The flooding of the Kampereiland during storm and discharge induced breaching

C. A. Brand



TU Delft

The flooding of the Kampereiland during storm and discharge induced breaching

by

C. A. Brand

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Friday December 10, 2021 at 13:45.

Student number:	4253388	
Project duration:	Febuary 1, 2021 – December 10, 2021	
Thesis committee:	Prof. dr. ir. M. Kok,	TU Delft, chairman
	Dr. ir. G. Dupuits,	HKV Lijn in Water, supervisor
	Dr. ir. R. J. Labeur,	TU Delft
	Ir. R. Slomp,	Rijkswaterstaat
	Dr. E. Ragno,	TU Delft

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

TU Delft

HKV LIJN IN WATER

Preface

After nine years of studying to become a Civil Engineer, the moment has come to finally conclude this stage of my life. This thesis is the final part of my MSc track in Hydraulic Engineering. I've had the pleasure of making this thesis at HKV Lijn in Water, where I could always ask for help, feedback and insights into my graduation project. For this I want to thank HKV for providing me with the guidance to successfully complete my graduation thesis.

I also want to thank HKV for still providing ample opportunities to ask questions, guide me and make me feel welcome at the company, considering the circumstances related to the pandemic. I enjoyed the presentations of other students during the studentencafés as well as the feedback and interest of my fellow colleagues showed in my thesis research.

Furthermore, I would like to thank all my committee members for their time and guidance during my thesis research. Matthijs, thank you for your insights not only by asking important questions, but also always keeping my spirit high with your positive attitude and guiding me through the graduation process. Guy, thank you for all your help setting up my model, the feedback on my report, being available whenever I could use a push in the right direction and keeping me on track throughout my graduation period. Elisa, thank you for the insights into extreme events, the good ideas on how to more clearly present my results and constructive feedback during the progress meetings. Robert, I greatly appreciate our meetings, all the information about the water system that you shared with me and helping me narrow down my research. I also want to thank Robert Jan, for your critical questions during my kick-off meeting, driving me to look into the breaching processes, which has proven to be a fine addition to my research. Lastly, I want to thank Roy, who was not part of my thesis committee, but helped me greatly with the information about the modelling of the IJssel- Vechtdelta, with the setup of my model and shaping my research during the early stages.

Additionally, I would want to thank my family and friends. Thank you so much for your support throughout my entire studies, always being there if I was struggling or doubting myself. Thank you for distracting me when I needed the distraction and keeping me focussed when necessary.

C. A. Brand
Rijswijk, December 2021

Summary

The Kampereiland is an island located at the south eastern part of the IJsselmeer in the middle of the Netherlands. This island serves a purpose to lower water levels in the IJssel- and Vechtdelta during high water, by being inundated. This inundation is meant to result in lower water levels in the IJssel near Kampen. However, the flooding of the Kampereiland is a complex case. There are numerous stochastic variables that are used to determine the water levels, as well as breaching possibilities and a compartment structure which is present on the Kampereiland. All these aspects have influence on inundation of the island. In this thesis research, the flooding of the island is analysed, during multiple different types of high water scenarios, as well as with a variation of breaches or no breaching. This is all done while taking the compartment structure on the Kampereiland into account.

To analyse how the Kampereiland floods, three main types of high water scenarios have been analysed. These types are storm dominated scenarios, which are defined by high wind speeds and low discharges. The second type of high water is the discharge dominant scenario. The high water levels in these scenarios are reached by high discharges from the Vecht and the IJssel rivers, in combination with low wind speeds. Lastly, a number of extreme events have been analysed, to give a worst case perspective of the flooding of the Kampereiland. In these scenarios, high wind speeds coincide with high discharges from the two rivers, resulting in extreme water levels in the Ketelmeer, Zwarte Meer and in the Ganzendiep.

Each of the analysed scenarios have outside water levels exceeding the crest height of the flood defenses surrounding the Kampereiland. The scenarios have been analysed for multiple breaching cases. Three different breach locations have been determined. The locations have varying crest heights, type of flood defense (overflow resistant or non overflow resistant), type of high water (storm dominated or discharge dominated) and different hinterland compartments. Each scenarios has then been used to run the model to determine water levels in each compartment. This is done for situations without a breach, a single breach or two breaches at one location. The determination of the water levels is calculated by the use of spillway formulas.

The results show that the Kampereiland mainly floods from west to east. Storm dominated scenarios lead to high water levels in the Ketelmeer, leading to overflow from here. In scenarios up to 32 m/s wind speeds without breaches, the flooding is contained to the compartments to the west of the N50. The entire island floods once water levels increase due to wind speeds of 37 m/s and higher. Adding breaching into the storm dominated scenarios, the results are shifted. Now the evaluated scenarios with 32 m/s also lead to flooding of the entire island. This case still leads to less high water levels on the Kampereiland than the scenarios of 37m/s without breaching, but every compartment is inundated.

The discharge dominated events are contained in the Willem Meyer- and Stikkenpolder. This is due to the presence of the old flood defense, which contains the flooding in cases with and without breaches.

Finally, the extreme events flood the majority of the Kampereiland, similarly to the storm dominated scenarios. The water levels that occur in the Zwarte Meer and Ganzendiep are higher during the extreme events. They also last longer than in the storm dominated scenarios. This results in a small inflow from the north and southeast, while the western side of the Kampereiland rapidly fills up. Breaching during these extreme events leads to higher water levels when the breach occurs in the overflow resistant part of flood defense 225. The rising velocities in the west are also the highest in this case. Eastern compartments have higher rising velocities in case of breaching in flood defense 101 (along the northern boundary).

Contents

List of Figures ix

List of Tables xi

1 Introduction 1
1.1 Background of the research . . . 1
1.2 Objective . . . 2
1.3 Research questions . . . 2

2 The project location and its flooding 5
2.1 The water system of the IJssel- and Vechtdelta . . . 6
2.1.1 The wind dominated part of the delta . . . 6
2.1.2 The discharge dominated part of the delta . . . 8
2.2 Dike trajectories surrounding the Kampereiland . . . 8
2.3 Literature review . . . 10
2.3.1 Historic flooding events . . . 10
2.3.2 Compartmentalisation of land to reduce flood risks . . . 12
2.3.3 Breaching process . . . 12

3 Methodology 17
3.1 Return periods . . . 18
3.2 Sensitivity of the system to parameters . . . 19
3.2.1 Locations 1 and 2 along the western side of the Kampereiland . . . 21
3.2.2 Location 3 along the northern side of the Kampereiland . . . 24
3.3 Conceptual model . . . 26

4 Model setup 29
4.1 Assumptions in the model . . . 29
4.2 Breaching process. . . . 30
4.2.1 Breaching stages . . . 30
4.2.2 Approximating multiple breaches at a single location . . . 31
4.3 Waterflow module . . . 31
4.4 Compartment structure. . . . 33
4.5 Scenarios . . . 34
4.6 Test case . . . 37
4.6.1 Input for the test case . . . 37
4.6.2 Test case without breach . . . 38
4.6.3 Test case with breach . . . 39

5 Model results 41
5.1 No breaches. . . . 41
5.1.1 Storm dominated scenarios . . . 41
5.1.2 Discharge dominated scenarios . . . 44
5.1.3 Extreme events. . . . 44
5.2 One breach . . . 47
5.2.1 Storm dominated scenarios . . . 47
5.2.2 Discharge dominated scenarios . . . 49
5.2.3 Extreme events. . . . 49
5.3 Two breaches . . . 50
5.3.1 Storm dominated scenarios . . . 51
5.3.2 Discharge dominated scenarios . . . 51
5.3.3 Extreme events. . . . 51

6 Discussion 55
6.1 The model results . . . 55
6.2 Influence of the assumptions . . . 56

7 Conclusions and recommendations of future research 59
7.1 Conclusion . . . 59
7.2 Recommendations . . . 62

Bibliography 65

A Breach in compartment boundaries 67

B Model output 69
B.1 Water levels over entire time series without breaching . . . 70
B.1.1 Storm dominated . . . 70
B.1.2 Discharge dominated . . . 72
B.1.3 Extreme event . . . 73
B.2 Water levels over entire time series with one breach . . . 74
B.2.1 Storm dominated . . . 74
B.2.2 Discharge dominated . . . 76
B.2.3 Extreme event . . . 77
B.3 Water levels over entire time series with two breaches . . . 78
B.3.1 Storm dominated . . . 78
B.3.2 Discharge dominated . . . 79
B.3.3 Extreme event . . . 80

List of Figures

2.1 Area overview with Kampereiland and surrounding urban areas 5
2.2 Type of mounds on Kampereilanden 6
2.3 Waterbodies and rivers near the IJssel-Vechtdelta 7
2.4 Main hydraulic loading influence 7
2.5 Lower limit failure probability flood defenses Kampereiland 9
2.6 Signal limit failure probability flood defenses Kampereiland 9
2.7 Regional flood defenses Kampereiland 10
2.8 Flooded areas in the 1926 flooding 11
2.9 Flood defense along the north side of the Kampereiland 13
2.10 The N765 as a elevated line element 13
2.11 Old flood defense along the southern side of the Willem Meyer and Stikkenpolder 14
2.12 Simulations with different compartment topographies 14

3.1 Locations of overflow 19
3.2 Wind data probabilistics 19
3.3 Return periods of different parameters 20
3.4 225 water level as function windspeed for different discharges 22
3.5 225 water level as function lake level for different windspeeds 23
3.6 225 water level as function discharge for different windspeeds 23
3.7 101 water level as function of windspeed for different discharges 25
3.8 101 water level as function of the lake level for different wind speeds 25
3.9 101 water level as function of the discharge for different wind speeds 26
3.10 Conceptual model 27

4.1 Scaling of breach width to simulate 2 seperate breaches 32
4.2 Sketches of the two types of overflow 32
4.3 Numbered compartment structure of the Kampereiland 33
4.4 Water level frequency lines at the Kampereiland 34
4.5 Test case setup with 3 compartments 37
4.6 Example of the input table for the used test case 38
4.7 Test case results with no breach 38
4.8 The breach height and water level in breach compartment during the test case 39
4.9 The water levels in the test case with a breach 40

5.1 The outside water levels used as input during a low discharge scenario with 32 m/s wind speed 42
5.2 The water levels in the compartments in a storm dominated scenario with no breach near maximum outside water level 43
5.3 The water levels in the compartments in a storm dominated scenario with no breach at the end of the calculation 43
5.4 Water levels during a storm dominated scenario without breaching at begin and end 44
5.5 Outside water level used as input for a scenario with 4000 m³/s discharge and 16 m/s wind speed 45
5.6 Water levels during a discharge dominated scenario without a breach around the maximum outside water level 45
5.7 Outside water levels in an extreme scenario, only differing in wind speed 46
5.8 Water levels during an extreme event with 3200 m³/s discharge and 32 m/s wind speed without breaching near maximum outside water level 46
5.9 Water levels during an extreme event with 3200 m³/s discharge and 37 m/s wind speed without breaching near maximum outside water level 46

5.10 Water levels during an extreme event with 100 m³/s discharge and 32 m/s wind speed with one breach around peak outside water level . . . 47
5.11 Water levels during an extreme event with 100 m³/s discharge and 32 m/s wind speed with one breach at the end of the calculation . . . 47
5.12 Water levels on the Kampereiland during storm dominated scenario with 100 m³/s discharge and 37 m/s wind speed at the start of the overflow . . . 48
5.13 Water levels in compartments 6 and 7 with no breach and a breach, for 4000 m³/s discharge. . . 49
5.14 Comparison of times reaching peak water levels in compartments in the center of the Kampereiland . . . 50
5.15 Outside water level which are used as input for extreme scenario with 3600 m³/s discharge and 37 m/s wind speeds . . . 52

7.1 Numbered compartments Kampereiland . . . 60

A.1 Water levels discharge dominated no breach Q4000U16D292 at peak and end with reduced seadike height . . . 67

B.1 Water levels in all the compartments for scenario KsrMp040Q0100U32D292 without a breach . 70
B.2 Water levels in all the compartments for scenario KsrMp040Q0100U37D292 without a breach . 71
B.3 Water levels in all the compartments for scenario KsrMp040Q4000U16D292 without a breach . 72
B.4 Water levels in all the compartments for scenario KsrMp040Q3200U32D292 without a breach . 73
B.5 Water levels in all the compartments for scenario KsrMp040Q0100U32D292 with one breach in compartment 3 . . . 74
B.6 Water levels in all the compartments for scenario KsrMp040Q0100U37D292 with 1 breach in compartment 3 . . . 75
B.7 Water levels in all the compartments for scenario KsrMp040Q4000U16D292 with one breach in compartment 10 . . . 76
B.8 Water levels in all the compartments for scenario KsrMp040Q3200U32D292 with one breach in compartment 3 . . . 77
B.9 Water levels in all the compartments for scenario KsrMp040Q0100U32D292 with two breaches in compartment 3 . . . 78
B.10 Water levels in all the compartments for scenario KsrMp040Q4000U16D292 with two breaches in compartment 10 . . . 79
B.11 Water levels in all the compartments for scenario KsrMp040Q3600U37D292 with two breaches in compartment 3 . . . 80
B.12 Water levels in all the compartments for scenario KsrMp040Q3600U37D292 with two breaches in compartment 9 . . . 81
B.13 Water levels in all the compartments for scenario KsrMp040Q3600U37D292 with two breaches in compartment 10 . . . 82

List of Tables

3.1 Combination of parameters that is most likely to cause the occurring water level for a return period of 1/3000 years at locations 1 and 2. 21
3.2 Combination of parameters that is most likely to cause the occurring water level for a return period of 1/300 years at location 3. 21

4.1 Overview of the calculated scenarios in this research. 35
4.2 Estimation of the probabilities by using Hydra-NL input data, per storm or discharge driven scenario. 36
4.3 Estimation of the probabilities by using Hydra-NL input data, per extreme scenario. 36

5.1 The rising velocities and maximum water levels per compartment for a scenario with a discharge of 100 m^3/s and wind speed of 32 m/s with a double breach in compartment 3. 52
5.2 The rising velocities and maximum water levels in the worst case scenario per compartment. . . 53

1

Introduction

The Netherlands is a country which has always had to deal with the threats of water. The sea on the northern and western side of the country and multiple rivers running through the entire country are consistent threats to safety. Considering that 26% of the country is below mean sea level and 29% of the country is flood prone [2], dealing with water related threats has become an important part of the Dutch way of life.

To manage the threat that the water poses to safety against flooding, an evaluation system is used in the Netherlands. Before 2017, this was based on the return period of the hydraulic loading that the flood defense should be able to withstand. In 2017 this has been changed. Now, the evaluation method is called the Wettelijk Beoordelingsinstrumentarium 2017 (WBI 2017). This evaluation approach is based on the safety against flooding, of every individual that lives in the Netherlands. Every person living in the Netherlands has a maximum probability of loss of life due to a flood, of 1/100.000 per year [20]. From this starting point, the maximum allowable failure probability of every flood defense in the Netherlands is calculated. This change in approach of evaluating safety against floods has led to changes in the safety standards of flood defenses. On a national scale, flood defenses are now evaluated to see if they meet the new safety standards that have been assigned.

Another part of flood safety is lowering water levels that occur, instead of increasing the resistance aspect of a flood defense. This insight has been used since the year 2000, to provide rivers in the Netherlands with more space to flow [13]. This large-scale project is called “Room for the River” and has been implemented in many projects over the last 20 years. The Reevediep bypass in the IJsseldelta, one of the final additions to the Room for the River projects, has been officially opened in 2019 [14].

1.1. Background of the research

The IJssel- and Vechtdelta is a complex water system with two major rivers which empty into two connected lakes, a storm surge barrier and a large area which is designed to inundate due to flood water from overflow and overtopping. Recently there have been many plans and projects to improve the protection against flooding of the area. Examples of these projects are the addition of the Ramspolkering and the bypass Reevediep. The hydraulic loading changes due to the implementation of the projects. This has been shown in detail in the study of Stijnen et al ([18]), for specifically the IJsseldelta Zuid (IJDZ) project, where the 2D water flow modelling program WAQUA [30] is used to show the new hydraulic loading conditions based on known hydraulic input in the IJsseldelta.

However, there has never been a detailed study on how the Kampereiland floods after the planned changes in the water system. The impact analysis of the addition of the bypass Reevediep [18] shows that hydraulic loads further downstream from the inlet of the bypass slightly increase. The location where these slight increases are expected, also correspond to the hydraulic loading of the primary flood defense which have gotten a far stricter safety standard in the WBI 2017. The new safety standard of this flood defense is 1/10000 years. Because a part of this flood defense has also been made susceptible to overflow for water levels that occur with a return period of 1/500 per year, this leads to contradictory demands. The susceptibility to overflow

has been implemented to reduce the water level increases near the city of Kampen, when the Ramspolkering closes. The overflow of primary flood defense 225 leads to inundation of the Kampereiland, which acts as an emergency flood storage to lower the water levels which would otherwise increase near Kampen.

The lack of detailed analysis of how the Kampereiland will flood leads to uncertainties of risk for the inhabitants. This uncertainty is further increased due to it being unknown whether the primary flood defense of 225 will withstand the hydraulic loads which correspond with the stricter safety standards that have been assigned to the trajectory in the Waterwet [11]. Due to the stricter safety standards, the hydraulic loads that need to be retained are higher than what the flood defense was designed for in the past. The primary flood defense 225, a connecting dike between the town of IJsselmuiden and Ramspol, most likely will not meet the required probability of safety of 1/10.000 [18]. According to the study of Stijnen et al ([18]), the probability that a breach will occur in the primary flood defense 225 is large. A very general insight into breaching of the primary flood defense is given in this study, but this does not cover the presence of the compartments on the Kampereiland. In these general breach analyses, breaching formulations have been used that are based on long-lasting high-water waves on the river. At the primary flood defense of 225, the storm surge on the IJsselmeer is a high-water situation as well, where the high-water duration is far shorter. This results in a very different type of high-water scenario, which also leads to a possibly different breaching process. Breaching scenarios in estuaries of rivers with both storm surges and large river discharges have not been studied in detail in the Netherlands.

A number of unknowns related to the flooding of the Kampereiland, have been listed here:

1. Whether the primary flood defense trajectory 225 meets the required failure probability of 1/10.000 years. It has been designed to withstand hydraulic loads for the design standards of 2003;
2. The consequences of a breach of the Ganzensluis (where according to recent insights, the hydraulic loads will slightly increase [18]) for the inundation of the Kampereiland are unknown;
3. Some general breach analysis of trajectory 225 has been done. This does not include the reduced inflow into the Kampereiland due to submerged flow which follows from compartments being filled up. This could strongly affect breach growth and width;
4. The sequence of flooding and what parts of the Kampereiland do flood, for different events is an uncertainty due to the regional flood defenses, old flood defenses and mounds located on the Kampereiland;
5. The risk for the inhabitants of the Kampereiland are unclear because the flooding sequence is unclear.

1.2. Objective

The goal of this research is to understand the flooding of the Kampereiland, which provides guidance for policy makers to better inform inhabitants of the Kampereiland of their flood safety situation, while also providing in-depth analysis of the role of the compartments of the Kampereiland during the inundation.

The compartments reduce the speed at which inflow into the island take place, by individually filling up first. This affects the inflow rate from the water levels outside of the Kampereiland. Whether this inflow reduction is relevant for the Kampereiland is part of this research. No other research has combined the compartment structure of the Kampereiland with breaching analysis thus far. In this, breaching plays a significant role because trajectory 225 might not meet the required safety standards. Breaching analysis is difficult to put into the existing model (WAQUA) due to the discretisation used. Through this research, indepth analysis of the influence of the reduced inflow due to compartments and breaching of the flood defense are combined. This covers three of the listed uncertainties in section 1.1.

1.3. Research questions

To find answers to the unknowns listed in 1.1, the main research question is formulated as follows: ***How does the Kampereiland flood during high water scenarios, while taking the uncertainties in the breaching process and compartmentalisation into account?***

By answering this main research question, the 3rd, 4th and 5th unknowns are answered. The first two unknowns are outside the scope of this research. This will be further elaborated upon in chapter 6.

