duration of four days, according to [33]. It takes thirteen days to increase from the lowest to the highest value for the water level.

Figure 5.10: Visualization of the discharge wave and lake level variation.

$$V_{\text{Ganzendiep}} = \max\Big(\sum_{t=0}^{T} Q_{225}(t)\cdot dt - V_{\text{Kampereiland}},\ 0\Big) \tag{5.3}$$

For every combination of parameters, the model calculates the volume in the area in front of the Kamperzeedijk, which can not be smaller than zero. This volume is compared with the water levels at that location, obtained from the WAQUA computations for trajectory 10-2. The results are shown in Figure 5.11. It can be seen that for lower discharges the water level varies a lot. However, this uncertainty reduces for larger volumes. It can also be seen that the maximum height is around six meters above NAP, which is much higher than the crest height of the Kamperzeedijk. This results from the fact that the Kamperzeedijk is modelled as a wall with infinite height.

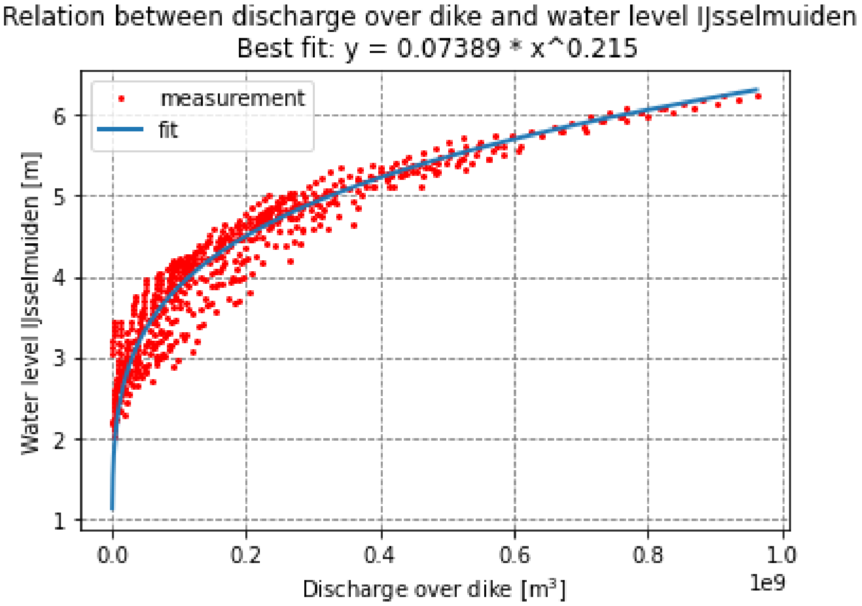


Figure 5.11: The relation between the discharge out of the Kampereiland and the water level in front of the Kamperzeedijk. The discharge is calculated with the created model and compared to the water levels from WAQUA. The fitted line is obtained using the linear algebra least squares method function from NumPy.

NumPy has a function to perform the linear algebra least squares method, which is applied to model the relation between the discharge flowing from the Kamperzeedijk into the Ganzendiep and the resulting water level. This function returns the least-squares solution to a two-dimensional linear matrix equation [2]. The fit obtained by this function is:

$$y = 0.07389 \cdot x^{0.215} \tag{5.4}$$

5.3. Data processing and probabilistic calculations

The output of the hydrodynamic model contains the water levels at all locations for the 2,710 combinations of input parameters. To describe the influence of various crest heights of trajectory 225, a probabilistic analysis is needed. Within this analysis, the computed water levels are linked to a probability and a water level exceedance frequency line is generated with HydraNL. This line shows the water level against its corresponding return period. As described earlier, HydraNL is a model that calculates the statistics of hydraulic loads, such as water levels and wave characteristics. However, HydraNL needs water levels for all 21,464 combinations to perform the probabilistic analysis. This means that approximately 20,000 values for the water levels have to be added to the data set. These are the following:

- Wind speeds 0 m/s and 10 m/s for the wind directions between 247.5° and 337.5°;
- The remaining wind directions for all wind speeds;
- The failing Ramspol barrier for all wind speeds and directions.

Assumed is that the data from the missing entries are legitimately represented by the available WAQUA computations. Note that these entries are not computed in the model as it was assumed that these combinations do not differ from the original situation. If they do not differ, the model makes no adjustments and the original WAQUA values remain the same. There is once more elaborated upon for each of the three listed missing value sets in the following paragraphs.

The wind speeds of 0 m/s and 10 m/s are excluded for two reasons. The first reason is that a storm is defined as the duration that the wind speed exceeds 10 m/s. Therefore, the situations with a wind speed 0 m/s and 10 m/s are excluded. Furthermore, from the WAQUA results is seen that these wind speeds lead to a water level much lower than the observed crest heights. No water flows over the crest and no changes in the water levels at Kampen and the Kamperzeedijk are found. Therefore, these situations do not differ from the WAQUA computations.

Five wind directions are taken into account in the model. In the other wind directions, wind is not blown in the direction of the overflow resistant part of trajectory 225 or onto the Kamperzeedijk. For some wind directions, the opposite is true: wind is blown out of the IJsseldelta in the direction of the IJsselmeer. As for the situation wind low wind speeds, this does not lead to high water levels in front of trajectory 225.

Lastly, in the case of a failing Ramspol barrier in combination with WNW wind, water can flow into the Zwarte Meer. This leads to a reduced water level in front of trajectory 225 and at Kampen, as seen in Figure 5.6. The hydrodynamic model is not able to compute the consequences of a failing Ramspol barrier and therefore the original WAQUA results are used.

Performing the probabilistic calculations

After the databases have been filled with all the original data, the probabilistic calculations are performed. This process is briefly described in this paragraph.

For these calculations, the 'Beoordelingsmodus' is chosen in HydraNL. This mode performs the calculations according to the WBI2017 standard, requiring calculations to be performed with the inclusion of both model uncertainty and statistical uncertainty. The magnitude of model uncertainty is defined with a mean (μ) and standard deviation (σ) and is dependent on location, orientation and dike characteristics. These values are known within HydraNL. The results are presented in the next chapter.

6

Model results

This chapter describes the model results from the hydrodynamic and probabilistic calculations. The hydrodynamic results are described by evaluating one specific scenario. The probabilistic results are separately described per dike trajectory.

The model computed the water level exceedance frequencies for the three dike trajectories for six different crest heights of the overflow resistant part of trajectory 225. The evaluated crest heights are the following:

- 2.2m +NAP	- 2.8m +NAP (*current crest height*)
- 2.4m +NAP	- 3.0m +NAP
- 2.6m +NAP	- 3.2m +NAP

For all six crest heights of trajectory 225, 2,170 combinations of parameters are used to evaluate a storm scenario. This makes a total of $6 \cdot 2,170 = 13,020$ scenarios. The hydrodynamic output of one of these scenarios is shown in Figure 6.1. This figure shows the results for a crest height of 2.2m +NAP, wind a speed of 32 m/s, a discharge of 1,500 m^3/s and a lake level of 0.35m +NAP. This rather extreme scenario has been chosen to serve as an example and to be able to describe what happens when water flows into the Kampereiland. Each of the 2,170 scenarios leads to a maximum water level at Kampen and at IJsselmuiden.

6.1. Hydrodynamic results

Figure 6.1 shows the model output for one of the hydrodynamic scenarios. In this specific scenario, the storm development profile is characterized by the maximum wind speed of 32 m/s. As described earlier, the storm starts with a wind speed of 10 m/s and increases to the maximum wind speed in a time span of 25 hours. The peak duration is two hours, whereafter it reduces to 10 m/s again. The wind direction, discharge on the IJssel and the lake level of the IJsselmeer have been kept constant and the time interval is set to 600 seconds. Based on these values, the water level in front of trajectory 225 and at Kampen are obtained from the WAQUA computations. These water levels are shown by the blue lines. The choice for a time interval of 600 seconds was primarily made because of computation time. Evaluating one hydrodynamic scenario (2,170 computations) costs around eight hours of computation time with this time step, linearly increasing to 800 hours with a time step of for example six seconds. A test computation with a time step of six seconds showed no differences compared to the 600 second time interval.

When the water level at trajectory 225 exceeds the crest height of 2.2m +NAP, water starts flowing into the Kampereiland and the first part starts to inundate. The discharge and the water level inside the Kampereiland are both indicated in the graph. Due to the phase difference, the water level at Kampen (dark blue line) keeps rising for another 45 minutes, whereafter it remains constant. At the moment that the first part of the Kampereiland reaches 1.2m +NAP, the second part starts filling up. When this part reaches 1.2m +NAP, both parts fill up to 1.6m +NAP, which is equal to the crest height of the dike in the east. From that moment, water starts flowing in the Ganzendiep. When the water level in front of trajectory 225 starts to decrease, the discharge rate decreases simultaneously. No more water flows over the crest as soon as the water level at trajectory 225 becomes below the crest. A database is created, containing the maximum water levels at Kampen and the volume in front of the Kamperzeedijk for every combination of parameters. This database is used for the probabilistic calculations. For this particular situation, the maximum water level at Kampen is 2.63m +NAP and the volume of water ending up in front of the Kamperzeedijk is $5.07 \cdot 10^7$ m^3. A relation between this volume and the resulting water level was derived in Chapter 5:

$$h_{\text{Kamperzeedijk}} = 0.07389 \cdot V^{0.215} \tag{6.1}$$

The database contains the maximum water levels for 2,170 combinations of parameters. Since HydraNL requires more data for the probabilistic calculations, the database is completed with original WAQUA data.