A structured approach is followed, to answer the main research question in steps, by answering multiple sub-questions. These sub-questions are listed below, including a first impression on how the sub-questions will be answered.

1. *What are the relevant flooding scenarios for the Kampereiland?*
   Answering this question gives insight into how the water system of the IJssel- and Vechtdelta functions. A first impression of these scenarios can be found in the already present research of the quick-scan of safety analysis which is referred to in Stijnen et al [18]. However, in this quick-scan analysis of the IJssel- and Vechtdelta, the focus is on wind dominated scenarios. In this thesis the discharge scenarios from the Vecht also play a role. Using the knowledge of the functioning of the water system of the IJssel- and Vechtdelta, the present WAQUA calculations of the IJssel- Vechtdelta and Hydra-NL, scenarios that lead to overflow of flood defense 225 and regional flood defense 101 will be used as input for the flooding analysis.

2. *What is the compartmentalisation structure on the Kampereiland?*
   In this sub-question, a subdivision of the compartments on the Kampereiland is made. This gives insight in the different compartments, which (old) flood defenses separate the compartments and gives the heights of these compartment boundaries. With this information, the flooding sequence of the Kampereiland can be specified more clearly using the found compartment structure, knowing what the average ground level is, when the compartment boundaries overflow and how large the capacity of each compartment is in total.

3. *What are the uncertainties in the breaching process and compartmentalisation structure?*
   The breaching process, predominantly based on empirical research, is a field of study in which a lot is still unknown. Whether breaching takes place is already an uncertainty for the flooding of the Kampereiland. Aside from this, the location, the amount of breaches, if there is a maximum breach width and the shape during the growth stages of the breach are all uncertainties that will be weighed against each other. The way these uncertainties are shown, is by giving insight into the effects that these uncertainties have. How different is the outcome based on different breach locations or number of breaches. How does this change the inundation? These are aspects of the breaching uncertainty which are treated. The compartment uncertainties are mainly due to how these compartments are chosen, what effect the boundaries and seperately filling up compartments have on the inundation speeds of the island.

4. *How does a breach during overflow impact the flooding of the Kampereiland, in a storm scenario?*
   General breach analyses that are currently available are based on data from river dike breaches. These follow from long high-water wave discharges in the rivers. Storm setup is a much faster process, which could lead to faster growth of the breach. Using the breach growth formulations of Verheij and van der Knaap [27] the breach size is computed, leading to inflow of water into the Kampereiland.

5. *How does a breach during overflow impact the flooding of the Kampereiland, in a high discharge scenario?*
   Here a similar analysis is done as in the previous sub-question, but the loading of the system is different. In this case, the system is forced by high discharge, leading to slower increases of water levels. Having both the storm setup and high discharge scenarios, these can be compared by showing the influence of the forcing on how the Kampereiland floods.

6. *Using the defined compartmentalisation structure, how does the flooding of the Kampereiland propagate through the island?*
   The defined compartmentalisation structure and the breaching analysis are now combined to show the propagation of the flooding of the Kampereiland. This shows the development of a flood, in what time sequence water levels on the island would rise, and at which location this would happen. The outcome of this analysis can be used to provide information to the inhabitants of the Kampereiland to know what can be expected during a flooding scenario. Another insight it gives is for policy makers to understand the sequence of the flooding of the Kampereiland.

2

The project location and its flooding

The Kampereiland is a small island located in the IJssel- and Vechtdelta. Together with Mandjeswaard, Polder de Pieper and the Zuiderzeepolder, this area is called the Kampereilanden (see Figure 2.1).

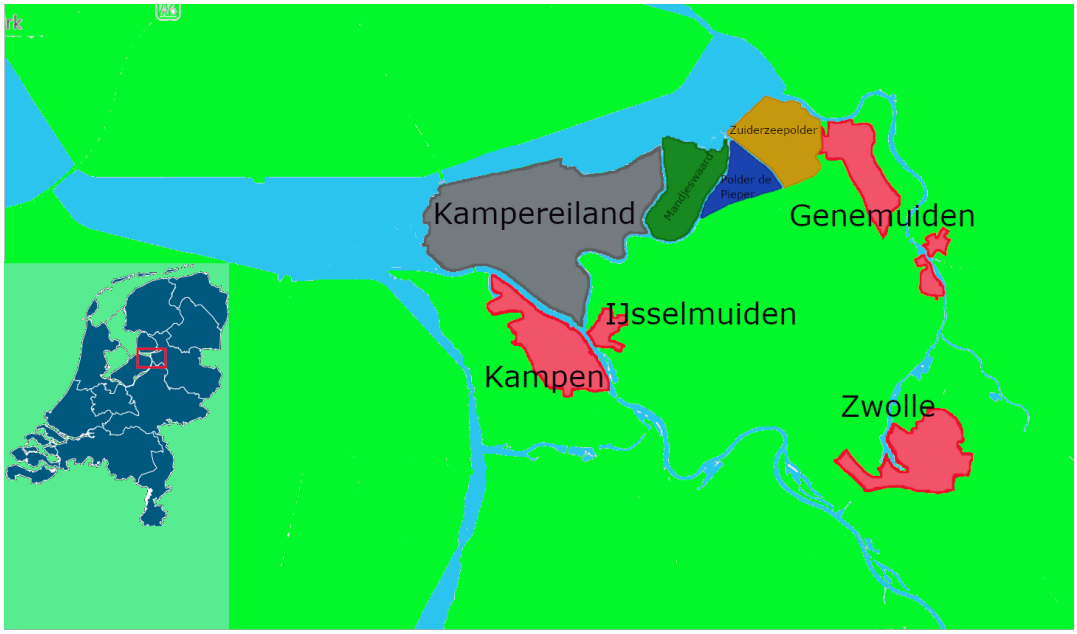


Figure 2.1: The Kampereilanden, with Mandjeswaard, Polder de Pieper and the Zuiderzeepolder. The main urban areas are marked red.

The Kampereiland is the largest of these islands and is the focus of this research. This island is in the most Western part of the province Overijssel. In 2020, the Kampereiland had 480 inhabitants, with most of the inhabitants being farmers [1]. Most of the inhabitants on the Kampereiland live on mounds, which are man-made high grounds, to locally increase the ground level of their property. Multiple different types of mounds were made on the Kampereiland against coastal floods in the past, as shown in Figure 2.2.

The presence of the mounds suggests that there is a necessity to protect property against water. The mounds protect the property of the inhabitants of the Kampereiland against floods, which is needed because the Kampereiland is an outer-dike area. This implies that there is less protection against flooding by the presence of flood defenses. This means that inhabitants themselves need to take more precautions to prevent damage due to flooding. This is especially important on the Kampereiland because this area is used as a water retaining area to lower water levels near Kampen when the Ramspolkering is closed.

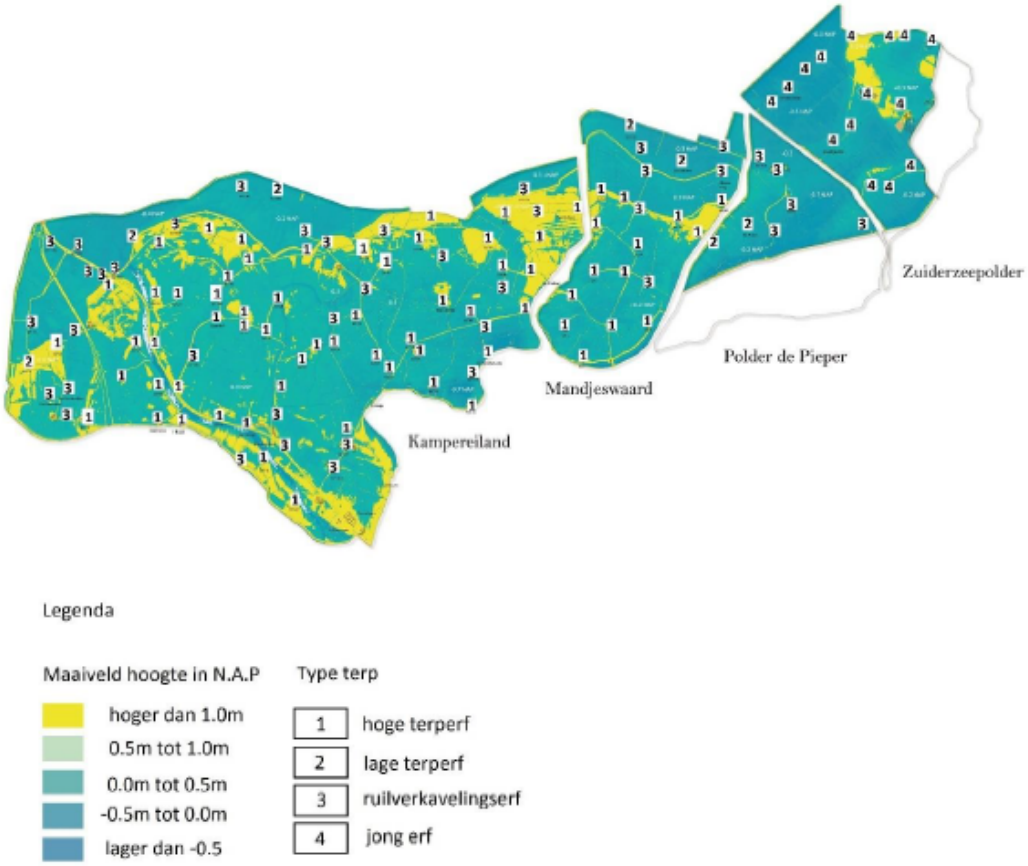


Figure 2.2: Type of mounds on the Kampereilanden [17].

2.1. The water system of the IJssel- and Vechtdelta

There are two rivers which flow into the IJssel- and Vechtdelta. These are the IJssel and the Vecht. Water in both rivers flows in Western direction. The IJssel directly flows into the Ketelmeer, whereas the Vecht first flows into the Zwarte water, then the Zwarte Meer, passes the Ramspolkering and finally discharges into the Ketelmeer. An overview of the surrounding area with the different lakes is shown in Figure 2.3.
The IJssel- and Vechtdelta can be subdivided into two areas. The first is the storm dominated part of the delta, the second is the discharge dominated part. The storm or wind dominated (in Dutch: windgedomineerd) part is the north-western part of the delta. This part has moved land inwards due to the addition of the Reevediep bypass to the IJsseldelta [19]. The discharge governed aspect (in Dutch: afvoergedomineerd) comes from the eastern and south-eastern end of the delta, where the inflow of the Vecht and the IJssel influences this. An estimate of the boundaries of these areas is shown in Figure 2.4.

2.1.1. The wind dominated part of the delta

One of the major components in this delta is the Ketelmeer. This lake connects the delta to the IJsselmeer, where the water from the IJssel- and Vechtdelta finally discharges. The water level in the IJsselmeer is managed between different bounds according to the seasons of the year. The desired bandwidths for the water levels lie between the -0.40 to -0.05m NAP [23]. Managing the water level between these boundaries is done with the help of the discharge locks at the boundary of the IJsselmeer with the Waddensea. As the Ketelmeer is in direct contact with the IJsselmeer, the water level in the Ketelmeer is directly related to the water level of the IJsselmeer.

Under normal circumstances, the Zwarte Meer discharges the water that flows into the lake from the Vecht, into the Ketelmeer. However, during storm scenarios with a strong wind coming from the North western direction, the water will flow in a reverse direction, from the IJsselmeer into the Ketelmeer and further into the Zwarte Meer. This can be prevented by the Ramspolbarrier, which is a large dam, made of reinforced

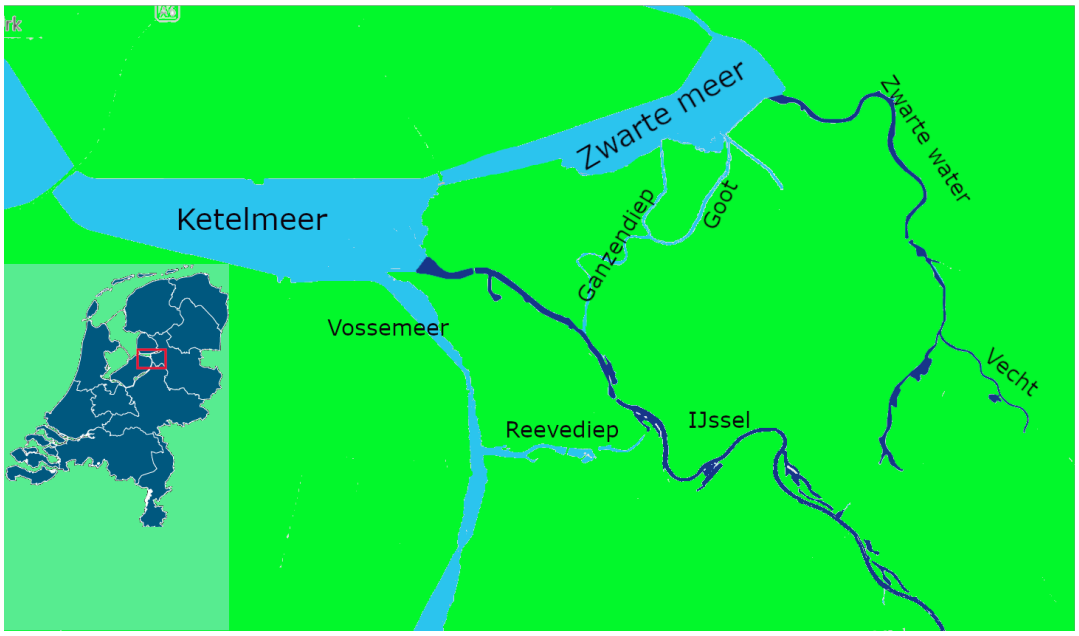


Figure 2.3: Water bodies in the IJssel- and Vechtdelta.

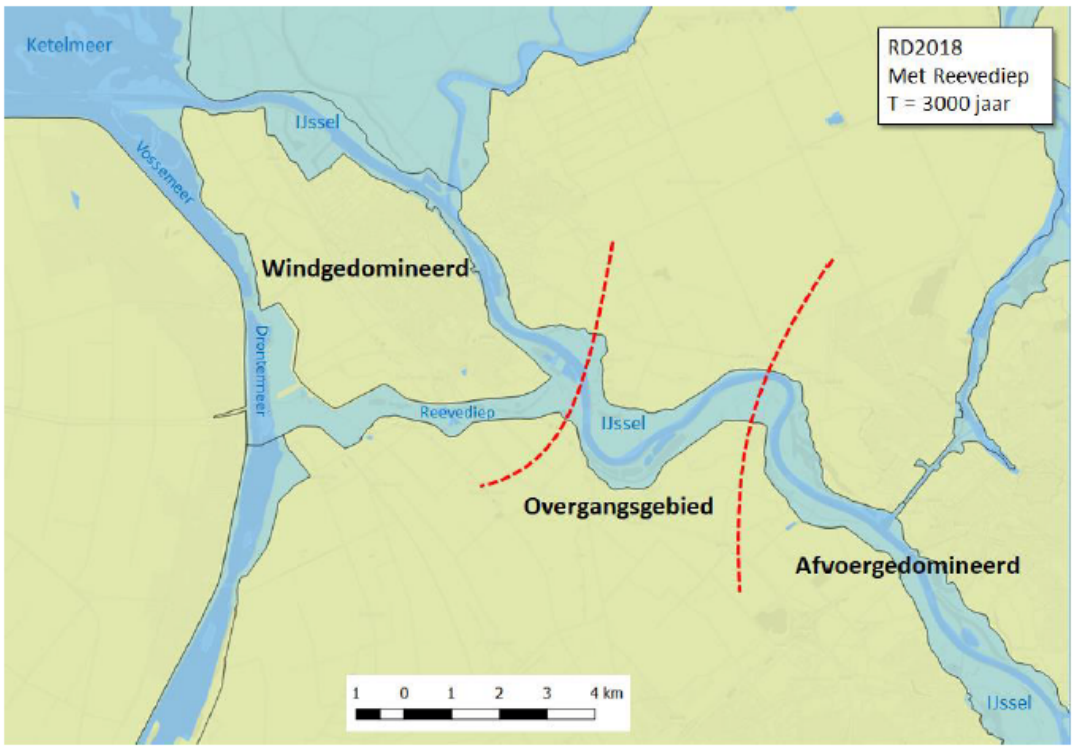


Figure 2.4: Wind and discharge dominated areas in the IJssel- and Vechtdelta [19].

rubber. This rubber can be inflated, leading to a blockage of the waterflow from the Ketelmeer to the Zwarte Meer. When inflated, the Ramspolbarrier is 10m high and 240m wide. This dam will be closed if 3 conditions happen simultaneously [12], namely:

- The water level on the Ketelmeer is higher than 0.5m +NAP;
- There is a strong wind from North-Western direction;
- There is a net discharge into the Zwarte Meer from the Ketelmeer.

2.1.2. The discharge dominated part of the delta

The discharge into the delta is influenced by two rivers, namely the IJssel and the Vecht. The IJssel flows into the delta from the southeast. Just to the south of Kampen, the intake structure for the Reevediep bypass is located. This is a side branch of the IJssel, which is used to reduce the peak discharge of the IJssel further downstream, during high discharge times. Part of the flow is redirected through the Reevediep. From the Reevediep, water flows through the Vossemeer into the Ketelmeer. The main reason for this Room for the River project is to lower the water levels at Zwolle by roughly 40 cm. Zwolle is located 15 km further upstream from Kampen.

Further to the northeast, the Vecht discharges water into the Zwarte Meer. There is a connection between the Zwarte Meer and the IJssel, through the Ganzendiep. This connection is in open contact at the end of the Zwarte Meer but closed off with the Ganzensluis at the intersection with the IJssel. It is important to note, that once the Ramspolbarrier closes, the Zwarte Meer also gets closed off. This means that the inflow of water from the Vecht cannot discharge into the Ketelmeer, thus the water level in the Zwarte Meer, Ganzendiep, Goot and Veneriete rise [17].

2.2. Dike trajectories surrounding the Kampereiland

In 2014 the Water Act was amended. This amendment led to a new evaluation method applied since 2017 [21]. In these new regulations, the safety standard of a dike trajectory is no longer based on the return period of the hydraulic loads, but now is determined by the failure probability of the trajectory.

The new policy set out in the update of the Water Act in 2014 involves several changes to the previously present regulations. Firstly, the primary flood defenses in the Netherlands are no longer treated per dike ring, but per dike trajectory. A dike ring is an area that is protected by a primary flood defense or high ground. The issue with using dike rings is the variation for the optimal standards. To deal with this in an economically more preferred way, in the new regulations, dike trajectories are used [15]. Dike trajectories are trajectories of primary flood defenses which have their own safety standard [29]. This allows for determining more optimal standards per flood defense system.

Since the new regulations use dike trajectories, this has also led to changes in the specific safety standards of these newly used trajectories. The determination of the safety standards follows from a probability of flooding of an area. This means that the safety standard is no longer based on the frequency of a certain load. Under the new legislation the probability of failure of the flood defense is calculated in a full probabilistic manner, for every failure mechanism. This is then combined to determine the total failure probability of the flood defense. The allowable failure probability of a flood defense is determined by the chance that a person loses his life due to a flooding. This is compared to the failure probability that is calculated for the flood defense to evaluate whether the flood defense suffices or not. The required safety standards of the flood defenses in the IJssel- and Vechtdelta are shown in Figure 2.5 and give the maximum allowable failure probability of the flood defense (in Dutch, this is called the ondergrens). If a flood defense does not meet the required safety standard, it needs to be strengthened to pass the requirement. However, improving the flood defense takes time. To make sure that the flood defenses always meet their safety standard, a signalling safety standard is used. This is an even stricter safety standard, which gives an indication that the current safety standard of the flood defense is nearing the maximum allowable failure probability. When this signalling safety standard is exceeded, the minister of Infrastructure and Environment is informed, so a process of improvement of the flood defense can be initiated. The accompanying signalling safety standards for the primary flood defenses in the IJssel- and Vechtdelta are shown in Figure 2.6.

As can be seen in Figure 2.5, dike trajectory 225 has a safety standard of 1/10000 per year. However, due to the implementation of the Ramspolkering, one of the requirements was that the north south orientated part of trajectory 225 had to be adjusted to overflow during high water circumstances, according to a water level with a return period of 1/500 years (+2.87m NAP) [16]. This is to reduce the water levels at Kampen, due to the addition of the Ramspolkering.

The dikes along the northern and eastern side of the Kampereiland are not primary flood defenses but are classified as regional flood defenses. This means that these flood defenses are meant to protect the hinterland from the regional water bodies located in the area. The flood defenses are meant to reduce the area impacted



Figure 2.5: Dike trajectories in the IJssel- and Vechtdelta with their accompanying safety standards [31]



Figure 2.6: Dike trajectories in the IJssel- and Vechtdelta with their accompanying signalling safety standards [31]

by a flood [29]. These flood defenses have a safety standard of 1/500 per year and parts of these flood defenses are meant to be susceptible for overflow during high water scenarios [6]. The regional flood defenses along the Kampereiland are shown in Figure 2.7.

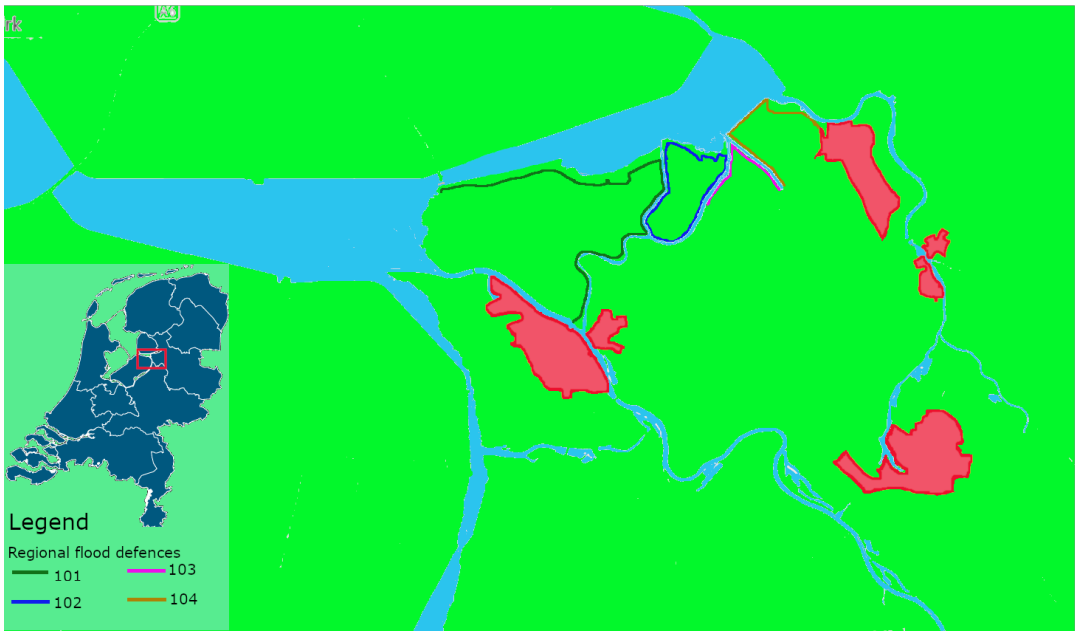


Figure 2.7: The regional flood defenses along the Kampereilanden and the main urban areas (in red).

2.3. Literature review

There are a few different aspects for which literature research needs to be done. Firstly, the water system has changed a lot over the years, partially due to flooding events in the past. These flooding events give insight into how breaches in the past have occured, how these took place and what the effects of these breaches were. Historic flood events can give insight into where breaches might take place. Besides historic breaches in the past, the effect of the compartment structure and the breaching process itself are two more aspects in this research that require extra attention. This is to better understand these processes, to be able to make founded decisions regarding assumptions and making choices in what to take into account for this research.

2.3.1. Historic flooding events

There have been multiple breaches due to flooding events that occurred in the past in the Netherlands. Floods due to high discharges and storm surges are important for this research, since these are the two main hydraulic forcings in the IJssel- and Vechtdelta.

High discharge river floods

In the thesis of Ten Voorde [22], multiple historic flooding events have been analysed based on available data such as old maps and documentations of floods and the accompanying breaches that occured. In detail, the thesis research performed looked into the breaching process which occured during 7 different years, namely 1784, 1799, 1809, 1820, 1855, 1861 and 1926. In the analysis, an important conclusion is that in all these years, the main cause of breaching was due to ice dams on the rivers. These dams prevented the discharge of melt water. Currently, this cause for breaching is far less likely due to the less severe winters but also due to the consistent use of the river system for shipping purposes. As shown in the last century, breaches and floods have occured less. However, due to higher and stronger flood defenses, the effects of a breach in the current water system also leads to much larger consequences.

Another interesting conclusion which is more likely to be beneficial for this study, is that in most cases, multiple breaches took place closely located to the previous breach. The breach widths seem to differ greatly, varying from lower than 50 meters up to above 250 meters.

The last large river flood was found in 1926, in which large areas along the Meuse, Waal and IJssel were flooded, as shown in Figure 2.8. These floods were a result of heavy rainfall which started to fall in the start of

December 1925 in the Ardennes. This caused the water levels in the Meuse to increase, eventually resulting in floodings in Limburg. The discharge measured in the Meuse at Luik was 3500 $\frac{m^3}{s}$, whereas the normal discharge was roughly 250 $\frac{m^3}{s}$. The first flood defense that breached was in Nederasselt, on the first of January 1926. The combination of extreme rainfall, melting ice and an upcoming storm proved to be too much for the flood defense [3].

Extreme rainfall was also the cause that led to high water levels on the Rhine river. The first flood defenses to fail due to these extreme water levels were along the Waal. A breach occurred near Erlecom, leading to the flooding located just northeast of Nijmegen (see location 13 in Figure 2.8).



Figure 2.8: The flooded areas during the flood of 1926 [15].

Storm surge floods

The most recent storm surge flooding in the Netherlands was the flooding of 1953, in the province of Zeeland. This flooding event lead to 2000 deaths combined. Most of these fatalaties were in the Netherlands. The flood happened during a northwestern storm in combination with springtide, leading to very high water levels. Flood defenses breached at more than 150 different locations in multiple provinces. The flooding in 1953 initiated the Delta works program, where a system a storm surge barriers, flood defenses and improvements took place to protect the Netherlands from further flooding events.

Another fairly recent storm was the Xynthia storm that caused a flooding in France. This again occured due to a storm coinciding with high tide, leading to extreme water levels. The risk of flooding was not clear to the local population [8], which is something both the 1953 flooding and the flooding in 2010 in France had in common. This can be improved by better communication between local authorities and the local population. It is very important to have a clear chain of command of who does what and which organisation is responsible for what. This leads to clear distribution of tasks, such that all important actions and information is distributed as well as possible. This also includes keeping the public up to date on simple measures they can take during floodings, what they definitely should not do and what they can expect during a flooding event [8]. This is also something that is part of this research, where the sequence of flooding of the Kampereiland gives more information on what can happen in what order, so that the inhabitants can be informed.

It was concluded for the Xynthia flooding that multiple breaches occured during the event, in close proximity to each other [8]. This was also determined in the thesis of Ten Voorde [22]. This is useful information to take into consideration when defining the breaching locations that will be analysed in this research.

2.3.2. Compartmentalisation of land to reduce flood risks

Compartmentalisation means the division of an area into a number of smaller compartments. This is often done by inflatable water retaining structures, roads or railroad tracks or by fixed water retaining structures such as dikes. This compartmentalisation allows certain compartments to fill up quickly, while the flood water will not travel further land inwards. There are 3 main advantages of using compartmentalisation for reducing flood risks [5]. These are:

1. The inflow of flood water is reduced.
   The water level in the compartment behind the breach increases rapidly, reducing the water level difference over the breach.

2. When high water duration is over, water will flow out of the system through the breach.
   Because water is retained within the compartment, water levels in this compartment will be high. Once the outside water level lowers again, water will start flowing out of the flooded area back into the water system.

3. During flow reversal, flow velocities are low, providing possibilities for breach closure.
   When the flow direction shifts from water flowing into the polder to an outward direction (water flows out of the polder into the water system), the flow velocities are low. This time provides possibilities to close the breach in an earlier stage, reducing further inflow into the system.

On the Kampereiland, much of the compartmentalisation structure follows from mounds, roads and old water retaining structures. These create smaller compartments on the island. Examples of these are shown in Figures 2.9, 2.10 and 2.11. These higher line elements in the form of roads are boundaries for the water flowing into the Kampereiland. These compartment boundaries enclose smaller areas.

In a study of the innundation of a Dutch river polder, the effect of how detailed the compartment structure should be is partly evaluated in a sensitivity analysis [7]. In this study, a sensitivity analysis is performed by using three different topographical realisations, in which more and more simplifications are made. This simplification is varied in multiple ways, such as taking both minor and major polder dikes into account, varying the different types of surface covers and using a variety of friction coefficients.

If no polder dikes are used at all, the propagation velocity to the furthest location is found to be twice as large as when only taking the major polder dikes into consideration. When taking both major and minor polder dikes into consideration (see Figure 2.12) the propagation velocity is only slightly reduced compared to the simulation with major compartment dikes [7].

2.3.3. Breaching process

The breaching process of a flood defense is something that is difficult to predict, due to the large number of uncertainties that are involved. These uncertainties vary from type of subsoil, to the shape and loading of the flood defense and to the saturation level of the flood defense. This makes the moment of initiation hard to determine. However, once the initial breach has taken place, the process has been studied a fair amount.



Figure 2.9: The regional flood defense on the northern side of the Kampereiland, just east of the Ramspolkering.



Figure 2.10: The N765 road, located on a compartment dike.

Examples of these studies are the research of Verheij and van der Knaap into a formula that can be used to determine the breach width [27] and Visser into the breaching process of a sand-dike [28].

These studies show large simularities in the steps that occur during breaching. Both of these studies split the breaching process into a few stages. The first step is the initiation of the breach itself. After this, the breach grows in a vertical direction and in depth (thus decreasing the height of the crest). During this time,



Figure 2.11: An old flood defense along the southern side of the Willem Meyer- and Stikkenpolder.

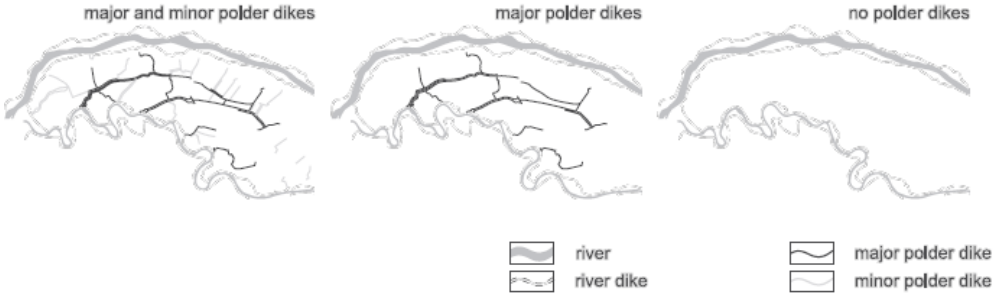


Figure 2.12: The three different topographies regarding polder dikes [7].

the discharge through the breach is still relatively small. Once the breach is fully grown in a vertical direction, meaning that the bottom of the breach is equal to the ground level behind the breach, the breach develops in a horizontal direction [27] [28]. The discharge through the breach drastically increases while the breach grows in width. Therefore, accurately estimating the breach width is important.

The upside of the calculation method of Verheij and van der Knaap is that this formula is useable for both cohesive and non cohesive materials in the core of the dike. This grants flexibility in the usesage of the formula through adjustments in the critical velocity. This is the velocity that is necessary to bring soil particles in motion. In the most recent study of Verheij and van der Knaap, the Verheij and van der Knaap formula has been updated to no longer have an empirical set maximum value to the width of the breach. Both the formulations by Verheij and van der Knaap and Visser have been tested against known cases and their measured breach widths. However, the formulation of Visser is more focussed on the sediment transport and is derived for sand dikes only. In the breaching formulation of Verheij and van der Knaap, the focus is on the water level difference over the breach. Since this is known in detail, this formulation is expected to suit this thesis research well. This in combination with the fact that clay is present in the area, using only formulations based on sand transport will likely lead to far larger breaching widths than in reality. The formula of Verheij and van der Knaap is also suggested in a manual for making flooding calculations in the Netherlands, made by Deltares [4].

In a manual for making flooding calculations in the Netherlands, the initiation of a breach is advised to be chosen at one of two moments. Either a fixed moment in time (when the maximum outside water level is reached) or at a fixed water level [4]. In combination with this, the breaching formulation of Verheij and van

der Knaap is advised, since this most accurately combines the breach growth with the water level difference inside and outside of the breaching flood defense. In the manual it is also assumed that higher elevated line elements such as roads are expected to not breach, due to the compaction of the subsoil and the width of the road.

3

Methodology

To answer the research questions listed in section 1.3, a model in Python is made that calculates the water levels on the Kampereiland, in each compartment. The model is necessary to also implement the compartment structure and to model the breaching. This is not available in the current WAQUA model. The water levels on the Kampereiland are dependent on the occurring water levels on the Ketelmeer and Zwarte Meer. For this reason, it is important to know what parameters are of influence on the water level near the locations of breaching. Both WAQUA calculations and Hydra-NL are used to determine this. WAQUA is the modelling programme that calculates the occurring water levels at specific locations in time, whereas Hydra-NL is a programme that determines the probabilities of occurrance for the calculations performed by WAQUA.

To start this chapter, a parameter analysis is performed, which is split into two parts. Section 3.1 is the first part, which explains the return periods of different stochastic parameters in the system. The return period is used in probabilistic analysis of the occurring water levels at a specific location. This return period gives information about the probability that a specific value or event occurs within a time window. For example, if a return period of a particular value of the wind speed is 100 years, this means that based on historical data, that wind speed has occurred once every 100 years.

This is followed by section 3.2 which gives insight into the effect of each input parameter on the resulting water level. The probability of each stochastic parameter (which is used in WAQUA), as well as the influence that each paramter has have now been found. With this information, the most influencial stochastic parameters can be determined in the IJssel- Vechtdelta.

Lastly, section 3.3 describes the conceptual model that is used to find the answers to the research questions. This explains the steps which are made in the model to calculate the different water levels. The input of the model is directly related to the findings of the previous two sections. These relate to the chosen scenarios that will be calculated with the model. The modelling part of the conceptual model is then elaborated on more specifically in chapter 4, where each stage of the Python model is explained with the formulas that are used.

3.1. Return periods

As mentioned above, the return period gives the probability that a certain value or event occurs within a time period. Different stochastic parameters are used to calculate water levels in the IJssel- Vechtdelta. Each of these parameters have different probabilities of occurrance for different values. These are explained below.

A specific water level can be obtained by multiple different combinations of input parameters. For instance, a high discharge on the IJssel combined with a lower wind speed can lead to the same water level as a low discharge with a high wind speed. At the Kampereiland, the water level is computed with a WAQUA model. This model uses the following stochastic parameters to determine the water levels:

- Wind direction
- Wind speed
- Lake level on the IJsselmeer
- Discharge from the IJssel
- Discharge from the Vecht
- Open/Closed Ramspolbarrier

The wind has a large effect on the occurring water levels. The water levels are not only affected by two different wind input parameters as stated above (wind direction and the occurring wind speed), but also in multiple different ways. Wind flowing over a stretch of water causes the water to tilt into the direction of the wind, leading to increased water levels. This is called wind setup. Another effect of the wind is that it forms waves, which also increase water levels through wave setup. In the IJssel- and Vechtdelta, wind setup is of the order of magnitude of meters, compared to a few decimeters for the wave setup. Both lead to an increase of the water level and both wind and wave setup lead to overflow and overtopping at lower water levels, of the flood defenses.

The lake level on the IJsselmeer is a parameter that can be influenced partially by human intervention. This is done by making use of the discharge locks at the north- eastern and western boundaries of the IJsselmeer, in Kornwerderzand and Den Oever respectively. However, this is not fully controllable since it is impossible to discharge water from the IJsselmeer to the Waddensea if the water levels on the outside of the Afsluitdijk are higher than those inside the Afsluitdijk. The IJsselmeer is in open contact with the Ketelmeer and therefore influences the occurring water levels in the IJssel- Vechtdelta. The lake level on the IJsselmeer also has impact on the water level in the Zwarte Meer since there is an open connection while the Ramspolbarrier is open. This impacts the starting point of the water level at location 3 in figure 3.1 directly.

The discharge from the IJssel and the Vecht both play a role. The Vecht has an influence in the north-eastern part of the delta, whereas the IJssel is more prominent in the south-eastern part of the Ketelmeer. Because overflow locations in both flood defense 225 and 101 are considered (see Figure 3.1), both discharges are relevant.

The last parameter that is discussed in this section is the barrier condition of the Ramspolbarrier. The barrier condition of the Ramspolbarrier states whether the barrier should be open or closed, while taking the probabilistics of it failing to close (when it should be closed) into account. There are two different scenarios for the barrier condition. The first is that the Ramspolbarrier is always open (thus it fails to close when it should). The second is the scenario where the Ramspolbarrier closes as intended once the criteria for closing are met. During a closed barrier condition, the flow between the Zwarte Meer and the Ketelmeer is blocked. This barrier will be closed when flow from west to east takes place, leading to increasing water levels near flood defense 225. However, due to the closing, water levels behind the Ramspolbarrier (at flood defense 101) will also rise since the water flowing into the Zwarte Meer from the Vecht can now no longer discharge in the Ketelmeer.

Each of these input parameters are stochastic, meaning that they have a statistical distribution. These distributions are used to be able to compute the probabilities of occurring hydraulic loads. This is what Hydra-NL

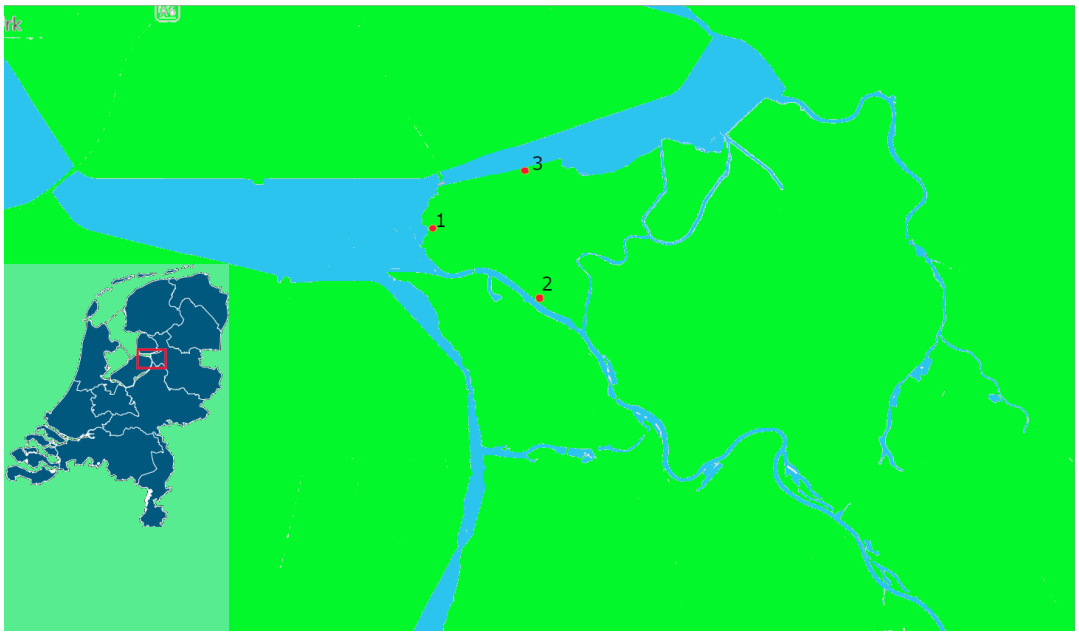


Figure 3.1: The three locations for which the parameters are analysed, to determine the influence of each parameter.

does. This probabilistic modelling program matches an occurring water level to a probability, based on the combination of parameters that lead to that specific water level. Return periods give an indication in these probabilities, which are shown below for the important parameters. The distribution of the wind direction is based on input from the wind-field at Schiphol. This is the database that is used in the pre-existing WAQUA calculations. The return period of wind speeds given a western wind and the probability of occurrence per wind direction is shown in Figure 3.2.