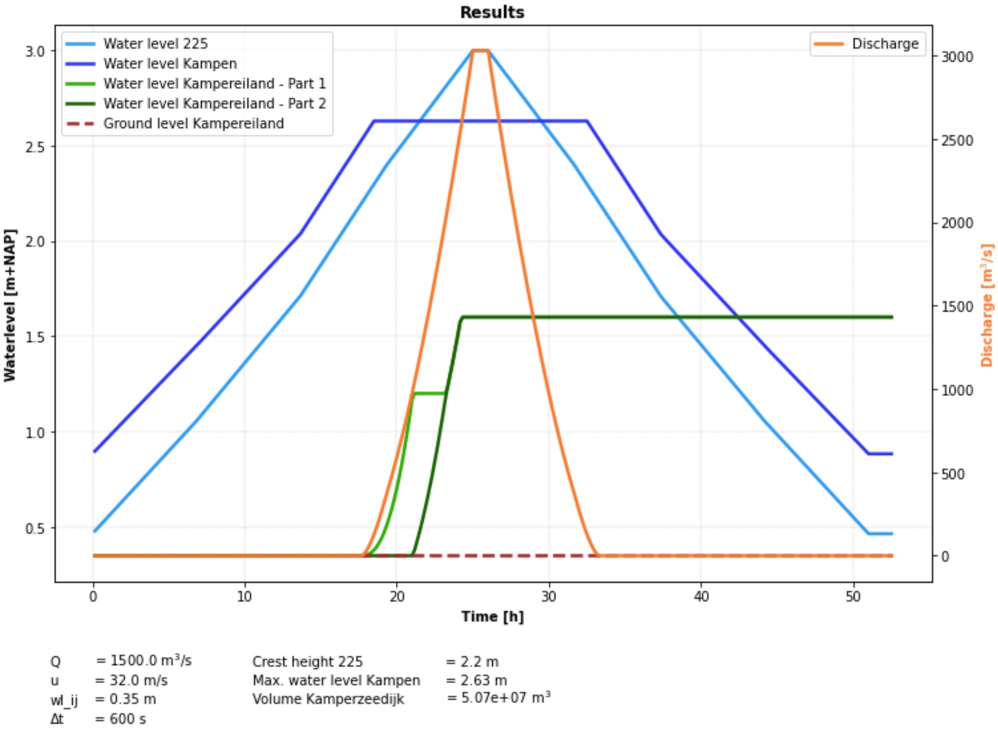
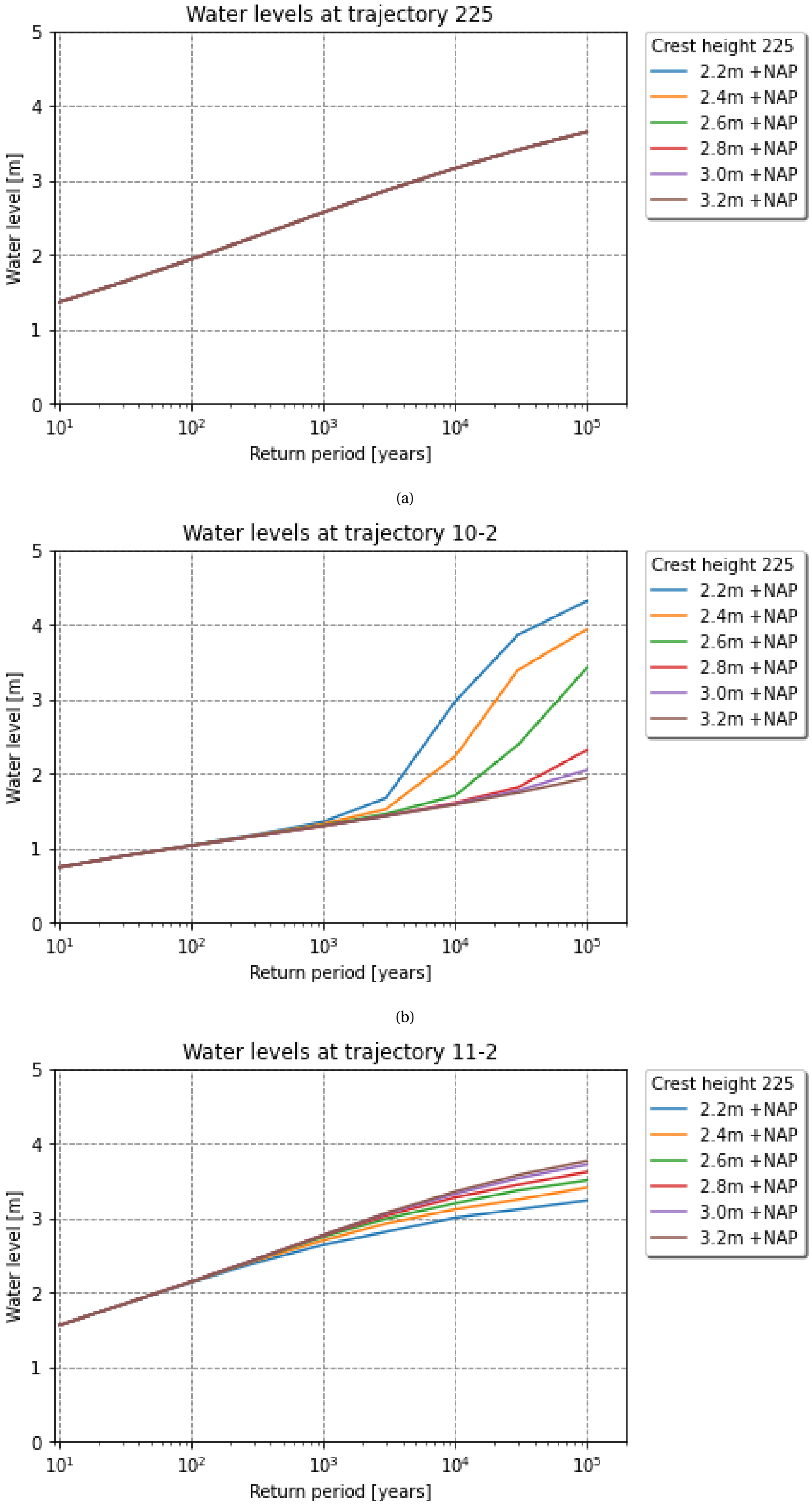


Figure 6.1: Hydrodynamic output of one of the 2,170 computations per crest height. It shows the storm development and the resulting water levels at various locations as a function of time.

6.2. Probabilistic results

HydraNL provides water levels and their corresponding exceedance frequencies. These data are converted into graphs, showing the water level exceedance frequency lines. These lines are shown in Figure 6.2. These lines are computed with both statistical uncertainty and model uncertainty taken into account. Model uncertainty can lead to local inexplicable errors at specific return periods, which may lead to inconvenient results. The results only show relatively small and constant errors and therefore the results are interpreted with the inclusion of model uncertainty. Some figures showing the difference between the situation with and without model uncertainty can be found in Appendix C. The following paragraphs comprise a more extensive elaboration upon the observations for each individual trajectory. These observations form the basis for the conclusions, which are found in Chapter 8.



(a)

(b)

(c)

Figure 6.2: Return periods for various crest heights at IJsselmuiden, Kampen and in front of trajectory 225. These results are computed with both statistical uncertainty and model uncertainty taken into account.

6.2.1. Trajectory 225

The water level exceedance frequency lines for trajectory 225 are shown in Figure 6.2a. It can be seen that all lines coincide, meaning that the water level in front of trajectory 225 remains unaffected by the crest height. This is a direct consequence of the model set-up, as no changes were made to the water levels at this location. Based on this line, an estimation can be made on the inundation frequency of the Kampereiland. The Kampereiland inundates when the water level exceeds the crest height. In Figure 6.3, the lines indicating the return periods of these water levels are shown. The actual return periods can be found in Table 6.1.

Furthermore, the water levels in front of this trajectory appear to be lower than the water levels at trajectory 11-2, but they exceed the water levels at trajectory 10-2.

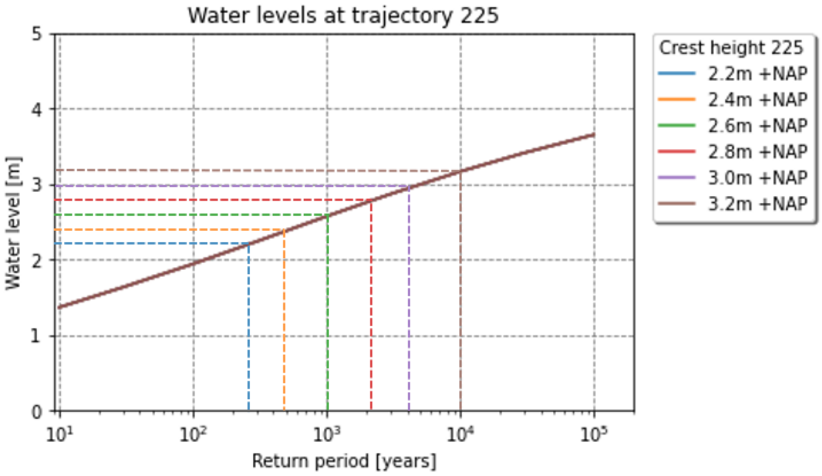


Figure 6.3: Inundation frequency of the Kampereiland.

6.2.2. Trajectory 10-2 – IJsselmuiden

The results for trajectory 10-2 are shown in Figure 6.2b. For lower return periods, all lines coincide. It is clear that for higher return periods, lower crest heights of trajectory 225 lead to higher maximum water levels at this location. At a certain return period, the slope of the lines immediately increases, whereafter it flattens again. For lower crest heights, this immediate slope increase occurs at lower return periods.

The changes in the slope of the line require further elaboration. To evaluate this specific line pattern, one of these lines is shown in a separate figure, together with the water level exceedance frequency line of trajectory 225. These are shown in Figure 6.4. Showing the lines for all crest heights leads to a disorganized overview and therefore only the lines for one crest height are shown.

The shapes of the lines are explained step by step, beginning with trajectory 225. When the water level exceedance frequency line of trajectory 225 exceeds the crest height, the Kampereiland starts inundating. This is indicated with the red marker in Figure 6.4. As described before, the water level exceedance frequency line of trajectory 225 is not affected by the overflow of water and the slope remains constant.

The water level exceedance frequency line for trajectory 10-2 has a more complex shape and consists of three parts. The line shows a constant slope, until a return period of 3,000 years, whereafter an immediate increase of the slope can be seen. At a return period of 30,000 years, the slope reduces again. These three parts are evaluated individually in the following paragraphs.

The water level in front of the Kamperzeedijk is subject to two different influences: the storm characteristics at that location and the inflow of water from the Kampereiland. The first part of the line is only determined by the storm characteristics, as no water leaves the Kampereiland. At a return period of 3,000 years, the slope immediately increases, due to the additional load from the water leaving the Kampereiland. Simultaneously, the magnitude of the storm increases as well. The relation between the volume flowing into the Ganzendiep and the resulting water level was derived in Chapter 5 and shown in Figure 5.11. The slope in the left part of the graph is rather steep. This means that when there has little or no water flowed from the Kampereiland into the Ganzendiep, a small additional volume leads to a rather high increase of the water level. At higher return periods with more water flowing into the Ganzendiep, this same amount of water leads to a lower increase of the water level. This causes the slope reduction at higher return periods.

When the water level exceedance frequency line of trajectory 10-2 exceeds its crest height, the dike starts to overflow. This effect has not been incorporated in the hydrodynamic model and therefore the line reaches water levels exceeding the crest height of trajectory 10-2.