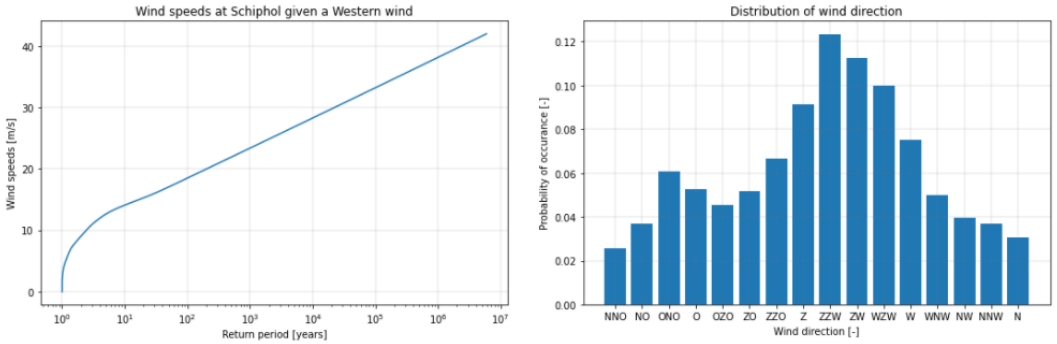


Figure 3.2: The return period for wind speeds given a western wind (left) and the probability of occurance of each wind direction at Schiphol (right). Obtained from Hydra-NL

The return periods for the non-wind related parameters are shown in Figure 3.3.

3.2. Sensitivity of the system to parameters

The probabilistics of the stochastic parameters are known. This can be used in combination with the importance of each parameter to determine scenarios which will be used in the flooding analysis of the Kampereiland. To give a first impression of the important parameters, the design points of Hydra-NL are used. This is done for three locations.

Assumed breaching locations

There are three locations chosen to initiate a breach. These breaches will take place at the locations shown in figure 3.1 in section 3.1. These locations have been chosen due to a number of different factors. The first

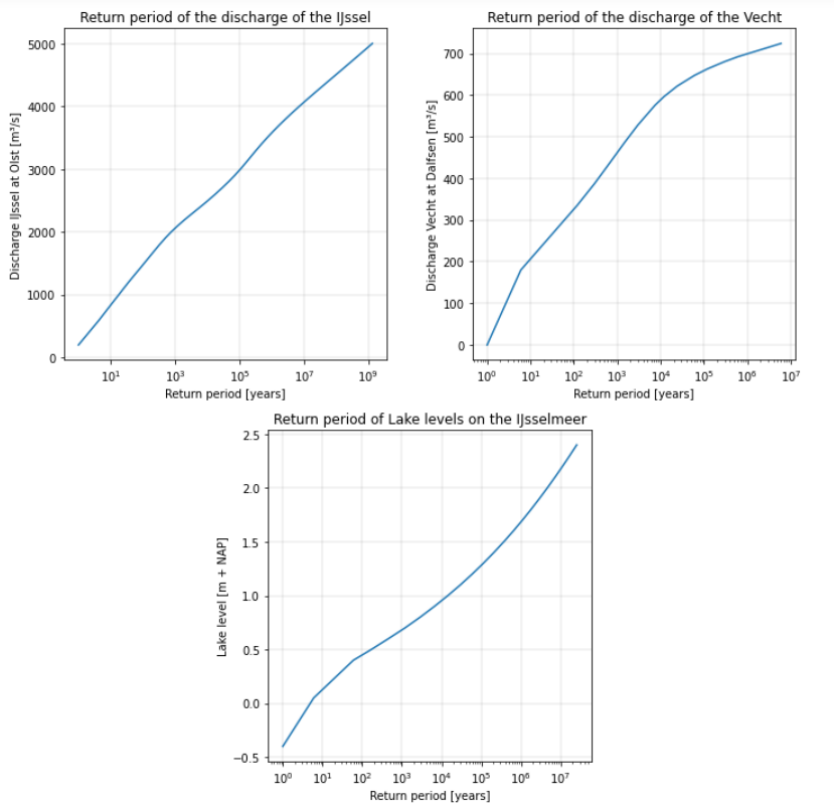


Figure 3.3: The return periods of the discharge on the IJssel (left), the Vecht (right) and the lake level on the IJsselmeer (bottom). Obtained from Hydra-NL.

factor in this is the type of flood defense which is present. The second factor which is taken into account is the type of the hydraulic loading which is dominant at the location. The last aspect which determines the choice of location is the type of compartment which functions as hinterland directly behind the location. This will influence the speed in which the compartment fills up. This again influences the inflow discharge.

Location 1 is located along the overflow resistant part of flood defense 225. This location is designed to overflow, and thus has a lower crest height than the other parts of flood defense 225. The water level at this location is storm dominated, thus mainly affected by high wind speeds. The hinterland behind this location is a small compartment, which will quickly fill, leading to an inflow discharge which will quickly become submerged inflow.

The second location is more upstream of the IJssel, where the storm dominance is less. The influence of the discharge of the IJssel is more important compared to location 1. The flood defense at this location has a substancially higher crest height and a steeper inner slope, which is not made to overflow. The hinterland is made up of a middle-sized compartment.

Finally, the last location is along the northern side of the Kampereiland, where the discharge of the Vecht plays a role in the water level, compared to the IJssel discharge for the other two locations. This location is again made to overflow and therefore has a less steep inner slope and a lower crest height than the rest of the regional flood defense along the northern side of the Kampereiland. The compartment behind this location is large and has a low ground level, resulting in a long freeflow inflow.

Hydra-NL design points

Hydra-NL identifies the design point for specific return periods. This design point is composed of the most likely combination of parameters that lead to the water level with that return period. For different locations, also different parameters are taken into account. For locations 1 and 2, the discharge of the Vecht is not a contributing factor to the water level, whereas for location 3 it is. In Table 3.1, this design point is shown for

location 1 and 2, along flood defense 225. This has been done for the water level which has a return period of 1/3000 years, which is the water level for which the overflow resistant part of flood defense 225 will overflow. A similar table is shown in Table 3.2, for a water level with a return period of 300 years, for location 3. Again, this is the water level for which only the overflow resistant part of flood defense 101 will overflow.

Table 3.1: Combination of parameters that is most likely to cause the occurring water level for a return period of 1/3000 years at locations 1 and 2.

Location	**Situation Ramspol barrier [-]**	**Contr to exc freq [%]**	**Wind direction [-]**	**Lake level [m+NAP]**	**Discharge IJssel [m³/s]**	**Windspeed [m/s]**	**Occuring water level [m+NAP]**
1	Open	0.3	WNW	-0.22	375	34.8	2.84
	Closed	99.7	WNW	-0.1	450	31.6	2.84
2	Open	0.6	WNW	-0.22	375	34.4	2.97
	Closed	99.4	WNW	-0.1	450	31.6	2.97

Table 3.2: Combination of parameters that is most likely to cause the occurring water level for a return period of 1/300 years at location 3.

Location	**Situation Ramspol barrier [-]**	**Contr to exc freq [%]**	**Wind direction [-]**	**Lake level [m+NAP]**	**Discharge Vecht [m³/s]**	**Windspeed [m/s]**	**Occuring water level [m+NAP]**
1	Open	41.8	W	0.8	400	11.2	1.26
	Closed	58.2	W	0.64	355	16	1.26

The contribution to the exceedance frequency applies to the barrier condition of the Ramspolbarrier. It relates how many of the total number of combinations that lead to the water level of that return period, to how often it occurs that the Ramspolbarrier is open or closed. Table 3.1 shows that for the water levels at the trajectory of 225, for the water level that has a return period of 1/3000 years. This is mainly obtained through combinations while the Ramspolbarrier is closed (99.7% and 99.4% of the time). However, this percentage is strongly reduced when looking at location 3 (Table 3.2). The closing of the Ramspolbarrier indicates a storm situation, as this barrier closes when the water level at the Ketelmeer is 0.5m+NAP and water flows from the Ketelmeer into the Zwarte Meer. The shift of this exceedance frequency gives reason to define multiple different scenarios, which not only take the storm situation with a western orientated wind as input, but also scenarios which take higher discharge or lake levels into account. The shifting of the exceedance probability can also be related to failing of the Ramspolbarrier, in which case it will not be closed. This leads to water level increases during a storm from the west, at location 3. For this reason, high water scenarios for both an open and closed Ramspolbarrier will be considered in the model.

3.2.1. Locations 1 and 2 along the western side of the Kampereiland

The analysis of parameters is split into two different parts. Location 1 and 2 are analysed in this subsection, whereas location 3 will be analysed separately. This is because the parameters that play a role differ due to the location. The water levels at location 1 and 2 are affected by the wind, discharge of the IJssel, the lake level on the IJsselmeer and the closing situation of the Ramspolbarrier. For location 3 the discharge of the IJssel is not taken into account. The discharge of the Vecht is however a parameter that plays a role.

To see how each parameter influences the system, the results of the WAQUA calculations have been analysed. To do this, variations have been made in which the water level has been plotted against different parameters, while keeping other parameters as a constant value. This way the influence of different parameters can be shown in a clearer way.

First the water level is shown as a function of the wind speed. This is done for multiple discharges of the IJssel, keeping the lake level as a constant input parameter. The result is shown in Figure 3.4, which shows

that lower discharges have a bigger effect on the water level at lower wind speeds. The discharge barely influences the water level in the midrange of wind speeds from 20-30 m/s, whereas at high wind speeds the discharge influences the water level more again.

A similar thing is done for the other parameters, such as the lake level and the discharge from the IJssel. In figure 3.5 the water level at trajectory 225 is plotted against the lake level on the IJsselmeer. For low wind speeds, the influence of the discharge is larger for low lake levels. However, the influence of the discharge is much larger once high wind speeds also occur. This makes the wind speed relatively important since the discharge graph does not drastically change unless the wind speeds increase. For higher discharges, the influence of the wind speed also increases, making the influence of the wind speed more independent of the lake level, thus decreasing the influence of the lake level on the occurring water level.

Figure 3.6 shows that even for very low discharge values and lake levels, the occurring water levels are high due to just an extreme wind speed. It also shows the interaction between the very high discharges and wind speeds again.

The graphs have been made with a barrier condition that is closed. This is chosen since the occurring water levels due to a closed barrier are higher than for a barrier condition in which it is open.

In conclusion, the wind speed is of a greater influence on the water levels at trajectory 225 than the discharge. However, the discharge does play an important role in the rare event where a heavy storm and a large discharge wave coincide.

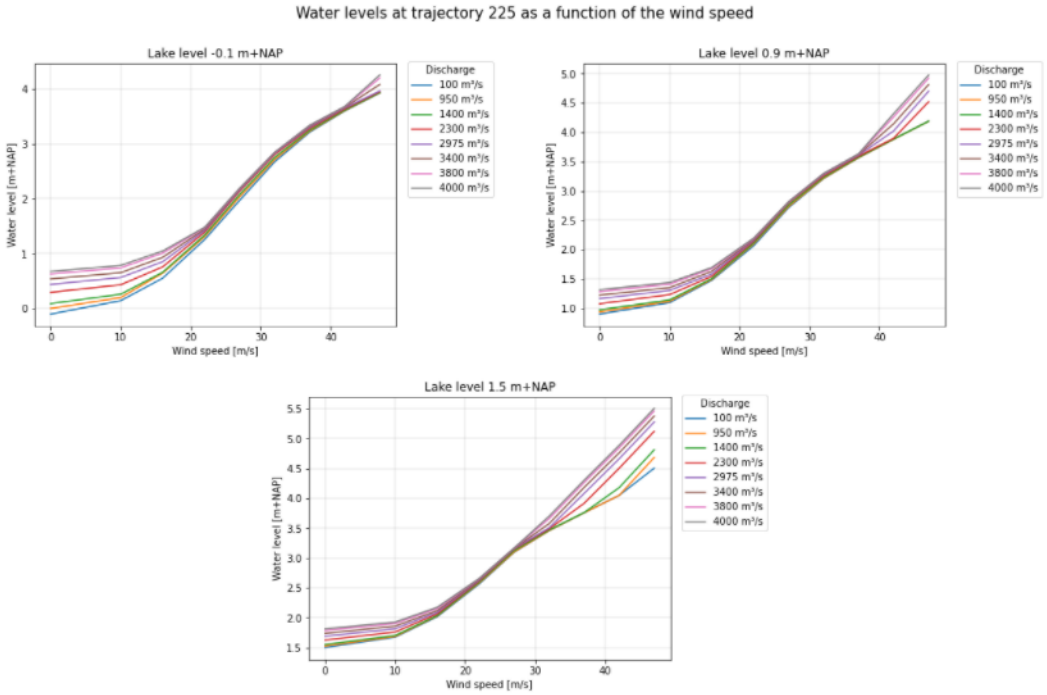


Figure 3.4: Water levels at trajectory 225 as a function of the wind speed, for different discharges and lake levels. The wind has a western direction during a normally functioning Ramspolbarrier (closing when the criteria are met).

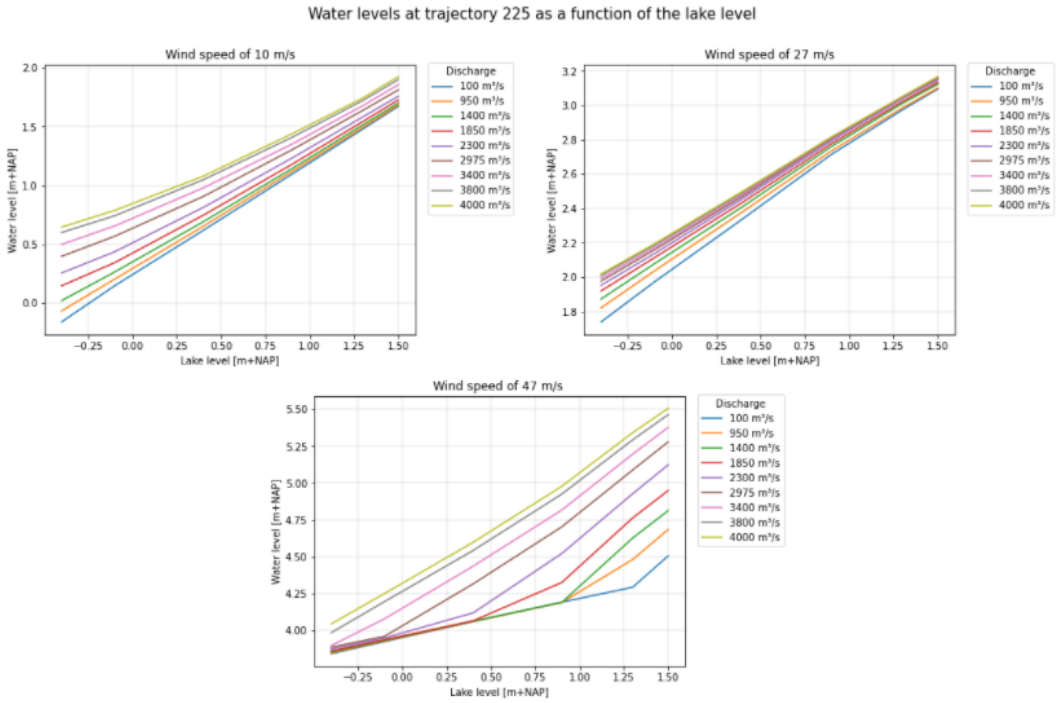


Figure 3.5: Water levels at trajectory 225 as a function of the lake level, for different discharges and wind speeds. The wind has a western direction during a normally functioning Ramspolbarrier (closing when the criteria are met).

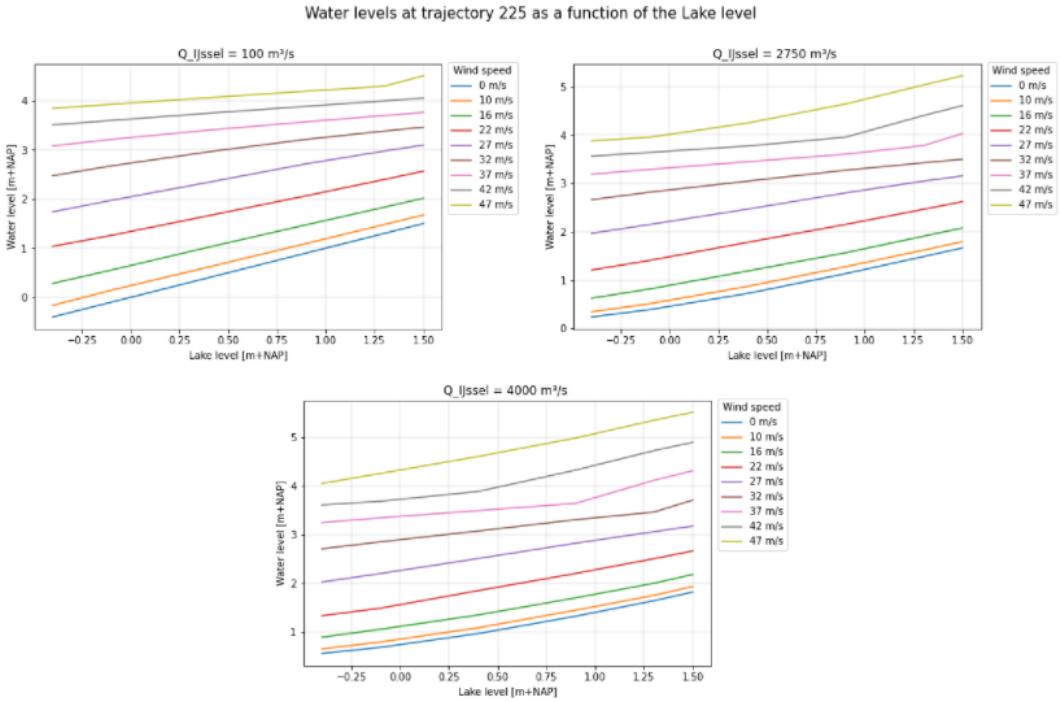


Figure 3.6: Water levels at trajectory 225 as a function of the discharge, for different wind speeds and lake levels. The wind has a western direction during a normally functioning Ramspolbarrier (closing when the criteria are met).

3.2.2. Location 3 along the northern side of the Kampereiland

A large difference for location 3 as compared to location 1 and 2, is that the water levels here are not affected by the discharge of the IJssel but by the discharge of the Vecht. Similar graphs have been made as in Section 3.2.1, for this location.

The first of these graphs is shown in figure 3.7. The influence of the discharge is relatively even, whereas the influence of the wind speed becomes stronger from wind speeds above 30 m/s. The graphs there suddenly have a large gradient change, showing the influence of the wind speed on the water level changes. This gradient change is similar for all discharges.

The discharge is of greater influence on the water levels at flood defense 101 during lower lake levels, as shown in figure 3.8. At wind speeds in the order of 25 m/s, the influence of both the discharge and the lake level of the IJsselmeer increase, leading to larger water levels changes.

Figure 3.9 shows that the occurring water level is more strongly influenced by lower discharges and wind speeds when low lake levels are present. The influence of different wind speeds is larger than the influence of the discharge, which gives a similar gradient for every wind speed line.

For location 3, the barrier condition is also analysed, in which both the scenario of the barrier being closed as it is supposed to, and always open options are evaluated. It was expected that two different options would lead to the highest water levels. This is during a storm from the west, with an open Ramspolbarrier, meaning water can flow from the Ketelmeer to through into the Zwarte Meer, increasing the water levels at location 3. The second scenario leading to high water levels would be during a closed Ramspolbarrier with discharge from the Vecht causing the water levels to gradually rise, while an eastern wind would cause extra wind setup. The eastern orientated winds resulted in a negligible effect on the water levels. The water levels due to an open Ramspolbarrier have slightly higher resulting water levels for this location. This again shows that the western orientated winds have a large impact on the resulting water levels, even for location 3.

It can be concluded from these figures and the barrier condition of the Ramspolbarrier that also for location 3, the wind speed in combination with a western orientated wind are largely contributing parameters that have a relatively strong influence on the occurring water levels.

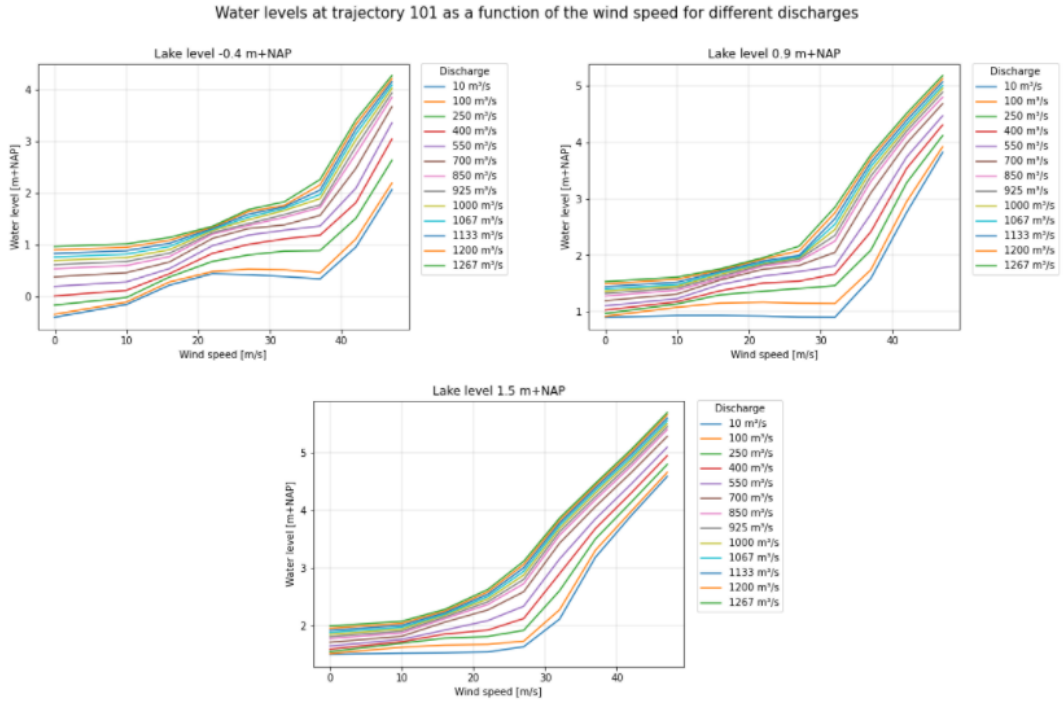


Figure 3.7: Water levels at trajectory 101 as a function of the wind speed, for different discharges and lake levels. The wind has a western direction during a normally functioning Ramspolbarrier (closing when the criteria are met).

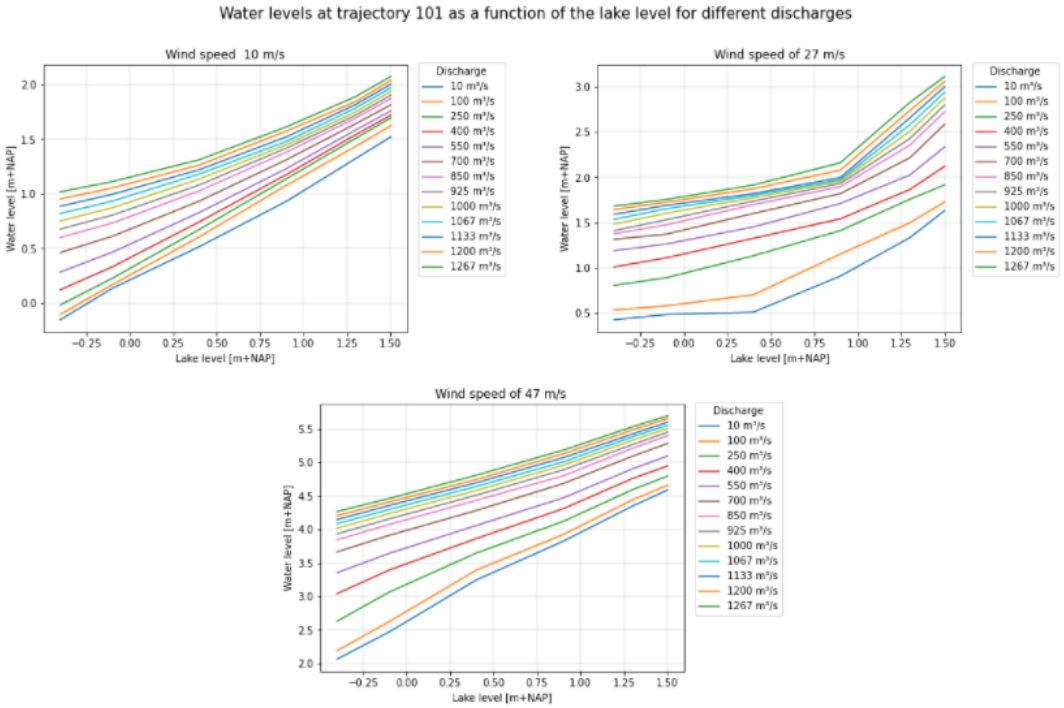


Figure 3.8: Water levels at trajectory 101 as a function of the lake level, for different discharges and wind speeds. The wind has a western direction during a normally functioning Ramspolbarrier (closing when the criteria are met).

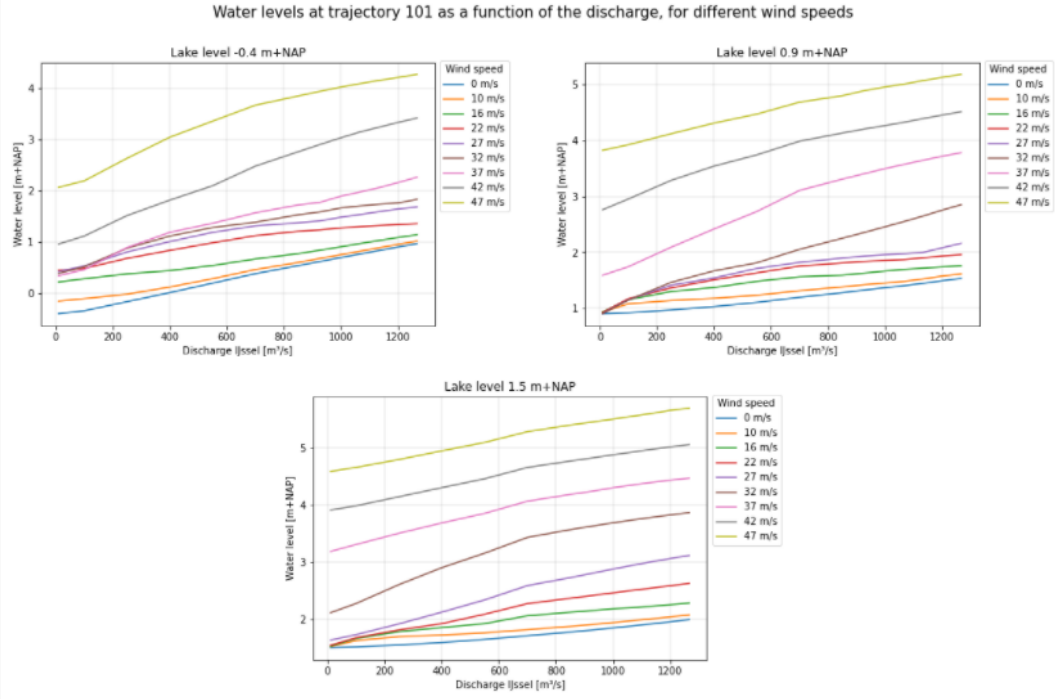


Figure 3.9: Water levels at trajectory 101 as a function of the discharge, for different wind speeds and lake levels. The wind has a western direction during a normally functioning Ramspolbarrier (closing when the criteria are met).

3.3. Conceptual model

The conceptual model shows the model that is set up in the form of an image, which is elaborated on in the following chapter. The conceptual model (figure 3.10) shows the different aspects of the model, in different stages. It also gives a clear overview of how each aspect is connected to one another.

The conceptual model visualises the different aspects that are used to compute the water levels on the Kampereiland during a breach, while taking the compartment structure of the Kampereiland into account. The combination of a breach with the compartment structure of the Kampereiland is hard to do with currently available WAQUA models due to the small time steps required to properly simulate the breaching of the the flood defense. The breaches in WAQUA are simulated as instantaneous drops of the crest height with a fixed width. The used breach width is then based on an assumption. By using the Python model, which calculates the breach width per time step, the making of an assumption can be circumvented.
The conceptual model has two input types. The first are the outside water levels which are obtained from the WAQUA model. This WAQUA model has an official status, in which the water levels are computed while taking water level setup due to wind and waves into account as well. From initial assessments, this water level setup on the Kampereiland is in the order of half a meter (when not taking the compartmentalisation boundaries into account). This is however not added into the computed water levels in the python model used in this thesis research.

The second part of the input of the model is the compartment structure which is defined based on AHN (Algemeen Hoogtekaart Nederland [10]). How the compartmentalisation of the island exactly interacts with the tilting of the water level caused by wind is hard to tell. A wind from the west will cause water levels in the east to increase, resulting in an earlier time at which overflow of the eastern compartment boundary will occur. At the same time, in the western end of the compartment, the water levels are lowered due to the wind skewness, leading to longer periods of free flow discharge into the compartment. What the magnitude of the tilting of the water level is when all compartment boundaries are added to the model, is hard to predict. The boundaries also shelter against the wind.

In the way the Python model is set up currently, the outside water does have this wind and wave setup in the final water level, however the water levels in the compartments is determined as an average. The set up has

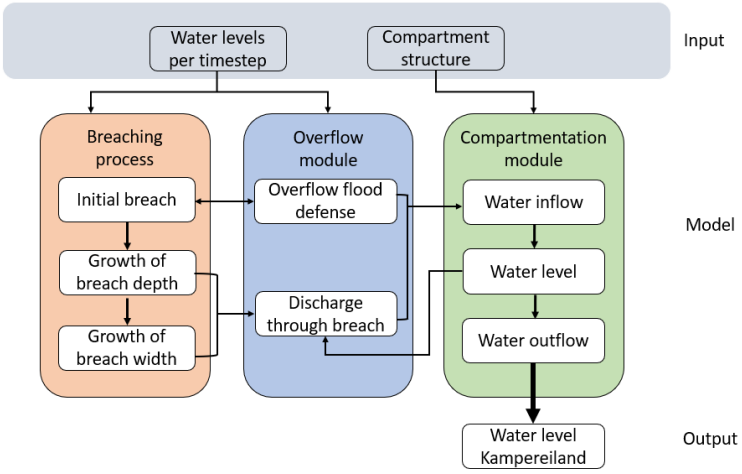


Figure 3.10: Conceptual design of the model.

not currently been added in the model results on the Kampereiland. This would require a coordinate system in the model, which can use spacial variations of the water level based on the coordinates of the computation.

The three computational modules follow, where the breaching module is initiated once the outside water level exceeds the crest height of the flood defense. This then leads to the growth of the breach and inflow into the compartment due to overflow over the crest and a discharge through the breach. The defined compartment structure is combined with this inflow to determine the water levels in each compartment. The compartments are connected to each other by the compartment boundaries. Water flow between two adjacent compartments is possible due to overflow over the boundary. The model then calculates the change in water level in every compartment, per time step. This is used to calculate the new water level per timestep in every compartment.

A more detailed explanation of the model is given in chapter 4.

4

Model setup

In this chapter, the conceptual model of figure 3.10 is further elaborated on. First, in section 4.1 the main assumptions of the model are explained. In the following section, the first module in the conceptual model is explained in more detail (section 4.2). This is the breaching module, where the used breaching formulation is treated. Section 4.3 elaborates on the way the waterflow into the Kampereiland is modelled. Next, the compartment structure is shown and explained in section 4.4. The last part of the conceptual model are the scenarios that are used as input of the model. These are treated in section 4.5. To finalise this chapter, a test case is shown in section 4.6. This section shows a simplified example which is run by the model, to show how the model works and what the results of the model are. This test case is also used to check whether the results are correct.

4.1. Assumptions in the model

In the model, a number of assumptions have been made. These assumptions have been listed below.

- **A breach is initiated once the outside water level exceeds the crest height of the flood defense**
  Predicting when a breach will happen is difficult and requires a detailed analysis of all the failure mechanisms. Performing this analysis is outside the scope of this research. It is therefore assumed that a breach is initiated when the outside water level exceeds the flood defense crest height at the three locations explained in 3.2. This creates a fixed moment of breach initiation. This is also suggested in a manual for making flooding calculations by Deltares [4].

- **Three locations have been chosen for the breach locations.**
  There are assumed to be three locations where breaching in the flood defenses occurs. Two of these locations are along flood defense 225, which is located along the western boundary of the Kampereiland. The third location is along the northern boundary of the Kampereiland, in flood defense 101. The assumed locations differ in type of flood defense, the size hinterland compartment, the ground level of the hinterland compartment and type of high water loading (either more storm dominated or more discharge dominated). The exact locations are shown in Figure 3.1. A more indepth elaboration of the locations is given in subsections 3.2.1 and 3.2.2.

- **A maximum of two simultaneous breaches can take place at the same time.**
  Assumed is that a maximum of two breaches can occur simultaneously. Since a breach is initiated based on the moment of overflow, it is assumed this can happen at multiple locations at the same time. However, in section 2.3 it has been explained that simultaneous breaches generally happen in close promixity to each other. To accommodate for this in the model, two breaches in adjacent compartments have been computed. The total discharge flowing through these two breaches combined is then compared to the total discharge flowing through a singular breach with two times the width. This way, a fit is found for the value to multiply the breach width to get a discharge roughly equal to two different breaches. By doing this, multiple breaches in the same compartment can be modelled. The three breach locations are still maintained, to limit the number of extra scenarios that need to be computed. The options become limited, by either no breach, a single breach at one of the three locations, or a breach with an increased width (to simulate the double breach) at a single location.

- **The outside water level is not affected by the inflow of water into the Kampereiland**
  The water level on the IJssel or in the Zwarte Meer flows into the Kampereiland. It is assumed that the outside water level is not affected by the inflow into the Kampereiland. This assumption is made on the basis that the volume of water present in the IJsselmeer, Ketelmeer and Zwarte meer is significantly larger than that which can be stored on the Kampereiland (volumes determined by using managementplans of Natura 2000 [24] [25] [26]). In total, the combined volume of the three lakes is roughly 130 times the total volume of water which could be stored on the Kampereiland. Therefore, this is assumed to have minimal effects on the outside water levels.
- **The compartment structure is assumed using main boundaries**
  The reason to limit the compartment structure to only use the major compartment boundaries has to do with the level of detail and the model run time that follows. Using more detail in the compartment structure leads to more compartments, resulting in longer calculation times. In research of the effects of compartment boundaries in the Land van Maas and Waal [7], the largest influence on the total time needed to fill up the inundation area was found by implementing the major compartment boundaries to the system. Minor boundaries and small waterways only led to a slightly longer inundation time. Therefore it is assumed that implementing only the major compartment boundaries is sufficient to determine the effect of the compartment boundaries for the flooding time of the Kampereiland.
- **The inner compartment boundaries on the Kampereiland do not breach**
  It is assumed that breaches only occur in the flood defenses along the outer boundary of the Kampereiland. The inner compartment boundaries do not breach. To determine if this is indeed the case, a fully probabilistic analysis into all failure mechanisms of the compartment boundaries needs to be performed. This is a timely and detailed analysis, which is not part of the scope of this research. In a guidance report for making flooding calculations, it is also assumed that higher elevated line elements such as roads and railways do not fail. Considering the width and the extra consolidation of the ground that takes place before constructing, these infrastructures are assumed to not breach [4].
- **The skewness caused by wind is taken into account in the outside water levels, but not on the Kampereiland.**
  As explained in section 3.3, the outside water levels are computed with skewness caused by wind (the skewness is the tilting of the water surface, due to the influence of wind). How this skewness precisely interacts with boundaries, due to the sheltering and the increases in water level is outside the scope of this research. In the current python model, average water levels in each compartment per timestep are calculated, thus not taking the skewness caused by wind into account. More details on this are given in section 4.3.

4.2. Breaching process

Once the water level exceeds the crest height of the flood defense, water starts flowing into the first compartment of the Kampereiland and the breach is initiated. The growth of the breach is modelled by using the formulation of Verheij and van der Knaap [27]. In this breach formulation, the breach growth is assumed to happen in three stages.

4.2.1. Breaching stages

The first stage is the so-called null-phase, in which the breach is initiated. The next stage is called the deepening phase, in which the breach has a fixed width, while only the depth increases. This deepening continues until the ground level of the breach compartment is reached. In used regulations to simulate breaching, the time this lasts for sand dikes is assumed to be roughly 10 minutes [4]. In the model used for the calculations in this thesis research, this deepening phase is modelled by using a linear reduction of the crest height over these 10 minutes, to equalize the crest height with the inside ground level.

After the deepening phase, the final phase starts. This phase is called the widening phase. The breach won't grow deeper, since the sill is already at the ground level of the hinterland. The width of the breach is then determined by equation 4.1.

$$B(t) = 1.3 * \frac{g^{0.5} * (\Delta h)^{1.5}}{u_c} * \log\left(\frac{1 + 0.04 * g}{u_c} * t\right) t \tag{4.1}$$

In which:
B(t)=Breach width as a function of time [m]
Δh=difference outside water level and water level in the flooded area [m]
t=time [s]
g=gravitational constant [$\frac{m}{s^2}$]
u_c=critical flow velocity for erosion [$\frac{m}{s}$]

The breach width can be calculated per time step using this formulation, based on the difference in water level difference in and outside of the Kampereiland. One of the key reasons to use this equation is because it specifically takes the water level differences outside and inside the breach in consideration. By doing this every time step, the discharge flowing through the breach is consistently dependent on the water level behind the breach, leading to either free flow or submerged flow into the Kampereiland. During submerged inflow, the discharge is reduced based on the water level difference outside and inside the island. Therefore, using this breaching formulation compared to other breaching formulations, is not only used because it is advised in guidelines for making flooding calculations, but also because the focus of the formula is the difference in water levels inside and outside of the breach.

4.2.2. Approximating multiple breaches at a single location

As stated in section 4.1, to simulate two breaches at a single location, the width of the breach is adjusted, such that it still leads to a representative discharge through the breach. To check the scaling that is required for the breach width to get a roughly equal value for the discharge through the breach, two comparisons have been ran with the model. First, a breach is simulated in both compartment 3 and 1 (see figure 4.3), which are located adjacent to each other. The discharge through both of these breaches is calculated, while also calculating the combined discharge through both of the breaches. Next, another simulation is ran with only one breach in compartment 3. In this simulation, the breach width is increased by a factor two. The breach discharge is then compared, to see whether the scaling of the breach width by a factor two gives reasonable results. The results for the comparison are shown in figure 4.1. The resulting discharge is very similar in the two different cases. This is largely influenced by the outside water level being nearly equal in both locations, as well as the breaching width of the two seperately simulated breaches being very close to each other. A number of other simulations with different high water scenarios and other adjacent compartments have been compared in a similar manner, with similar results. The scaling factor of two is therefore used to simulate two breaches in the same outer compartment boundary.