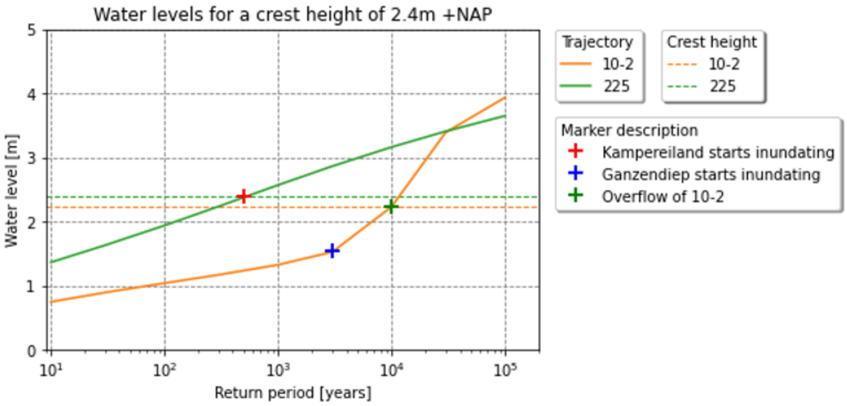


Figure 6.4: Water level exceedance frequency line for trajectory 225 and 10-2 for a crest height of 2.4m +NAP. The markers indicate the start of the described events.

6.2.3. Trajectory 11-2 – Kampen

The water level exceedance frequency line of Kampen is shown in Figure 6.2c. As expected, this line at Kampen increases for an increasing crest height of trajectory 225. Depending on the crest height this only happens for water levels with a return period of 1,000 years and more. After a certain point, the water level increase is reduced and the line flattens. This flattening starts earlier for lower crest heights of trajectory 225. These lines are much smoother than those of trajectory 10-2. Furthermore, the differences between the results are much smaller than for the situation at trajectory 10-2.

Table 6.1: Exceedance frequency of different dike sections for various crest heights of the overflow resistant part of trajectory 225.

Crest height 225 [m +NAP]	**Kampereiland + (225)** [years]	**Kampereiland + (Ganzendiep)** [years]	**Kamperzeedijk + (10-2)** [years]	**Kampen (11-2)** [years]
2.2	250	1,000	5,000	> 100,000
2.4	500	3,000	10,000	> 100,000
2.6	1,000	10,000	20,000	75,000
2.8	2,000	30,000	80,000	30,000
3.0	4,000	30,000	> 100,000	20,000
3.2	10,000	> 100,000	> 100,000	15,000

6.3. Overview

A dike starts to overflow when the water level exceeds its crest height. To summarize the results in one overview, the return periods for the water level exceeding the crest height at each trajectory are shown in Figure 6.5.

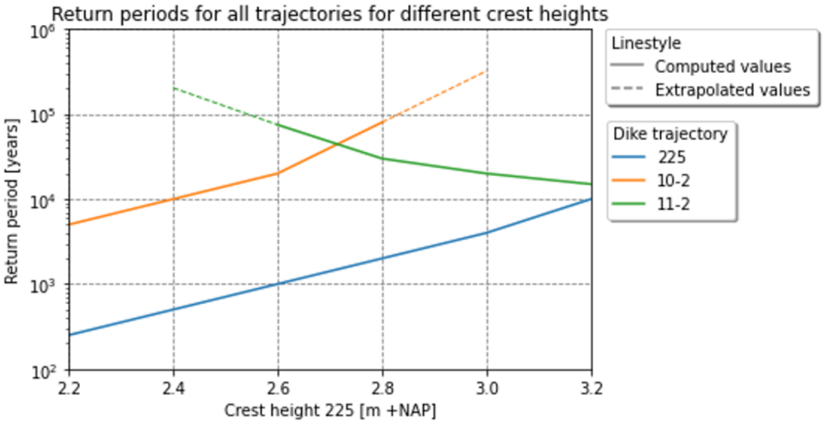


Figure 6.5: The water level exceedance frequency of the crest height at each trajectory, as a function of the crest height of trajectory 225.

7

Discussion

Before a conclusion can be drawn, the model results require a discussion. This discussion is separated in two parts: the model results are discussed in Section 7.1, whereafter the influence of the assumptions is discussed in Section 7.2.

7.1. Model results

The outcomes of the model, showing the influence of the crest of trajectory 225 on the water levels at Kampen and at the Kamperzeedijk, were as expected. Some probabilistic calculations were made with the original WAQUA results, which are compared to the model output in Figure 7.1. These results show the situation with a crest height of the overflow resistant part of trajectory 225 of 2.8m +NAP and include both model and statistical uncertainty.

The model results for the water levels in front of trajectory 225 are the same as the WAQUA results, as there is no discrepancy between the lines. The water levels at trajectory 10-2 are underestimated by the model. The order of this underestimation is constant for the range between return periods of $1\cdot10^1$ years until $3\cdot10^4$ years. At this point, the lines start to converge. As concluded in Table 6.1, this is due to the influence of water flowing out of the Kampereiland. The relation between the discharge into the Ganzendiep and the resulting water level is empirical. Based on this graph, it seems that this relation should be adjusted to be consistent with the WAQUA computations. This leads to an underestimation of the water levels in front of the Kamperzeedijk. The results at trajectory 11-2 are in line with the WAQUA computations. As soon as the Kampereiland starts to inundate (return period of 2,000 years, see Table 6.1), the slope reduces.

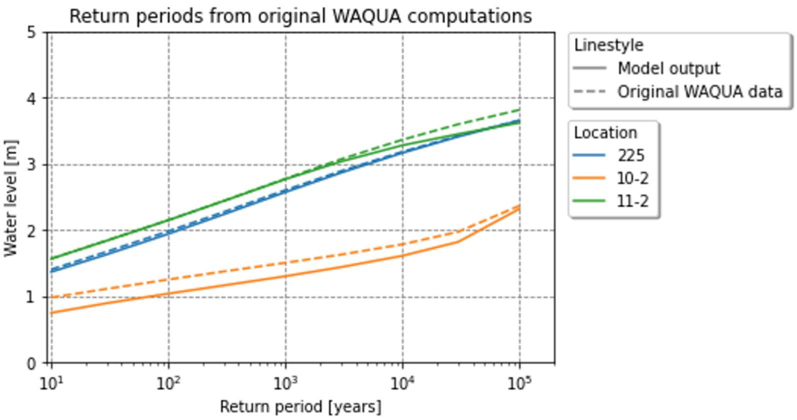


Figure 7.1: Comparison between the water level exceedance frequency lines from the model results and from WAQUA computations for all dike trajectories. The results have been processed with HydraNL and include both statistical uncertainty and model uncertainty.

Hydrodynamic calculations

No evaluation was made on the maximum calculated discharge rates over the crest. In the, rather extreme, situation shown in Figure 6.1, the maximum discharge over the crest of trajectory 225 is equal to 3,000 m^3/s.

Despite being one of the most extreme situations observed in this research, this discharge is enormous. Divided over a width of 2,500 meters, this is equal to 1.2 m^3/sm. In [28] is written that tests with an Overtopping Simulator indicate that critical overtopping rates can sometimes exceed 75 l/sm without damaging the inner slope if this dike has a strong inner slope. Despite this part has been made resistant to overflow, the calculated overtopping rates in the model are sixteen times higher. The discharge rates are in the order of 1,000 m^3/s for less extreme situations with a more moderate wind speed and a higher crest height. This is still five times higher than during the tests performed with the Overtopping Simulator and it is therefore questionable whether this crest can resist these discharge rates.

7.2. Influence of assumptions

Several assumptions were made at the beginning of this research. The possible influences of these assumptions on the model results and conclusions are described in this section.

Hydraulic loads and failure mechanisms

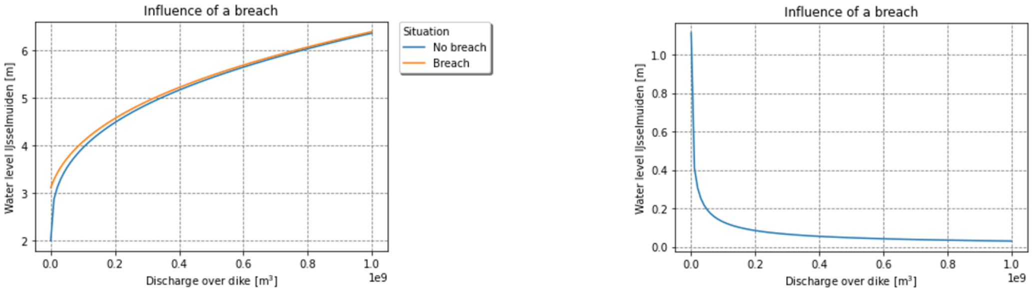
The different origins of the hydraulic loads make this delta a complex system. This situation was simplified by only taking the water levels into account and neglecting wave impact. In reality, wind induced wave impact contributes substantially to the hydraulic load. Wave run-up levels become highest when the dike trajectory is perpendicular to the wind direction, which is the case for trajectory 225 during a storm at the IJsselmeer. For trajectory 225, this means that water starts ending up inside the Kampereiland at an earlier stage than described by the model. However, the overtopping volumes are expected to be small compared to the overflow volumes and they do not lead to significant inundation levels. Since the overflow resistant part has been strengthened to resist the additional load from the overflow of water, it is not expected that the overtopping of waves decreases the strength of the dike. Trajectory 11-2 is parallel to the storm wind direction and therefore the magnitude of the wave run-up is expected to be small compared to the situation at trajectory 225. Expected is that the inclusion of wave impact does not lead to a significant change in the result interpretations.

Assumed was that dikes do not breach, but in reality they have a probability of doing so. This assumption affects the results in two ways: the inundating process and the interpretation of the water level exceedance frequency lines. These possible influences are described below.

As a limitation in this research, the only way the Kampereiland inundates is by water flowing over the overflow resistant part of trajectory 225. If this part happens to breach, this process develops faster. A situation with a dike breach is similar to a situation with a lower crest height: more water flows into the Kampereiland and less water flows onto the IJssel. The neglected failure probability of the overflow resistant part leads to an uncertainty in the presented water level exceedance frequency lines for trajectories 10-2 and 11-2. The water level exceedance frequency lines at trajectory 10-2 are underestimated and those of trajectory 11-2 are overestimated. The magnitude of this error depends on the failure probability of the overflow resistant part of trajectory 225.

A dike breach in trajectory 225 can also occur along the IJssel, causing water to enter the Kampereiland form another location. This is more likely to happen when high discharges on the IJssel are experienced. Assuming there is no storm, the wind does not induce high water set-up levels. This situation could lead to increased water levels in front of the Kamperzeedijk, but these effects are expected to be smaller due to the absence of strong wind. When there is a storm when the dike along the IJssel breaches, no negative consequences arise for Kampen. The Kampereiland inundates faster and in combination with the strong wind this leads to a more extreme situation for the Kamperzeedijk.