4.3. Waterflow module

In the waterflow module the flow of water over the flood defense and through the breach is calculated using spillway formulations. This is connected to the size of the breach through both the height of the sill at that timestep and the width of the breach. The height of the sill is reduced during a time period of 10 minutes

The type of water inflow through the breach is dependent on the water level behind the breach. During free flow, the water level inside does not affect the water level outside of the boundary. During submerged flow, the outer water level is affected by the water level inside the breach. This leads to two different situations, shown in Figure 4.2. If the water level is lower than the sill of the breach, the free flow spillway formula (equation 4.2) is used.

$$Q_{ff} = \frac{2}{3} * \sqrt{\frac{2}{3} * g} * m * B * \Delta H_1 * \sqrt{\Delta H_1} \tag{4.2}$$

With:
g = gravitational constant [$\frac{m}{s^2}$]
ΔH_1 = overflow height [m] (outside water level - sill height)
m = discharge coefficient [$\frac{\sqrt{m}}{s}$]
B = overflow width [m] Q_{ff} = discharge over the sill in free flow condition [$\frac{m^3}{s}$]

As soon as the water level in the flooded area becomes equal to the sill height of the breach, the submerged spillway formula can be used instead.

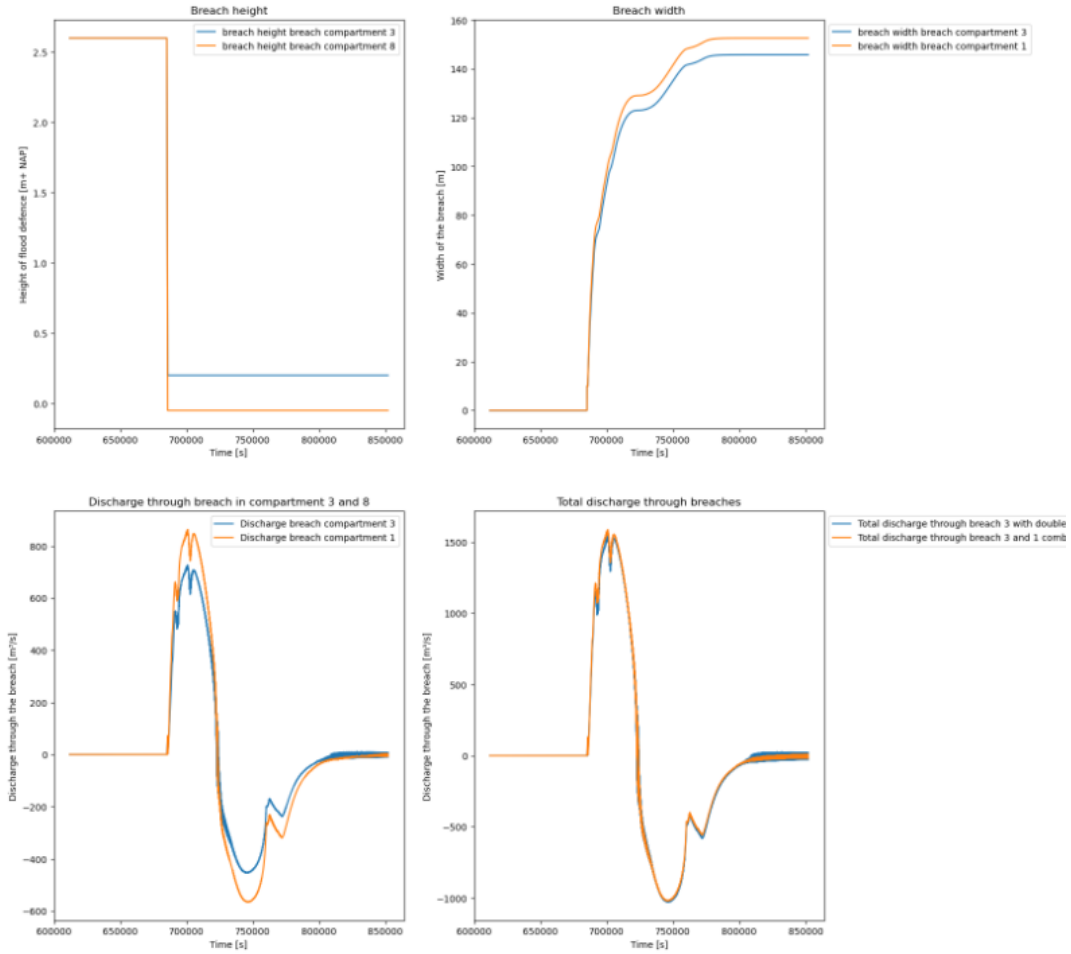


Figure 4.1: The breach heights, widths and discharges through the breaches in two scenarios.

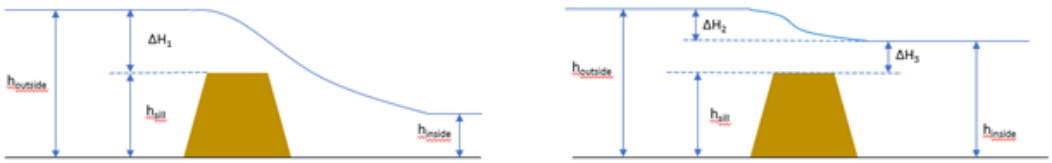


Figure 4.2: Sketches of the water line during free flow (left) and submerged flow (right) over the sill. Equations 2 and 3 are used to calculate the discharge over the sill in the two situations.

$$Q_{sf} = c * B * \Delta H_3 * \sqrt{2 * g * \Delta H_2} \tag{4.3}$$

With:
c=discharge coefficient [-]
ΔH_2=overflow height (outside water level-inside water level) [m]
ΔH_3 = overflow height (inside water level-sill height) [m]
Q_{sf} = discharge over the sill in submerged flow condition [$\frac{m^3}{s}$]

The flow between different compartments is also modelled by using the spillway formulations. The model determines whether the discharge from one compartment to another should be calculated by free flow, submerged flow or that it should be 0. The direction of the flow is also indicated by the addition of a sign to the formulas. This sign is determined based on if water flows in (+) or out (-) of the compartment. This is used

to calculate the total discharge into and out of each compartment per timestep. This way, all compartments are connected with the surrounding compartments. The discharge changes in each compartment are then combined with the area of every compartment to determine the average water level change. The calculated water level changes are then added added to the water levels of the previous timestep. The newly calculated water level is then used as the starting point for the next time step.

4.4. Compartment structure

In the final module of the model, the compartment structure of the Kampereiland is combined with the waterflow module. The compartment structure is comprised of the heights of the compartment boundaries which are determined from AHN3 [10], the length of these boundaries, the area of the compartment and the average ground level in the compartment. The boundaries of the compartments are mainly made of roads on the island and old flood defenses, which are higher elevated line elements compared to the average ground level of the Kampereiland.

The entire island is split into 19 compartments, seperated by major boundaries. Most of these boundaries are roughly 1 meter higher than the local ground levels. This causes the compartments to fill up like seperate boxes, due to overflow once the boundaries are exceeded. The two most significant boundaries are the causeway of the N50, which runs from the northwestern end of the Kampereiland to the south, past Kampen. The other boundary is the old flood defense along the northern side of the Kampereiland. The defined compartment structure is visualised in Figure 4.3.

Combining the compartment structure with the waterflow module, the water level in every compartment is computed per timestep. This water level directly influences the inflow of the water during the next timestep, through the spillway formulas.

When the water level exceeds the boundary of the compartment, outflow will occur, meaning inflow into the adjacent compartment, again defined through the spillway formulas of equation 4.2 and 4.3.

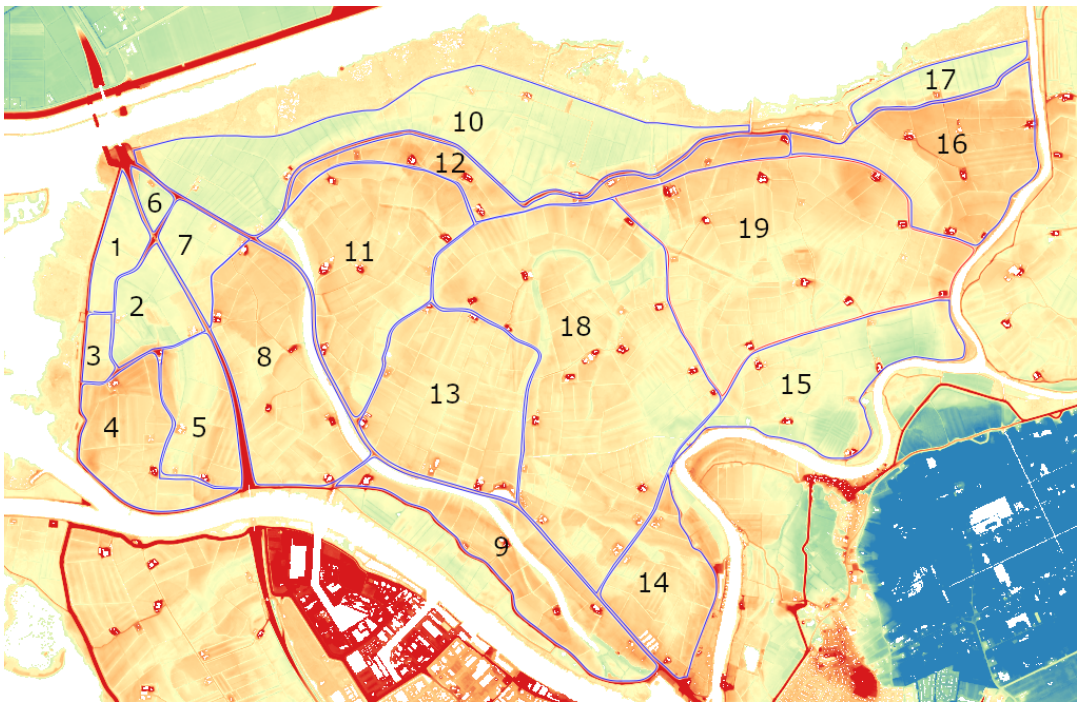
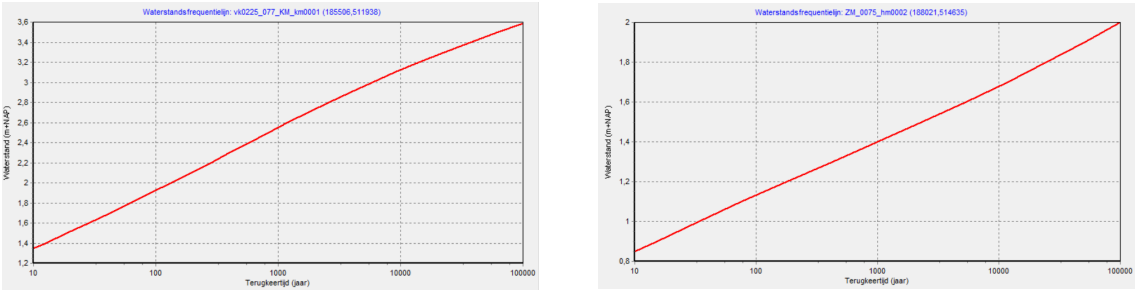


Figure 4.3: The numbered compartment structure of the Kampereiland.

This compartment structure is used to determine what happens when the Kampereiland floods. It influences the order of inundation and the total time needed to fully flood the Kampereiland.



(a) At the Ketelmeer (western side)

(b) At the Zwarte Meer (northern side)

Figure 4.4: Water level frequency lines at the Kampereiland

4.5. Scenarios

The choice of the used scenarios is based on the findings of sections 3.1 and 3.2. This determination of the used scenarios is also the answer to the first research question. As a large part of the input of the model, it is a crucial part of the research. The findings in these sections have shown that water levels along flood defense 225 (the western side of the Kampereiland) will only exceed the crest height during high wind setups, while along the northern boundary water can flow into the island either during storms or due to higher discharge levels of the Vecht. The outside water level in WAQUA is a result of multiple stochastic parameters, as explained in chapter 3. The scenarios that will be used to run the model need to be chosen in a way that the different combinations span the possible high water scenarios, such that the research questions can be answered. The two main stochastic parameters for these choices are the wind speed and the discharge values per scenario. A more detailed elaboration on this is given in the next paragraphs.

The computation time of the model is an element to take into consideration. The model requires about 30 minutes of run time with timesteps of 10 seconds, which produce results without too much disturbances. In the case of larger timesteps, the volume of water flowing into compartments becomes so large that the resulting water level heavily fluctuates between two timesteps.

Using all combinations of parameters that WAQUA uses to determine the water levels, a total of 22464 combinations need to calculated. Running the model set up in this thesis research for all combinations would take roughly 470 days. Using one computer, this is not realistic for this research. Therefore, the number of scenarios that are calculated need to be reduced.

The starting point for the scenario choices stems from the design points found from Hydra-NL. As explained in section 3.2, the design point is the most probable combination of parameters to lead to a certain water level. From these scenarios onwards, the list of scenarios has been expanded, to create variability in the input, covering a wide range of storm and discharge dominated scenarios of high water. The total number of scenarios has been reduced by not taking scenarios into account that do not lead to overflow along flood defenses 225 or 101. In doing this, scenarios leading to water levels with return periods larger than 1/600 years are not accessed. This is the return period for which water levels exceed the crest height according to Hydra-NL (see Figure 4.4). The numerous scenarios that are used in this research lead to water levels with return periods varying from 1/600 to 1/10000 years.

To reduce the number of scenarios further, the Ramspolbarrier is assumed to close as intended. Hydra-NL output shows that the water levels leading to overflow mainly take place while the Ramspolbarrier is closing as intended. Scenarios in which this is not the case (Ramspolbarrier that fails to close) are not used in this research.

The lake level on the IJsselmeer is a stochastic parameter which is better controllable due to the discharge locks present in Kornwerderzand and Den Oever. Because this parameter is subject to human influence, only scenarios varying from -0.1m to +0.9m are used. Most of the scenarios that have been calculated have a lake level of 0.4m +NAP. This is because very few scenarios with -0.1m +NAP lake levels lead to overflow, while the chance of occurence of 0.9m +NAP is rare.

Table 4.1: Overview of the calculated scenarios in this research.

Type	**Storm dominated scenario**	**Discharge dominated scenario**	**Extreme scenario**
	KsrMn010Q0100U32D292	KsrMp040Q2975U16D292	KsrMp040Q2750U32D292
	KsrMn010Q0100U37D292	KsrMp040Q2975U16D315	KsrMp040Q2975U32D292
	KsrMn010Q0500U32D292	KsrMp040Q3200U16D292	KsrMp040Q3200U32D292
	KsrMn010Q0500U37D292	KsrMp040Q3400U16D292	KsrMp040Q3200U37D292
	KsrMp040Q0100U32D292	KsrMp040Q3400U16D315	KsrMp040Q3400U32D292
	KsrMp040Q0100U37D292	KsrMp040Q3600U16D292	KsrMp040Q3400U37D292
	KsrMp040Q0100U42D292	KsrMp040Q3600U16D315	KsrMp040Q3600U32D292
	KsrMp040Q0500U32D292	KsrMp040Q3800U16D292	KsrMp040Q3600U37D292
	KsrMp040Q0500U37D292	KsrMp040Q3800U16D315	KsrMp090Q2750U27D292
	KsrMp040Q0500U42D292	KsrMp040Q4000U10D292	KsrMp090Q2975U27D292
	KsrMp040Q0950U32D292	KsrMp040Q4000U10D315	
	KsrMp040Q0950U37D292	KsrMp040Q4000U16D292	
	KsrMp040Q0950U42D292	KsrMp040Q4000U16D315	
	KsrMp040Q1400U32D292		
	KsrMp040Q1400U37D292		
	KsrMp040Q1400U42D292		
Total	16	13	10

Furthermore, the main stochastic parameters that define the water levels calculated by WAQUA are the wind speed and the discharge of the IJssel and the Vecht. As shown in chapter 3, the different western wind directions lead to similar water levels (with WNW being the most dominant direction leading to overflowing water levels) and the influence of winds from the east generally lead to lower water levels, even during high discharge scenarios from the Vecht. From the different design points generated by Hydra-NL, only the wind directions from the west (270°), west-northwest (292.5°) and northwest (315°) are used. These are the dominant wind directions that follow from Hydra-NL design points. The wind speeds for which the crest height of the flood defenses are exceeded start from 27 $\frac{m}{s}$ (in combination with high lake level and discharge) and higher. This means that in the storm dominated and extreme scenarios, these are the wind speeds taken into consideration. For the discharge dominated scenarios, wind speeds of 16 $\frac{m}{s}$ and lower are considered. These are the lowest discrete values of the wind speeds that are provided by WAQUA.

For the discharge, nearly all discretizations are used. The lower values of the discharges are used in the storm dominated scenarios. In the discharge dominated scenarios, values of roughly 3000 m^3/s and higher are used. The average discharges do not lead to water levels that overflow the crest height of the flood defense, unless a storm is also present (wind speeds of higher than 16 m/s). This is done for the two most prominent wind directions, as explained in the previous paragraph.

Finally, a number of very extreme cases are calculated, by combining both high wind speeds and high discharges. These cases are occur far less frequent, but give a worst case scenario. These scenarios lead to water levels which correspond to return periods of roughly 1/10000 years.

The end result is the list of scenarios shown in Table 4.1. To give a very rough estimate of the probability of occurrence for each scenario, the input data of Hydra-NL is used. Take note that in this input data, correlations between the stochastic values are not taken into account. High discharge values correspond lead to higher lake levels. In calculating the probabilities shown in Tables 4.2 and 4.3, this is not accounted for. Therefore, the probability of the scenarios occuring will be higher in reality. Another thing to note is that the probabilties used for the different values of the discharge relate to the probability of that discharge value being the peak value. Due to this, the probabilities of lower discharge peak values are strongly under-represented by the used probability in the calculation. Lastly, it is also worth mentioning that these are estimated probabilities for this exact scenario. In reality, numerous very similar scenarios can occur, leading to the probabilties of specific water levels which are calculated far more accurately by Hydra-NL.

Table 4.2: Estimation of the probabilities by using Hydra-NL input data, per storm or discharge driven scenario.

Storm dominated		**Discharge dominated**	
Scenario	Est probability of occurance	Scenario	Est probability of occurance
KsrMn010Q0100U32D292	3.90122E-06	KsrMp040Q2975U16D292	4.94719E-09
KsrMn010Q0100U37D292	3.45881E-07	KsrMp040Q2975U16D315	3.31264E-09
KsrMn010Q0500U32D292	1.74189E-06	KsrMp040Q3200U16D292	2.07459E-09
KsrMn010Q0500U37D292	1.54436E-07	KsrMp040Q3400U16D292	9.74456E-10
KsrMp040Q0100U32D292	2.08069E-07	KsrMp040Q3400U16D315	6.52495E-10
KsrMp040Q0100U37D292	1.84474E-08	KsrMp040Q3600U16D292	4.26922E-10
KsrMp040Q0100U42D292	1.66158E-09	KsrMp040Q3600U16D315	2.85867E-10
KsrMp040Q0500U32D292	9.29029E-08	KsrMp040Q3800U16D292	1.72945E-10
KsrMp040Q0500U37D292	8.23675E-09	KsrMp040Q3800U16D315	1.15804E-10
KsrMp040Q0500U42D292	7.41897E-10	KsrMp040Q4000U10D292	6.87514E-10
KsrMp040Q0950U32D292	1.41404E-08	KsrMp040Q4000U10D315	4.24147E-10
KsrMp040Q0950U37D292	1.25368E-09	KsrMp040Q4000U16D292	6.53701E-11
KsrMp040Q0950U42D292	1.12921E-10	KsrMp040Q4000U16D315	4.37718E-11
KsrMp040Q1400U32D292	2.75692E-09		
KsrMp040Q1400U37D292	2.44428E-10		
KsrMp040Q1400U42D292	2.2016E-11		

Table 4.3: Estimation of the probabilities by using Hydra-NL input data, per extreme scenario.

Extreme events	
Scenario	Estimated probability of occurance
KsrMp040Q2750U32D292	5.88732E-12
KsrMp040Q2975U32D292	2.19508E-12
KsrMp040Q3200U32D292	9.20498E-13
KsrMp040Q3200U37D292	8.16112E-14
KsrMp040Q3400U32D292	4.32368E-13
KsrMp040Q3400U37D292	3.83336E-14
KsrMp040Q3600U32D292	1.89426E-13
KsrMp040Q3600U37D292	1.67945E-14
KsrMp090Q2750U27D292	6.16108E-13
KsrMp090Q2975U27D292	2.29715E-13

Every scenario will be calculated in the model for multiple different breaching configurations.

- No breach
- 1 breach (location depending on the high water scenario)
- 2 breaches

The breach location depends on the high water scenario. The outside water level needs to exceed the crest height at a location for a breach to be initiated. This does not always happen for all three locations shown in figure 3.1.

4.6. Test case

To illustrate how the model works and to validate if it works as intended, a simplified model has been set up. In this section, the results of this are explained. There have been two different model runs with the test case. One where the model is ran without a breach and the other with a breach. The test case without a breach is used as a benchmark case. This case is checked first, to determine if the model works as expected. This is then compared to the test case with a breach, to check whether expected changes between the two are also shown in the model.

The model is set up in a way that the input is read from Excel tables automatically. Examples of the format for these Excel tables are shown in section 4.6.1.

4.6.1. Input for the test case

The test case is a simplified setup of compartments compared to the Kampereiland. This simplification is shown in Figure 4.5. The structure of the input data for the compartment boundary heights and lengths are shown in Figure 4.6. The area and ground level of each compartment is supplied, as well as the heights and lengths of the boundaries between compartments. An example of the lengths and heights is shown in 4.6. In these tables, the length of the boundary between compartment 1 and 2 is 10 meters, shown in the highlighted cell. The height of this boundary is 0.2m +NAP, which is made visible in the table on the right in the highlighted cell.

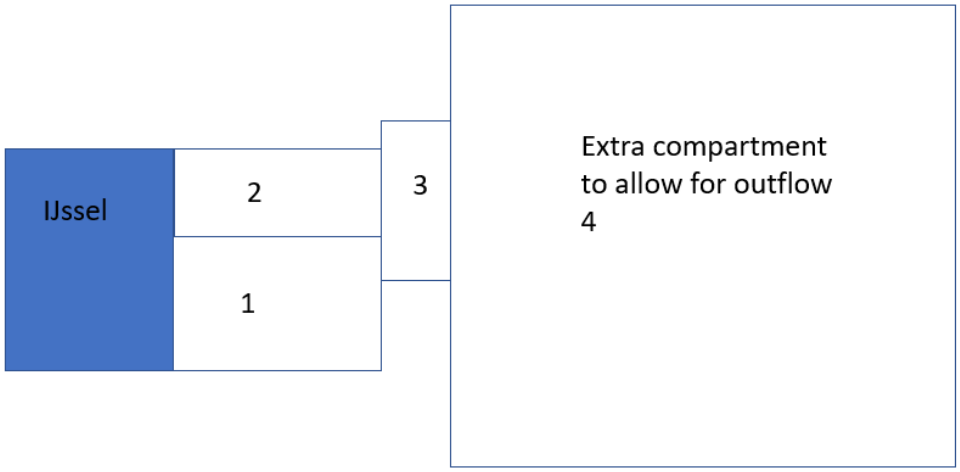


Figure 4.5: The compartment structure used in the test case.

For the test case, a constant outside water level is used, which makes checking values easier. Some values are manually checked to see whether the correct spillway formula is used. This also makes predicting the outcome more simple, such that the results can also be graphically checked.

Length boundary					
Compartiment nr	1	2	3	4	IJssel
1		10	5	0	20
2			10	0	10
3				20	0
4					0
IJssel					

Height boundary					
Compartiment nr	1	2	3	4	IJssel
1		0.2	0.3	0	0.4
2			0.5	0	0.4
3				0.2	0
4					0
IJssel					

Figure 4.6: Example of the lengths and heights of boundaries for compartments which are connected to each other.

4.6.2. Test case without breach

In the first run, the model is used to calculate the water levels in each compartment while no breach occurs. Expected is in this case that the water level in compartment 1 and 2 starts rising instantly and linearly, due to the outside water level being higher than the outside boundary height. Once the water level in the compartments exceeds the outside boundary, the inflow will change, since the inflowing discharge will now be a submerged inflow. This will show as a change in the slope in the graph. The water level inside the compartment now affects the inflowing discharge, thus the water level will no longer rise linearly.

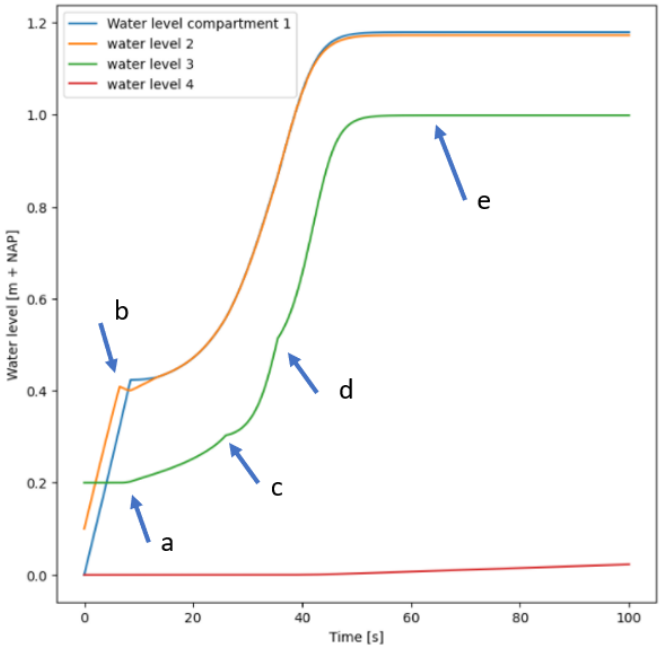


Figure 4.7: Water levels in each compartment in time, when no breach is present.

Figure 4.7 is the graph that is found as outcome of the model. As expected, the inflow in compartment 1 and 2 starts off linearly increasing, due to the constant inflow into the structure. Point a is the location where the water level in compartment 3 starts rising. The timestep after the water level in compartment 1 surpasses 0.3m +NAP is the first time the water level in compartment 3 starts rising.

At location b, we see that the inflow into compartment number 2 changes. As expected this happens when the water level in compartment 2 surpasses the boundary height, thus causing the inflow to change from free flow to a submerged inflow. The water level even slightly drops due to the outflow from compartment 2 into compartment 1. These two water levels then equalise due to the outside water level still flowing into the system.

The next reference point, location c, has a change in slope, since this is the water level at which the inflow from compartment 1 becomes submerged inflow. A similar change of slope is found at location d, which is the height of the boundary between compartment 2 and 3.

4.6.3. Test case with breach

Similarly to the test case without a breach, the model is also ran with a breach occuring in compartment 1. In this test case, the breaching formulation explained in section 4.2 is used to model the breach. Some random numbers are chosen for the breach width during the deepening phase and the duration of this phase.

The breach should start to develop instantly at timestep 0, due to the outside water level already being higher than the outside boundary of compartment 1. Thus, the deepening phase is instantly initiated. The final depth of the breach is reached after 10 seconds.

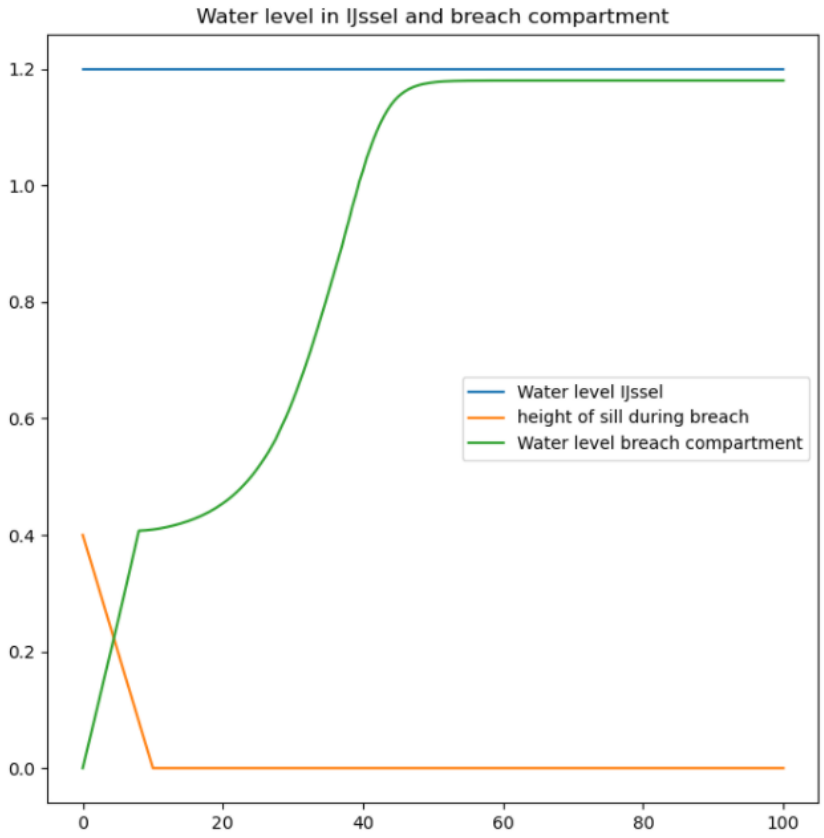


Figure 4.8: Sill height and water level in breach compartment.

Figure 4.8 shows that the sill height of the boundary indeed reaches the ground level of the breach compartment in 10 seconds. It is also visible that the water level rises faster in the breach compartment (compartment 1) than it did in the case of no breach. The water level also no longer rises linearly. At the point where the sill height crosses the water level, a slight change in slope is noticeable. This is due to the discharge through the breach is now submerged inflow, which is as expected.

The water levels in all compartments in case of a breach are shown in Figure 4.9. Here, similar reference points are added to check the results of the graph. At location a, we again see the change of slope in the water levels of compartment 1 and 2. However, in the case of no breach, the water level in compartment 2 reached a water level of 0.4m +NAP faster, this is not the case when a breach is present.

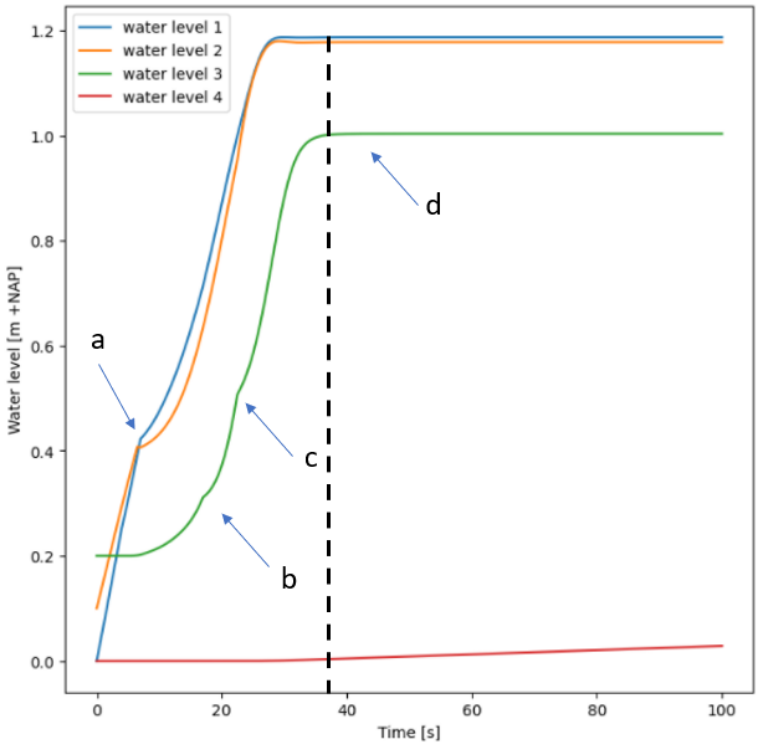


Figure 4.9: Water levels in all compartments over time, in case a breach occurs.

The main difference between the graphs with and without a breach is that the system fills up faster in the case of a breach. This is as expected due to the greater volume of water which flows into the system. The time to reach equilibrium for the system with a breach is roughly 40 seconds, compared to the 60 seconds in the scenario without a breach.

5

Model results

In this chapter the results of the model calculations are analysed. The model has been checked in section 4.6, where a simplified case was calculated and checked on logical outcomes. The results were checked and came back as expected, where numerical values have also been checked.

Following the check of the test case, the model is used to calculate scenarios for the Kampereiland, which differ in input parameters. The main difference between the calculated scenarios are the wind speeds and discharges used. Calculations have subsequently been made for a) No breach, b) a single breach and c) two breaches. First, the results of the scenarios without breaches are analysed in section 5.1. This is then followed by scenarios with a singular breach (section 5.2) and lastly for two breaches (section 5.3). For each breaching situation, the results are sub-divided into storm dominated, discharge dominated and extreme events.

5.1. No breaches

First the model is used to calculate the water levels on the Kampereiland without any breaches occuring. For the three different types of inputs of high water scenarios, namely storm dominated, discharge dominated and extreme events, the results vary strongly. The outside water level results in the flooding of the Kampereiland. The details of what floods on the Kampereiland is dependent on the water levels at different locations. An example of the outside water levels are shown in figure 5.1. In this, the naming convention is explained as the following:

Kxx M (p/n) xxxQxxxxUxxDxxx

In which:
K gives the closing situation of the Rampspolkering (sr for closing as intended, ao for always open);
M gives the lake level on the IJsselmeer (p = positive, n = negative, in centimeters +NAP);
Q gives the discharge of the IJssel in $\frac{m^3}{s}$ at Olst;
U gives the potential wind speed in $\frac{m}{s}$;
D gives the wind direction in degrees relative to the north.

5.1.1. Storm dominated scenarios

Storm dominated scenarios are the scenarios in which the discharge from the IJssel and Vecht is low, whereas the wind speeds are high. These wind speeds cause the water levels to rise due to waves and wind set up. For these scenarios, the wind speed is a big factor resulting in different peak water levels on the Ketelmeer. The main difference between the scenarios is the peak duration and the peak value of the water level, as a result of the higher wind speeds. The peak water levels that correspond to the storm dominated scenarios have varying return periods of between 1/1000 and 1/10000 years. The different wind speeds are the main driver for this high peak water level. Generally the peak water levels corresponding to 32 m/s wind speeds have a return period of roughly 1/1000 years. This increases with higher wind speeds, where 37 m/s corresponds to

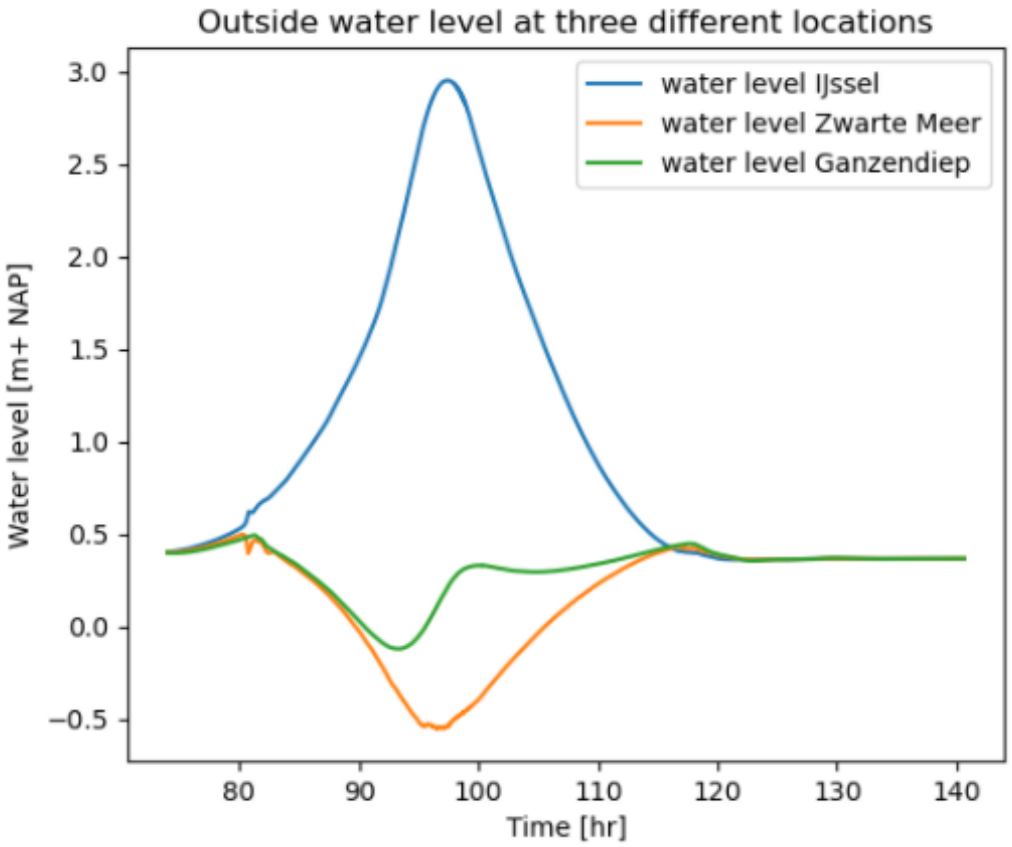


Figure 5.1: The outside water levels at the Ketelmeer/IJssel, the Zwarte Meer and at Grafhorst, for the combination of KsrMp040Q0100U32D292.

1/7000 years return periods. Finally, the very extreme cases of 42 m/s wind speeds result in water levels with return periods of 1/10000 years.

Due to the water levels on the Ketelmeer, the Kampereiland will start filling up from the west. In doing so, the compartments to the west of the causeway N50 (compartments 1 through 5 in Figure 4.3) start to fill up rapidly, leading to water levels of roughly 2 meters in a timespan of 3,5 hours. The different compartments to the west of the N50 all show a similar increase in water level since all these compartments are connected by relatively low compartment boundaries (see Figure 5.2). Due to this, water levels are quickly exceeding these boundary heights, leading to overflow between the different compartments. The N50 is a relatively high boundary in the system, when compared to the other boundaries in the western part of the Kampereiland. This causes the area to the west to act as a larger compartment once the water levels surpass 0.65 m+NAP. This is also visibile in Figure 5.3, where the equilibrium is reached a few hours after the peak water level has passed. The water level in the western compartments stays at 1.2m +NAP, which is the elevation of the N50 at the northern part of the Kampereiland.

Especially the more southern part of the N50, between compartments 5 and 8 is located high, with an average elevation of 3.5m+NAP. This causes the water levels in compartments 6 and 7 (just east of the N50, at the northern part of the highway) to increase early on. However, the time it takes before compartment 8 starts filling up is longer. Compartments 8 and 9 are the last two compartments that still inundate to the boundary height.

After the initial 3,5 hours, it is very clear that the outside water level has lowered again. The volume of water that flows into the system of the Kampereiland has reached a halt. Next, the redistribution of the water among the compartments happens. The water levels in the most western compartments reduces slightly, while water flows into the larger and more eastern located compartments in the middle of the Kampereiland. However,

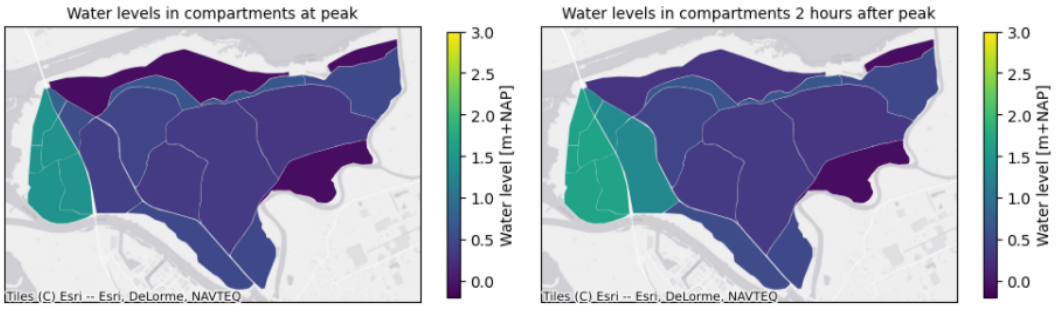


Figure 5.2: The water levels on the Kampereiland at and just after the maximum water level on the Ketelmeer for KsrMp040Q0100U32D292.

this volume of water is not enough to fill these compartments much more than a few decimeters (see the bottom two graphs in Figure 5.3). The water levels over the entire timeseries for this scenario are also shown in Appendix B.1.1.