Two alternative methods of water entering the Kampereiland have been discussed, but a dike breach from the inside can cause water also to flow out of the Kampereiland. In this research is assumed that all water leaves the Kampereiland in the east into the Ganzendiep. A dike breach in trajectory 225 could either increase the volume ending up into the Ganzendiep or cause the water to end up in the IJssel or in the Zwarte Meer. When the dike between the Kampereiland and the Ganzendiep breaches, a volume of $20.3 \cdot 10^6 m^3$ (areas II and III in Figure 4.7) can flow into the Ganzendiep. The influence of this additional discharges is shown



(a) The water levels for the situation with and without a breach.

(b) The difference between the situation with and without a breach.

Figure 7.2: The influence of a breach between the Kampereiland and the Ganzendiep on the water level in front of the Kamperzeedijk. Assumed is that the total volume of $20.3 \cdot 10^6 \mathrm{m}^3$ flows into the Ganzendiep.

in Figure 7.2. The influence of this breach is largest when no water flows into the Ganzendiep. The consequences of a breach are negligible when there is already water flowing over the crest.

The Ganzendiep has an open connection with the Zwarte Meer. The water levels at the Kamperzeedijk can possibly increase when a dike breach causes the water to flow into the Zwarte Meer. However, this part of the hydraulic system has not been investigated in this research, so the exact consequences remain uncertain. When water flows from the Kampereiland onto the IJssel, this typically means water from the Ketelmeer ending up on the IJssel, the Kampereiland functioning as a bypass. However, a smaller volume ends up in the IJssel due to the storing capacity of the Kampereiland. Despite a dike breach occurring, this area is still able to store some amounts of water. When this water had not flowed into the Kampereiland in the first place, it would have ended up in the IJssel. Therefore, assumed is that a dike breach on the inner slope of trajectory 225 along the IJssel does not induce negative consequences for the water levels at the IJssel.

Water level Kampen and Ganzendiep

Assumed was that the water level at Kampen remains constant as soon as water starts flowing over the overflow resistant part of trajectory 225, taking the phase difference into account. In the real situation, this is not likely to be the case, as the water levels can still increase due to water flowing onto the IJssel or due to the discharge of the IJssel into the Ketelmeer. As a consequence of this assumption, the water level exceedance frequency line at Kampen underestimates the actual water levels.

During a storm, an inundated Kampereiland is subject to wind induced water level set-up. The situations observed are characterized by a strong WNW wind blowing, increasing the water level in the eastern part of the Kampereiland. This water level set-up has not been incorporated in the model, but leads to more water ending up in the Ganzendiep than calculated. As shown in Appendix D, the water level set-up can reach values between 0.30 m and 0.90 m for wind speeds between 20 m/s and 35 m/s. This leads to a substantial tilting of the water level and to more water ending up in the Ganzendiep. However, it is not sure how this is affected by the compartments of the Kampereiland.

Hydraulic interdependencies between the Ganzendiep and the Zwarte Meer

There is an open connection between the Ganzendiep and the Zwarte Water. The Ganzendiep is shaped as a basin and the water levels increase under the influence of a strong WNW wind. However, no interaction between these two water bodies has been incorporated in the model as this interaction is not known. The increase of the water levels at the Ganzendiep results in a higher flow rate in the direction of the Zwarte Meer. This neglected effect makes that the presented water level exceedance frequency lines at the Kamperzeedijk are overestimated.

Situation with increased discharge on the IJssel

This research focused on the consequences of a storm at the IJsselmeer. The Kampereiland has no function during a situation with increased discharges on the IJssel. Increased discharge leads to higher water levels and to the increase of failure probabilities of the dike trajectories along the IJssel. The consequences of a dike breach along the IJssel have already been discussed.

Discharge wave, lake level, wind rotation

In Chapter 5 was decided to neglect the time dependency of the discharge on the IJssel and the lake level at the IJsselmeer. These two stochastic variables were kept constant during the hydrodynamic modelling. The probability of a certain discharge, wind speed and water level occurring is incorporated in the probabilistic HydraNL computations. However, in a storm duration of two days, the discharge and water level can fluctuate. These fluctuations can lead to both lower and higher water levels occurring in the storm development. Some of the possible combinations of these fluctuations are shown in Appendix D (Figure D.2). The values for discharge and lake level used in the HydraNL computations are those in the middle of the storm period. It can be seen that this dashed line value for computations both over- and underestimates the real values, cancelling out the effect of fluctuation. Therefore, concluded is that the incorporation of these time dependencies would not lead to discrepancies in the model results.

The wind direction was also assumed to remain constant during the hydrodynamic modelling. The modelled wind directions were those leading to the highest water levels in the delta. Varying the direction during the storm situation will lead to less threatening situations in terms of maximum water levels. This simplification leads to an overestimation of the water level exceedance frequency lines.

8

Conclusions and recommendations

In this chapter, conclusions are drawn from results and the research questions are answered. It is important to realize that these conclusions are based on the aforementioned assumptions and limitations. The complexities leading to this research were listed in Chapter 2 and are shortly summarized:

- During a storm situation, the Ramspol barrier is closed to protect the Vechtdelta, but this increases the hydraulic loads on Kampen, as water can only flow into that direction;
- According to new insights the crest height of the north-south oriented part of trajectory 225 does not allow water to overflow in the intended situation, but less frequent;
- During a situation in which trajectory overflows as it is intended to do, it is unclear whether the Kampereiland is capable of retaining enough water to significantly lower the hydraulic loads on Kampen.

The conclusions are described in Section 8.1. This chapter ends with Section 8.2, listing the recommendations for future research.

8.1. Conclusions

The main objective of this research was to solve these complexities by quantifying the consequences of various crest heights of trajectory 225 on the water levels at Kampen and IJsselmuiden. The research question was formulated as:

How does the crest height of the overflow resistant part of trajectory 225 influence the water levels at Kampen and at the Kamperzeedijk during a storm situation at the IJsselmeer?

The answer to the main research question is based on those of the sub questions.

How does the current system function from a physical point of view?
This question has been answered in Chapter 4. The conclusions from this chapter are summarized.

Both a storm at the IJsselmeer and a high discharge at the IJssel can cause the water level near Kampen to rise. These water levels are dependent on several stochastic variables. In Chapter 4 it was found out that the water levels are mostly affected by the wind characteristics.

When water is blown from the Ketelmeer onto the IJssel, the water levels rise. By observing the crest heights of trajectory 225 and trajectory 11-2 along the IJssel, it seems unlikely that Kampen is flooded at an earlier stage than the Kampereiland. The safety standard of trajectory 225 is higher than the safety standard of trajectory 11-2 at Kampen. Despite the failure probability being dependent on the contribution of all failure mechanisms, it is strange to find a lower crest height.

When the water level at the Ketelmeer exceeds the crest height of the overflow resistant part of trajectory 225, most of the water will flow into the Kampereiland. This is as a result of its large width compared to the IJssel and the lower downstream water level. No more water flows onto the IJssel and the water level at Kampen stays more or less the same.

The Kampereiland consists of multiple compartments. If a breach occurs in one of the surrounding dikes, only the volume of one compartment flows through the breach. However, assumed was that no dike breaches occur, so these consequences have not been evaluated in this research. If the Kampereiland is completely inundated, the water leaves the area by flowing over the surrounding dike in the east. This is because of this dike trajectory has the lowest crest height of all surrounding dikes and the expected wind induced water level set-up as a result of WNW wind. This water is discharged in the Ganzendiep, which is the branch between this eastern dike and the Kamperzeedijk.

What is the exact role of trajectory 225 and the Kampereiland in the dike system?
Trajectory 225 surrounds the Kampereiland in the west and in the south. It consists of three parts: the Ramspol barrier, the overflow resistant part along the Ketelmeer and the regular part along the IJssel. The Ramspol barrier is inflated during high water conditions at the Ketelmeer to prevent water from flowing into the Zwarte Meer. Its safety standard is 1:10,000 and it has a probability of 1/100 of not closing.

The maximum water level at Kampen should reduce when water flows over the overflow resistant part during a storm. According to new insights, the crest height of the north-south oriented part of trajectory 225 does not allow water to overflow in the intended situation, but less frequent. This is also supported by the results of this research. The return periods for water levels exceeding the crest height are shown in Figure 6.3 and Table 6.1. For the current crest height of 2.8m +NAP, the return period is equal to 2,000 years.

The remaining part of trajectory 225 has to protect the Kampereiland from high water levels along the IJssel. Its crest is lower than the crest of trajectory 11-2 on the other side of the IJssel.

Summarizing: trajectory 225 has two functions. Its first function is to protect the Zwarte Meer, the Kampereiland and its inhabitants during a storm and from high water levels at the IJssel. When it is inundated, the possibility of increased hydraulic loads on the primary flood defences increases. Its second function is to reduce the hydraulic loads on Kampen during a storm by storing water, which makes these functions contradicting.

What are the consequences of an inundated Kampereiland for the Kamperzeedijk?
The influence of the filling up of the Kampereiland for the Kamperzeedijk is concluded by comparing the water level exceedance frequency lines of trajectory 225 with those of the Kamperzeedijk.

The return periods of the events corresponding to other crest heights of trajectory 225 are also shown in Table 6.1. It is concluded that the inundation of the Kampereiland does not immediately lead to a load increase in front of the Kamperzeedijk. This delay is the result of the storage capacity of the Kampereiland. As soon as the Kampereiland is completely inundated and water ends up in the Ganzendiep, the slope of the water level exceedance frequency line increases. This is not necessarily a bad thing. For steeper slopes, the relative difference between the return period of the inundation of the Ganzendiep and the overflow of the Kamperzeedijk becomes smaller. A smaller difference between these return periods means that the probability of the overflow of the Kamperzeedijk, given the fact that water flows into the Ganzendiep.

How does the crest height of the overflow resistant part of trajectory 225 influence the water levels at Kampen and at the Kamperzeedijk during a storm situation at the IJsselmeer?
The influence of the crest height at the water levels can be concluded from the water level exceedance frequency lines, shown in Figure 8.1. The following general conclusions are drawn, regarding the crest height of the overflow resistant part of trajectory 225:

- A higher crest height increases the maximum water levels at trajectory 10-2;
- A higher crest height reduces the maximum water levels at trajectory 11-2;
- With a crest height of 2.8m +NAP, Kampen floods earlier than IJsselmuiden.

Based on these conclusions, an advise is given on what should happen to the crest height of the overflow resistant part of trajectory 225. Because it overflows less frequently, trajectory 11-2 at Kampen overflows earlier than the Kamperzeedijk, despite both dike trajectories having the same safety standard. Based on the results from this research, a crest height of 2.7m +NAP leads to equal return periods for overflow at trajectories 10-2 and 11-2. The reduction of the crest height by ten centimeters increases the return period for overflow at Kampen from 30,000 years to 45,000 years. At the Kamperzeedijk, the return period is reduced from 80,000 years to 45,000 years. In reality these return periods are also affected by other failure mechanisms. A full dike assessment has to elaborate on this.

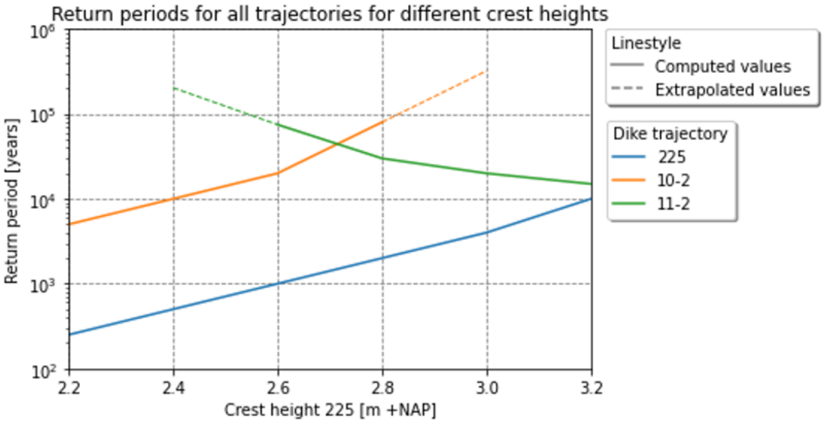


Figure 8.1: The water level exceedance frequency of the crest height at each trajectory, as a function of the crest height of trajectory 225.

Currently, a safety standard of 1:500 is assigned to the overflow resistant part of trajectory 225 to guarantee the overflow during a storm of a certain magnitude. According to WAQUA computations, it overflows less frequently. The inclusion of uncertainties adds some height to the dike to guarantee it is high enough to meet the standard. In most situations, a crest height exceeding the standard does not induce negative consequences, but provides an extra level of safety. This is different in the situation described in this research. An increased crest height of trajectory 225 induces negative consequences for the water level at Kampen. In the current situation, trajectory 225 is approved when it meets its safety standard. It would be more legitimate to assess trajectory 225 by quantifying its consequences on trajectories 10-2 and 11-2.

8.2. Recommendations for future research

Based on the conclusion and discussion, some recommendations are made for future research. These are shortly listed in this section.

- **Failure mechanisms**
  Exclusively based on the water levels, it is hard to draw conclusions regarding the level of safety for the discussed locations. When these water levels are transformed into failure probabilities by means of a dike assessment, a more supported conclusion can be formed on which crest height of trajectory 225 is best for the safety against flooding.

  To point out one specific mechanism: the magnitude of wave impact was not included in this research. Together with the discussed discharge rates over the overflow resistant part, it would be interesting to find out on the effect of this particular influence on the model results.

- **Hydraulic load interdependencies between Ganzendiep and Zwarte Meer**
  During a severe storm, high water levels can occur in the Ganzendiep. The open connection between the Ganzendiep and the Zwarte Meer was not included in the system analysis. The exchange between the Ganzendiep and the Zwarte Meer is expected to increase for higher water levels at the Ganzendiep. This may lead to lower actual water levels. Furthermore, the consequences of a high water level at the Zwarte Meer were not assessed. It may be interesting to extend this research with the inclusion of the hydraulic load interdependencies of the entire Vechtdelta.

- **Bifurcation Kampereiland – IJssel**
  Assumed was that as soon as the Kampereiland starts to inundate, no more water flows onto the IJssel. This does probably happen in reality and simultaneously the IJssel discharges into the Ketelmeer. More research to this situation could validate the assumption or come up with another clarification for the water movement.

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Glossary

Crest height	The height of a dike.
Delta	A system of river branches discharging in a lake or a sea.
Failure mechanism	The different mechanisms that can cause a flood defence to fail. Examples are overflow, sliding of the inner slope and piping.
Failure probability	The probability of a flood defence losing its water retaining function.
Flood defence	A structure to protect the country from the sea, lakes and rivers. Examples are dikes, dams and dunes.
Flood risk	The probability of an undesired event multiplied by the consequences.
Ganzendiep	The basin shaped branch between the eastern part of the Kampereiland and the Kamperzeedijk. It has an open connection with the Zwarte Meer.
HydraNL	A probabilistic model used to compute the statistics of hydraulic loads, such as water level and wave conditions.
Hydraulic load	Expression of load resulting from the water level and wave impact.
Kamperzeedijk	Also: trajectory 10-2. The dike in front of IJsselmuiden.
Model uncertainty	The uncertainty associated to specific models and occurs due to the fact that models show a simplified physical representation of reality.
NAP	Normaal Amsterdams Peil. A vertical datum. 0m NAP is approximately equal to the mean water level of the North Sea.
Overflow	Failure mechanism when the still water level exceeds the crest height of the dike.
Overtopping	Failure mechanism when the still water level is lower than the crest height of the dike, but the waves overtop.
Retention area	An area assigned to store excess water in times of high water levels.
Return period	Expression of probability of failure. A return period of 1,000 years is equal to an annual failure probability of 1/1,000. It does not mean that a structure fails once every 1,000 years.
Safety standard	The maximum allowable failure probability of a dike trajectory, written down in the Dutch Law.
Signal value	Since the failure probability can change over time, a signal value is introduced to guarantee the dike meets this safety standard. The signal value is also expressed as a failure probability and has a more strict value. Written down in the Dutch Law.

Statistical uncertainty	The uncertainty related to extreme value estimations for large return periods when only limited data are available.
Trajectory 10-2	Also: Kamperzeedijk. The dike in front of IJsselmuiden.
Trajectory 11-2	The dike in front of Kampen along the IJssel.
Trajectory 225	The dike surrounding the Kampereiland. Consists of the Ramspol barrier, an overflow resistant part and a regular part.
WAQUA	A computational model used to simulate water levels and water movements in two dimensions
WBI2017	Wettelijk Beoordelingsinstrumentarium 2017. A document consisting of three parts: guidelines describing the procedure of assessing dike trajectories, methods to derive hydraulic loads and computation guidelines.
Water level exceedance frequency line	A line showing water levels and their corresponding return periods.

A

Area overview

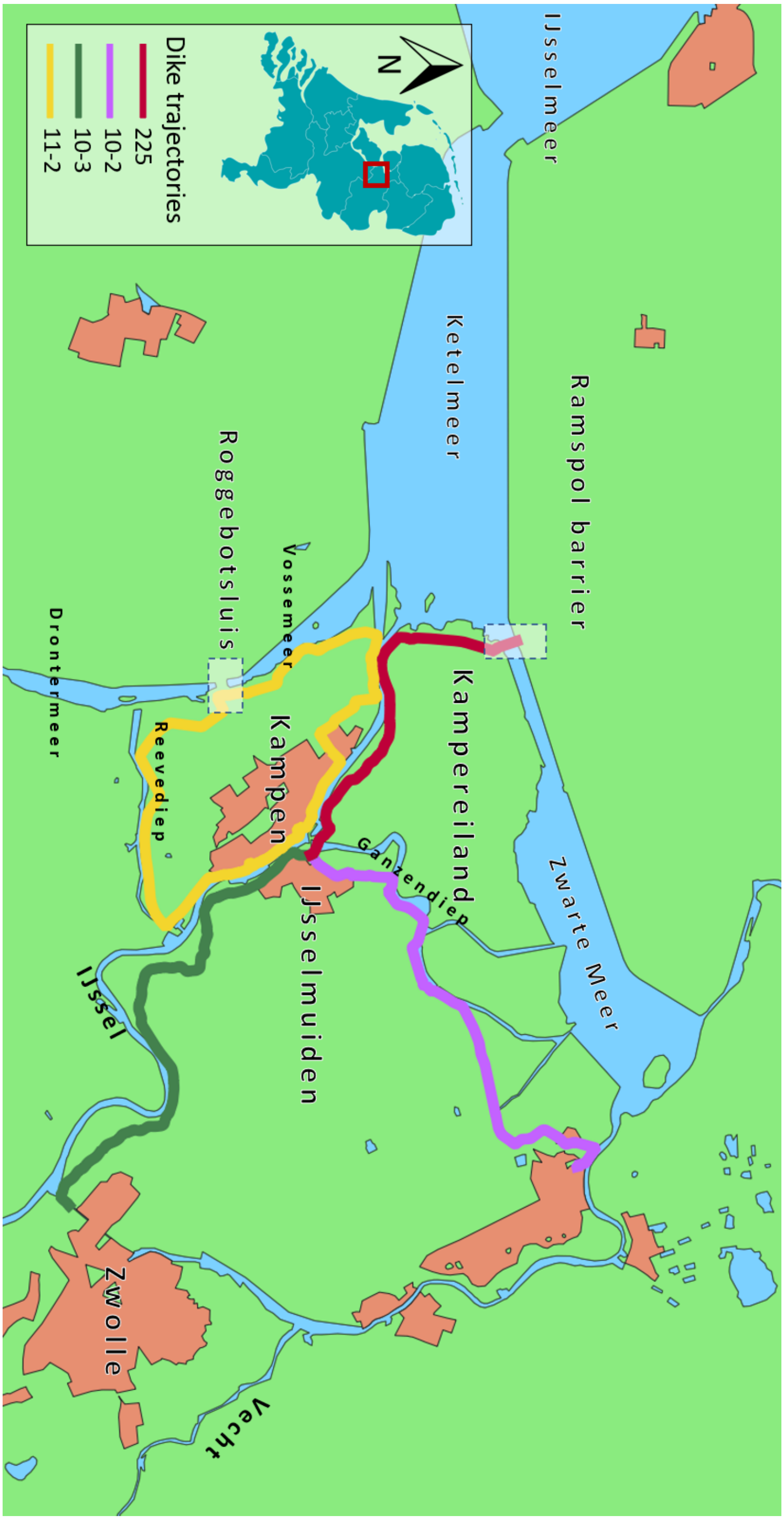


Figure A.1: An overview of the area with all cities, areas, water bodies and dike trajectories.

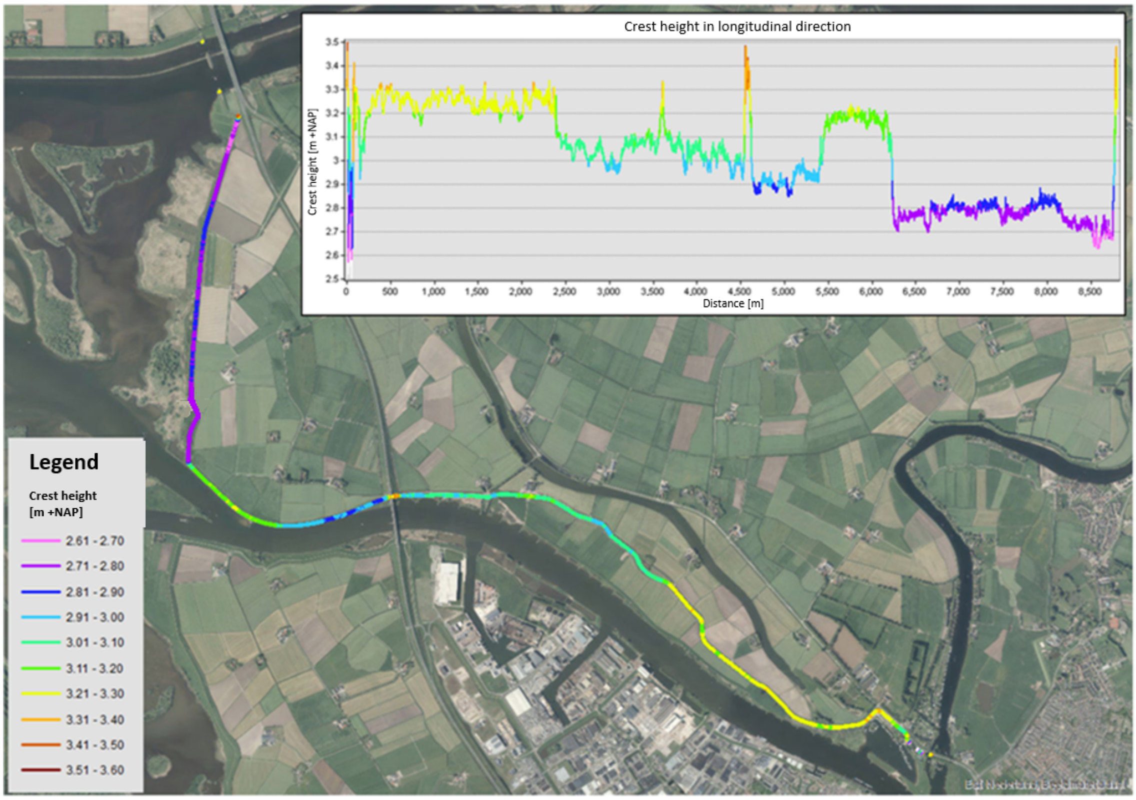


Figure A.2: The crest height along trajectory 225. Figure obtained from [26].

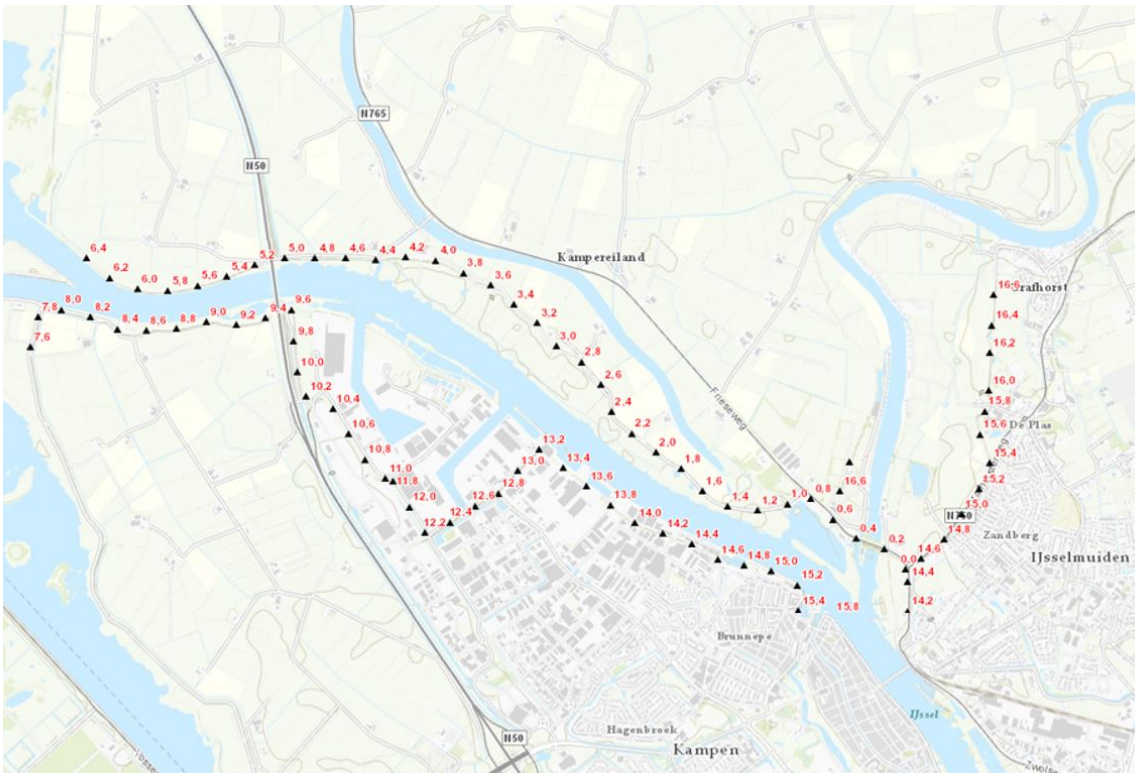


Figure A.3: Indication of hectometer post locations of dike trajectories 10-2, 11-2 and 225. These locations are used in Figure A.4 to indicate the crest height. Image reproduced from [4].

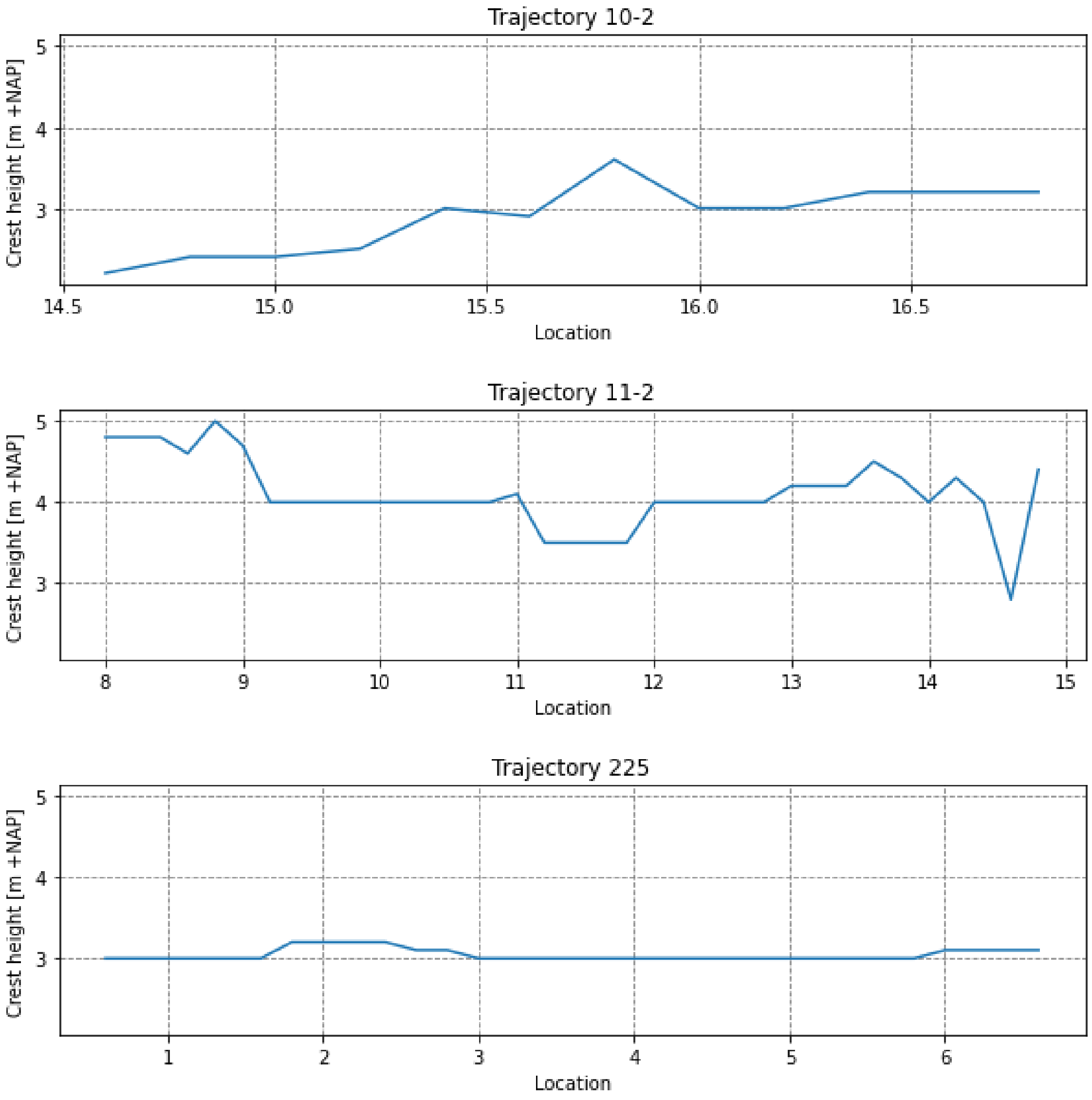


Figure A.4: Crest heights at different hectometer posts for dike trajectories 10-2, 11-2 and 225. Note that the increasing direction of some hectometer posts is from east to west, and some the other way around. The x-axis shows the location of the representative hectometer post as shown in Figure A.3. Data obtained from [4].

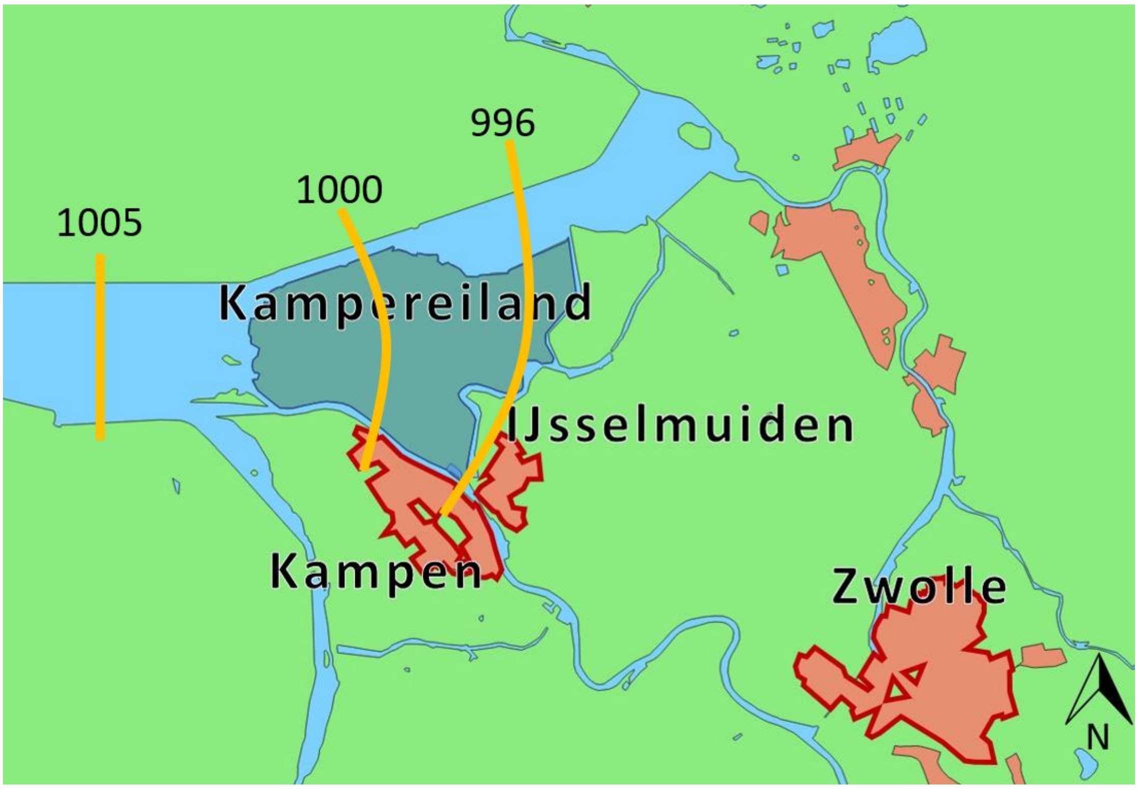


Figure A.5: Indication of the location of the different section lines referred to in Figure 5.9.

B

Model set-up

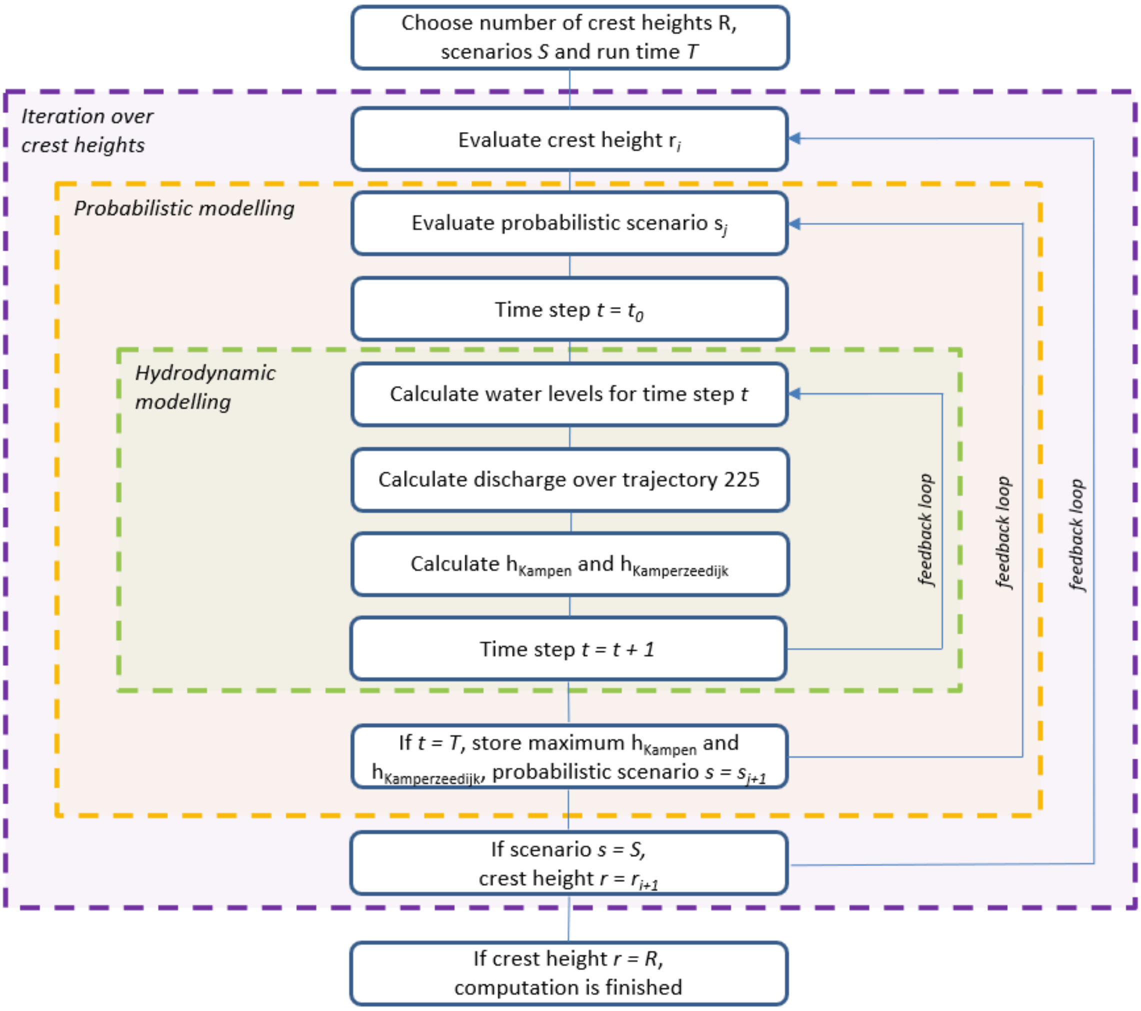
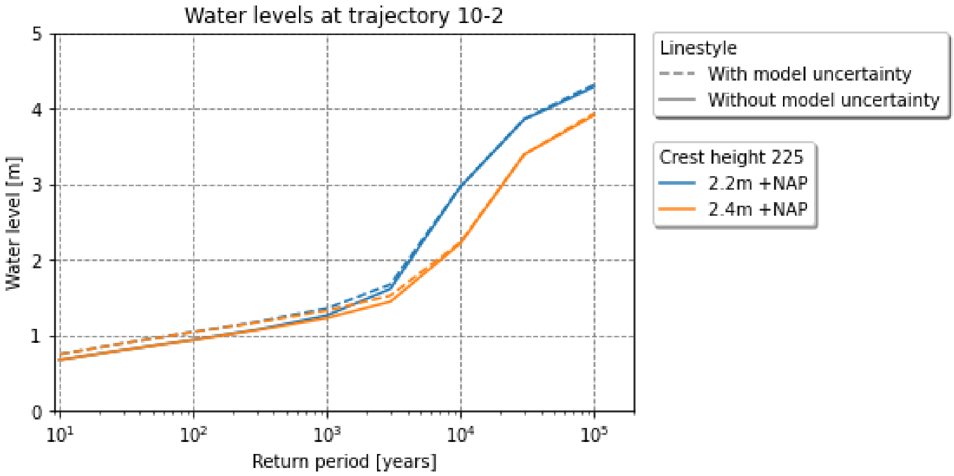


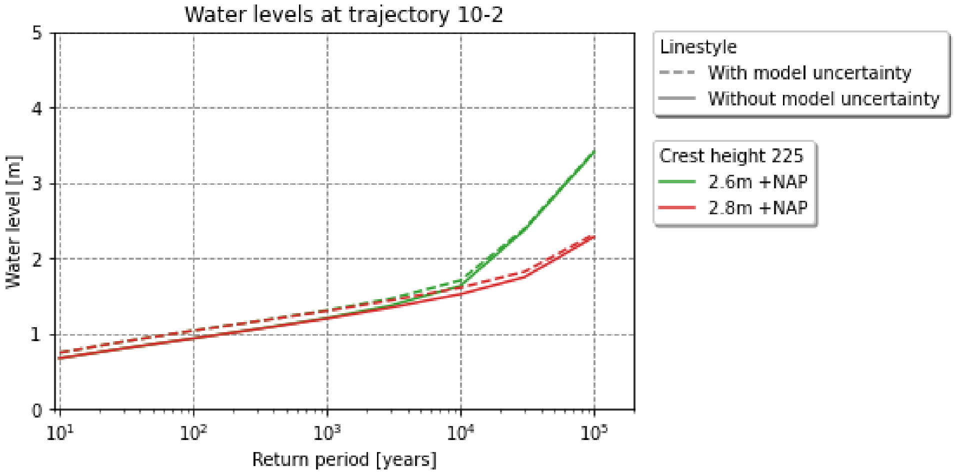
Figure B.1: Schematic visualization of the model set-up.

C

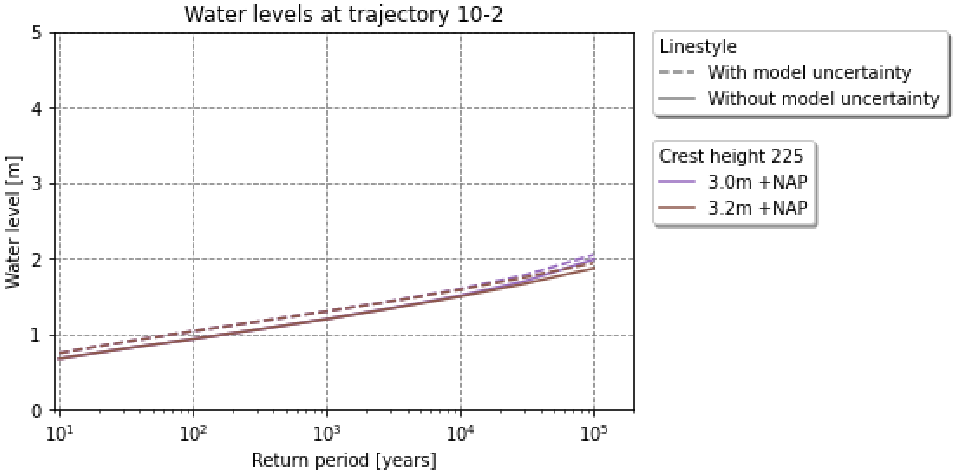
Model uncertainty



(a) Influence of model uncertainty at trajectory 10-2 for crest heights of 2.2m +NAP and 2.4m +NAP.

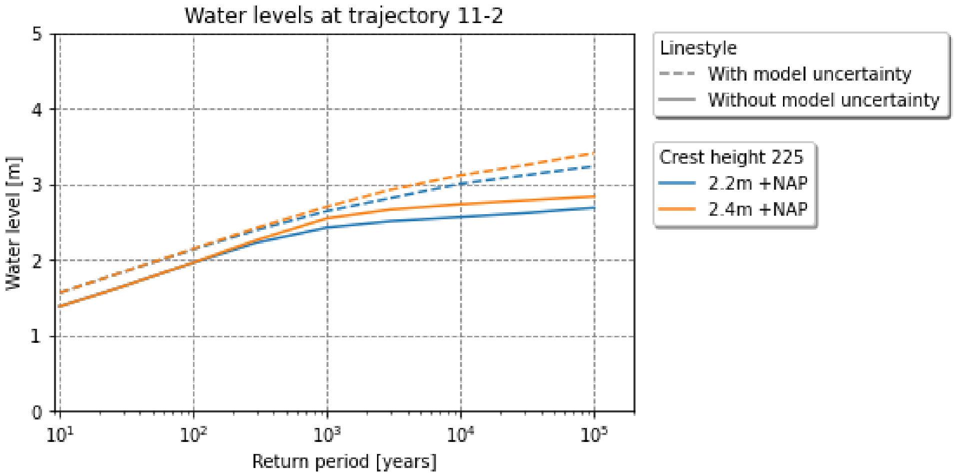


(b) Influence of model uncertainty at trajectory 10-2 for crest heights of 2.6m +NAP and 2.8m +NAP.



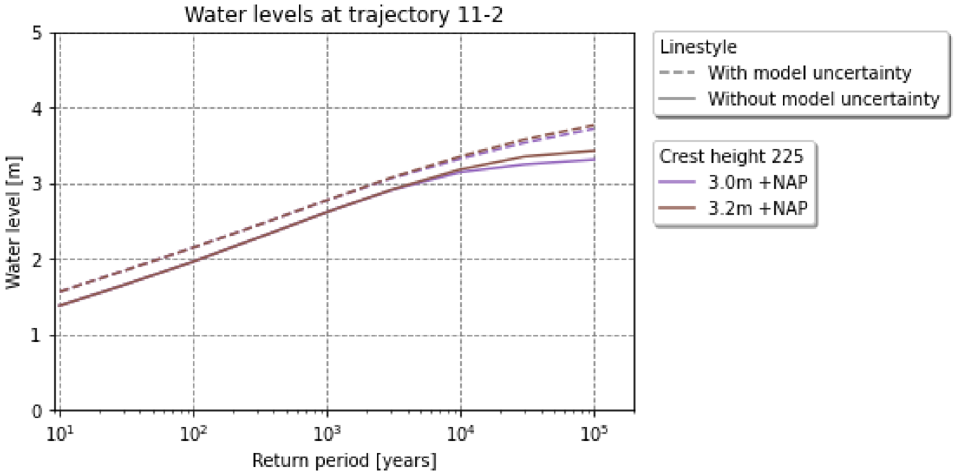
(c) Influence of model uncertainty at trajectory 10-2 for crest heights of 3.0m +NAP and 3.2m +NAP.

Figure C.1: Influence of model uncertainty at trajectory 10-2.



(a) Influence of model uncertainty at trajectory 11-2 for crest heights of 2.2m +NAP and 2.4m +NAP.

(b) Influence of model uncertainty at trajectory 11-2 for crest heights of 2.6m +NAP and 2.8m +NAP.



(c) Influence of model uncertainty at trajectory 11-2 for crest heights of 3.0m +NAP and 3.2m +NAP.

Figure C.2: Influence of model uncertainty at trajectory 11-2.

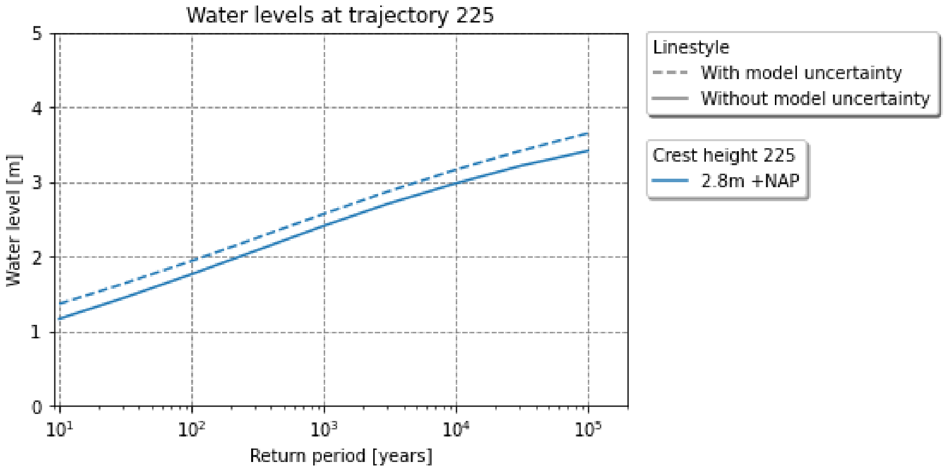


Figure C.3: Influence of model uncertainty at trajectory 225.

D
Discussion

Some additional theory and explanation to the discussion is provided in this Appendix.

Wind induced water level set-up

Wind set-up is described by the following formula:

$$h = 0.5 \cdot \frac{F \cdot C \cdot u^2}{g \cdot d} \tag{D.1}$$

with:

h = Water level set-up at one side of the basin [m];
F = Fetch [m];
C = Constant, equal to $3.5 \cdot 10^{-6}$ to $4 \cdot 10^{-6}$ for wind speeds ≥ 20 m/s [-];
u = Wind speed at a height of ten meters [m/s];
g = Gravitational constant, equal to 9.81 [m/s^2];
d = Depth [m].

The relation between wind speed and the wind induced water level set-up is shown in Figure D.1. This is for a situation with a fetch of 5,000 meters and a water depth of 1.25 meters, to represent the situation inside the Kampereiland when completely inundated.

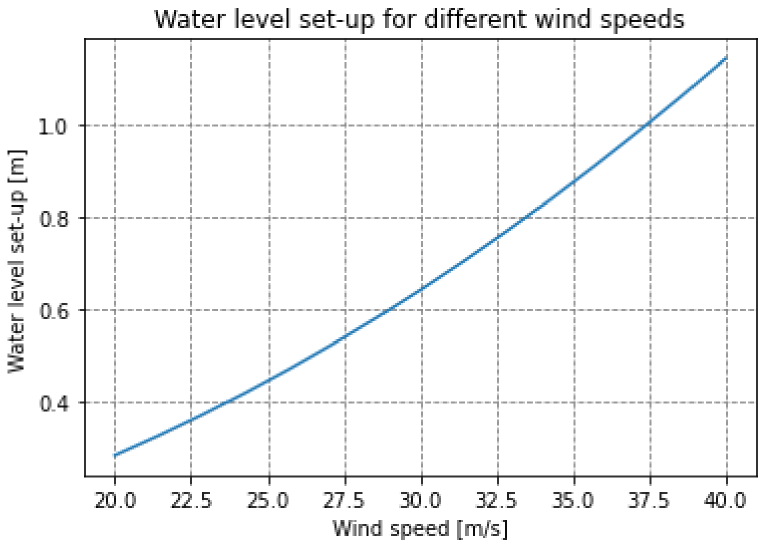
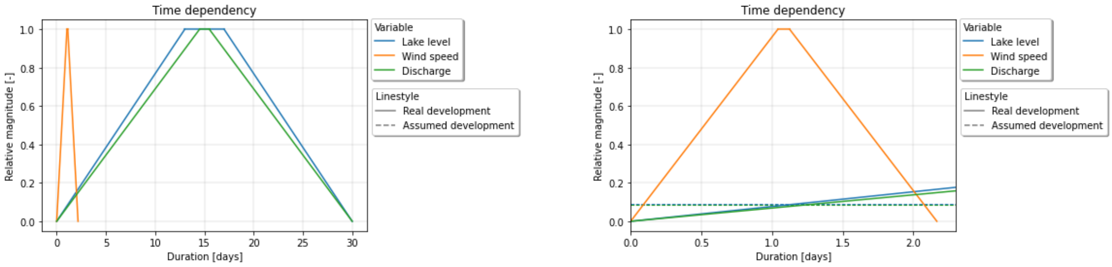


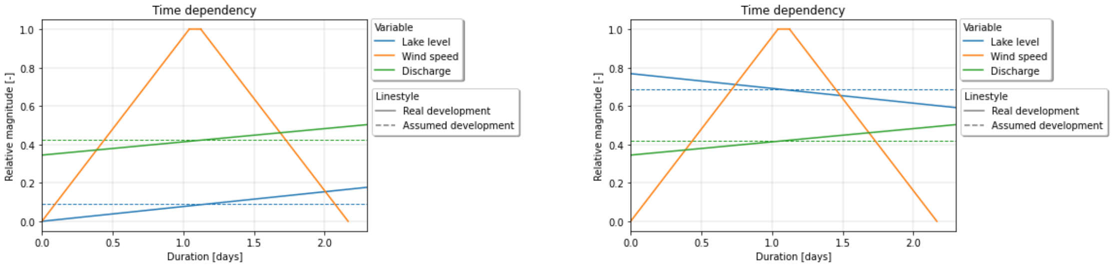
Figure D.1: Wind induced water level set-up for different wind speeds.
This graph shows the relation for F = 5,000 m, C = $3.5 \cdot 10^{-6}$, u = 30 m/s and d = 1.25m.

Discharge and lake level fluctuations



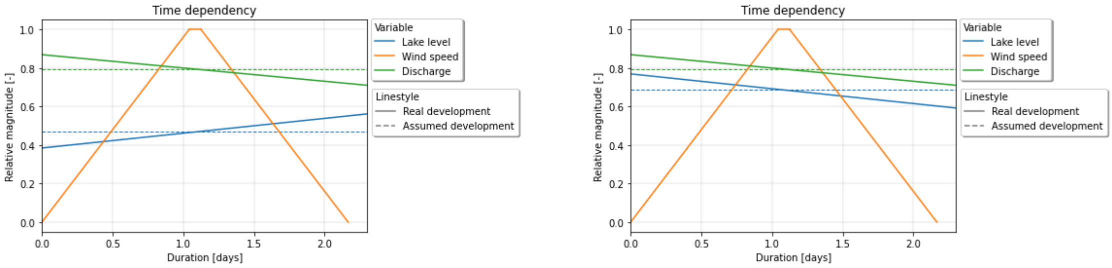
(a) Comparison of the time span for the development for wind, discharge and lake level.

(b) Same figure as (a), but focused on the storm duration.



(c) Increasing discharge and lake level.

(d) Increasing discharge and decreasing lake level.



(e) Decreasing discharge and increasing lake level.

(f) Decreasing discharge and lake level.

Figure D.2: These figures show the time dependency for discharge and lake level during the storm development. The solid lines show the real development for the discharge and the lake level. The dashed lines show the constant value used in the hydrodynamic computations. It can be seen that this dashed line value for computations both over- and underestimates the real values. This causes the effect of fluctuation to cancel out.