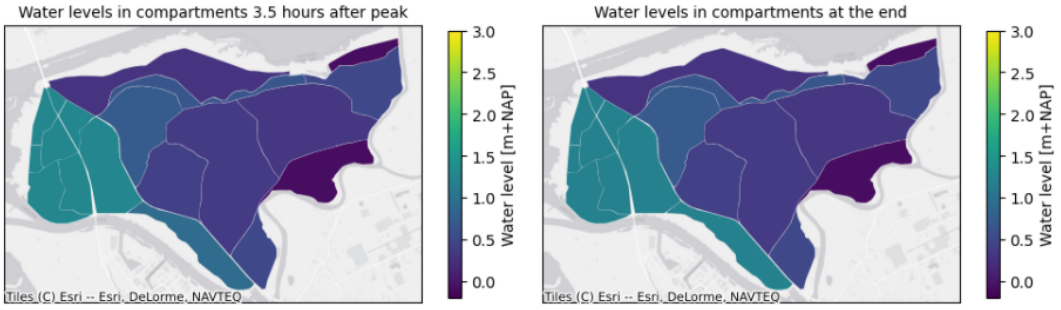


Figure 5.3: The water levels in the compartments after the outside water levels have started decreasing.

When the wind speeds in the storm dominated scenarios increase, so does the water level in the Ketelmeer, but also at Grafhorst. The sequence of flooding is clearly from west to east. Higher wind speeds that cause the water level at the Ketelmeer to also surpass the 3 meter crest height of the non overflow resistant part of flood defense 225 lead to more inundation which also travels further towards the east of the Kampereiland. In this case, the island fills up completely, aside from compartment 17, which is protected by the old flood defense present on the island.

When the IJsselmeer and Ketelmeer lake levels are higher, in combination with wind speeds surpassing 37 m/s the water level at Grafhorst also increases. This is a result of outflow of the Kampereiland along the south eastern border. The flooding is still initiated from the west, but now the water level at Grafhorst is influenced by the outflow out of the island. The time to reach an equilibrium state on the Kampereiland takes far longer, due to the increased water levels at Grafhorst. The water levels on the Kampereiland are constant after 7 hours in the scenarios with 32 m/s, where there is no outflow into the Ganzendiep. Reaching an equilibrium state takes 14.5 hours when this outflow is present. The resulting water levels on the Kampereiland are also higher while the island is filling up, by a few decimeters in most compartments. The increase of water levels at Grafhorst take place later, leading to a longer duration of inflow into the Kampereiland. Due to the lowest boundary of the Kampereiland being the southern boundary (1,55m+NAP) the water levels on the entire island end up following the outside water level at Grafhorst. Even in the scenarios where the discharge is at 100 m^3/s, the entire island will flood resulting in these water depths, as shown in Figure 5.4. The water levels for this scenario are also shown in Appendix B.1.1, where the water level development over the entire simulation is plotted.

In conclusion, in storm dominated scenarios without breaching only the western part of the Kampereiland floods in case of wind speeds of 32 m/s and lower. In the center of the Kampereiland, only a few decimeters of inundation takes place. When the outside water level increases due to the presence of wind speeds of 37

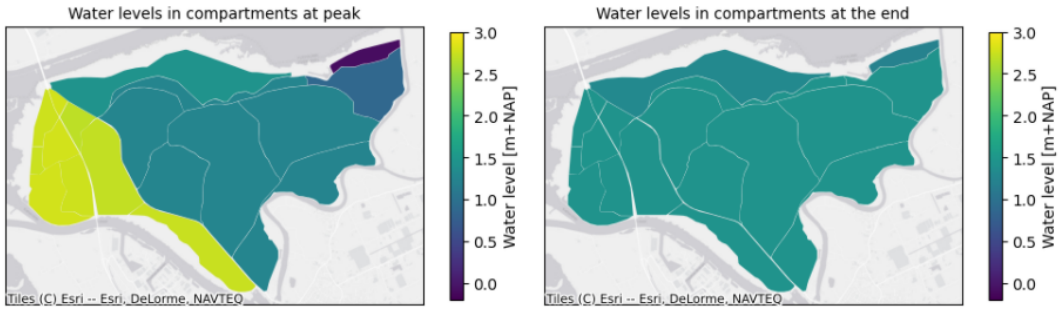


Figure 5.4: The water levels in the compartments at the peak of the outside water level and at the end of the simulation, during a scenario with no breach and 37 m/s wind speed.

m/s and higher, the entire Kampereiland floods. This flooding propagates from the west to the east over the island. Final water levels are 1.55m +NAP in this case.

5.1.2. Discharge dominated scenarios

A range of discharge dominated scenarios is modelled with the Python model created for this study. These discharges vary from 2975 m³/s to 4000 m³/s. Wind speeds in these scenarios are up to 16 m/s, from either the west northwest (292° degrees) or from the northwest (315°). In these scenarios, overflow happens once the water level in the Zwarte Meer rises above the boundaries of compartment 10 and 17 along the northern boundary of the Kampereiland. The scenarios for which this occurs fall within a range of return periods of 1/600 to 1/1000 years. The low end of this spectrum is made up of discharges of around 3000 m³/s. The highest discharges in the distribution is 4000 m³/s, leading to water levels with return periods of 1/1000 years.

The discharge dominated scenarios lead to overflow from the northern side of the Kampereiland. These scenarios never lead to water levels at the Ketelmeer surpassing the crest height of the flood defense 225 along the west side of the Kampereiland. Even for the most extreme discharge of 4000 m³/s of the IJssel, the water levels along the western side of the Kampereiland never exceed the crest height of flood defense 225. This is shown in Figure 5.5, which also shows that the rising velocity of the outside water level is much lower than it is in case of the storm dominated scenario shown in Figure 5.1. However, the peak duration of the higher water levels is much longer, when compared to the storm dominated scenarios. In the end, the resulting water levels on the Kampereiland are much more favorable in the discharge dominated scenarios. This is mainly due to the presence of the old sea dike. This is a compartment boundary that has a height of 1.85m+NAP. Due to this compartment boundary and the relatively low outside water levels, the water level in the compartment will never surpass the crest height of the old sea dike. Therefore, the water is contained in the Willem Meyer- en Stikkenpolder. This is shown in figure 5.6. The water levels over the entire simulation time per compartment are also plotted in Appendix B.1.2.

The rising velocity of the water level in compartment 10 is far lower than observed in the case of the storm dominated scenarios. Now, it takes roughly 6,5 hours for compartment 10 to equalise with the outside water level. This causes compartment 10 to overflow towards the west. In combination with the smaller compartment in the northeast of the Kampereiland, these are the only compartments that are inundated during a discharge dominated scenario without breaches. The old flood defense pretty much completely contains the flooding, confirming the hypothesis that was formed in the report of Rijkswaterstaat WVL for determining an actionplan for the IJssel-Vechtdelta [9]. Calculations in this thesis research support the hypothesis made in this actionplan and show that the flooding from the Zwarte Meer into the Kampereiland indeed takes place far more gradually and is contained in the outer polders of the island.

To conclude this section, the main result found is that the flooding of the Kampereiland in discharge dominated scenarios without breaching is contained by the old flood defense. This results in only the outer polders of the Kampereiland being inundated.

5.1.3. Extreme events

In the extreme events, high discharges and wind speeds are combined, to gauge the influence of this on the flooding of the Kampereiland. In the extreme cases, the wind speed still very much dictate the flooding of

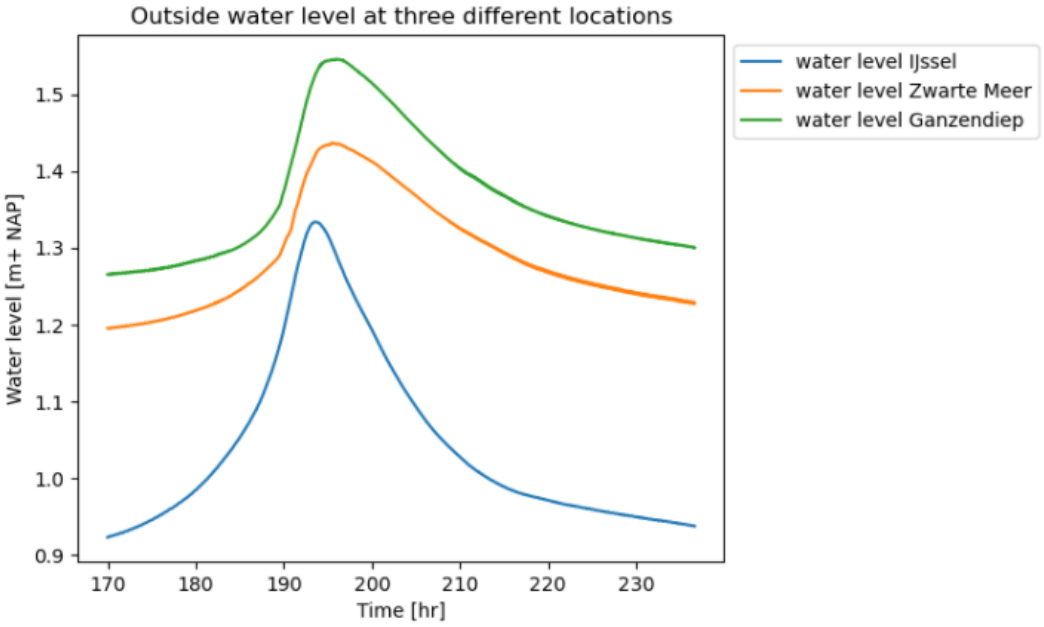


Figure 5.5: The outside water levels at the Ketelmeer/IJssel, the Zwarte Meer and at Grafhorst, for the combination of KsrMp040Q4000U16D292.

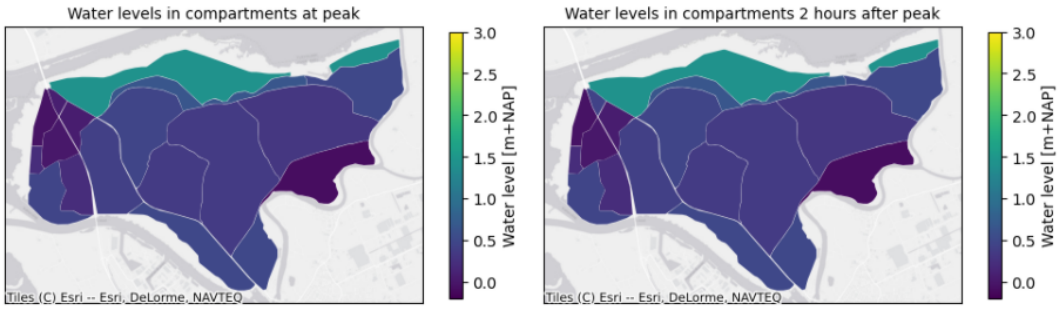


Figure 5.6: Water levels on the Kampereiland during the first hours after the maximum water level on the Zwarte Meer, in the discharge dominated scenario KsrMp040Q4000U16D292 without a breach.

the Kampereiland. The maximum water level that is reached both at the Ketelmeer and at Grafhorst strongly influence the flooding of the island, which are mainly determined by the wind speed that occurs. There are distinct differences noticeable when increasing the wind speeds, whereas increasing the discharges does not result in major changes in the flooding pattern of the Kampereiland. To show the differences on the outside water levels, Figure 5.7a and 5.7b are plotted. These figures clearly show the trend that the increase in wind speeds beyond 32 m/s leads to large changes in the occuring water level at Grafhorst and de Zwarte Meer.

These in return cause the larger compartments to quickly fill up. This difference is also noted here. Where in the case of a bit lower wind speeds of 32 m/s, after initial inflow, the outflow into adjacent compartments is larger than the inflow into the Kampereiland from the western side. This is the case until water starts flowing in from the southern regions of the Kampereiland. Figures 5.8 and 5.9 show the results of a scenario with the same discharge and lake level, but only a different wind speed (for the water levels in each compartment during the entire time series, see Appendix B.1.3). In case of the scenario where the wind speed is 32 m/s, the inflow into the Kampereiland is far lower after the initial western part of the island floods. After the initial flooding, water levels in the west already start to lower due to redistribution further towards the eastern compartments (see the right image in Figure 5.8). The rate at which water levels rise in the following compartments to the east of the N50 is much lower. As soon as the water level at Grafhorst starts exceeding the southern crest height of flood defense 101, suddenly the water levels in all the western compartments also rise, leading to a total increase in the water levels of the different compartments.



(a) KsrMp040Q3200U32D292

(b) KsrMp040Q3200U37D292

Figure 5.7: Outside water levels in an extreme scenario, only differing in wind speed

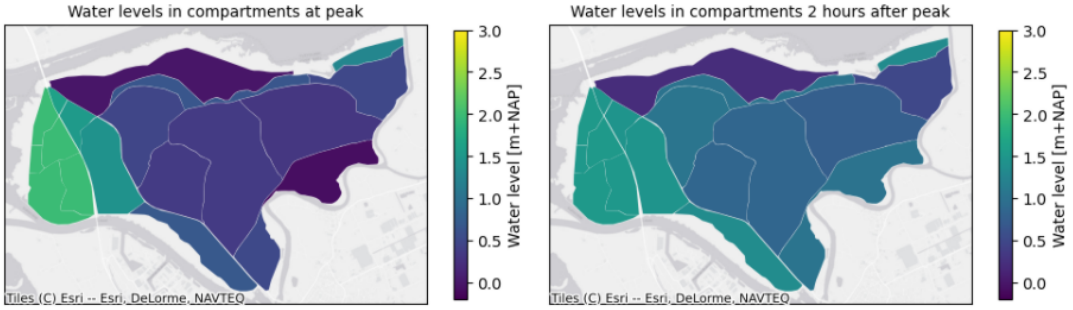


Figure 5.8: Water levels on the Kampereiland during the first hours after the maximum water level on the Zwarte Meer, in the discharge dominated scenario KsrMp040Q3200U32D292 without a breach.

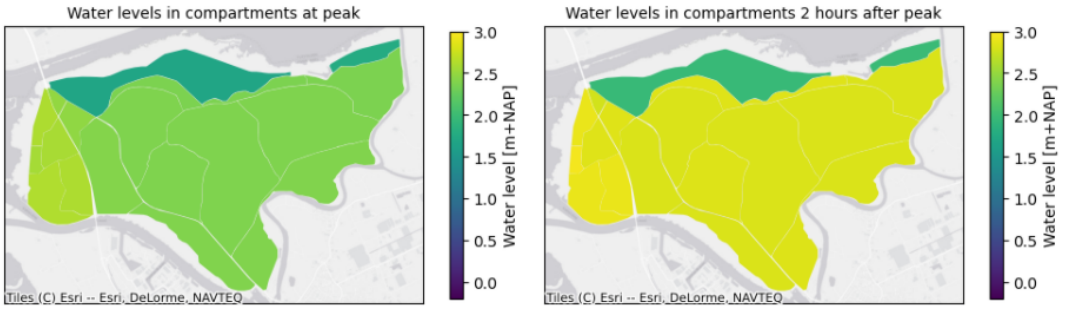


Figure 5.9: Water levels on the Kampereiland during the first hours after the maximum water level on the Zwarte Meer, in the discharge dominated scenario KsrMp040Q3200U37D292 without a breach.

In the case of wind speeds higher than 37 m/s, the inflow is far larger than in the case of 32 m/s wind speeds. Water levels rise above 2.5 meters in the western compartments, which then propagate further towards the east. As was seen in the case of 32 m/s, the redistribution causes a reduction of water levels in the western compartments, fast after the peak (roughly 2 hours, see Figure 5.8). However, in scenarios with 37 m/s, the inflow is large enough to not cause water levels in the west to reduce yet due to propagation further onto the island. It takes longer for the water levels to settle and eventually come to an equilibrium at roughly 1.5m +NAP.

To summarise the extreme events without breaching, the entire island ends up flooding. However, the water levels on the Kampereiland are significantly lower in cases with wind speeds of a maximum of 32 m/s. Once this wind speed is surpassed, the water levels on the Kampereiland increase to a maximum of 2.7m +NAP. This is more than half a meter higher than in the case of 32 m/s wind speeds. The time to reach equilibrium water levels als change due to later and higher water levels in the Zwarte Meer and at Grafhorst in case of 37 m/s wind speeds.

5.2. One breach

Next, the effect of breaching on the Kampereiland is shown by calculating the same scenarios as done above, but now for the case with a singular breach. Due to the way the breaches are modelled, not every scenario can be modelled with a breach at the three different locations shown in Figure 3.1. This is because certain scenarios do not lead to overflow at all three locations. Most high discharge events do not lead to overflow along flood defense 225. Therefore these locations will not be modelled with a breach for those scenarios.

The general outcome of an occurring breach is that the compartments fill up more rapidly and the total volume of water that flows into the Kampereiland is larger. However, the breach also leads to possible outflow from the breach compartment. This is mainly relevant for the breaches in compartment 3. Due to low crest heights of compartment boundaries to the west of the N50, these compartments are drained to roughly 0.5m+NAP when the outside water level reduces again. Water levels in the center of the Kampereiland stay higher due to the presence of relatively higher compartment boundaries.

5.2.1. Storm dominated scenarios

In the storm dominated scenarios, the main breaches that occur are located in flood defense 225. Here, the breaches occur either in the overflow resistant part which is 2.6m+NAP in height, or in the non overflow resistant part with a crest height of 3m+NAP. These breaches lead to a larger inflow of water during the storm, which in most cases leads to the entirety of the Kampereiland to be inundated. This includes most of the compartments that were not inundated in cases without a breach, such as the more central compartments (11, 12, 13, 18 and 19). These compartments are now fully inundated, up to the boundaries. The only compartment that still stays dry in most cases is compartment 17, which is the outer polder along the northern end of the Kampereiland (see Figure 5.10 and Figure 5.11). This compartment is enclosed on the southern side by the old flood defense. Due to the heights of the different boundaries, water flows out of the Kampereiland into the Ganzendiep from compartment 16 before it overflows into the most nothern compartment.

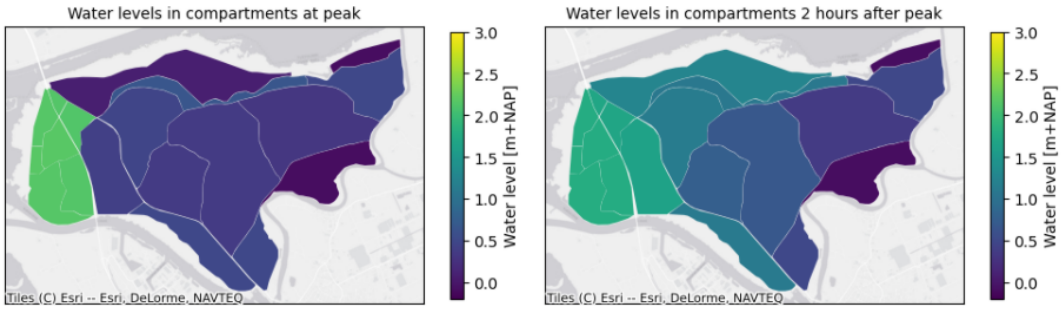


Figure 5.10: Water levels on the Kampereiland during the first hours after the maximum water level on the Ketelmeer, in the storm dominated scenario KsrMp040Q0100U32D292 with a breach in the overflow resistant part of flood defense 225.

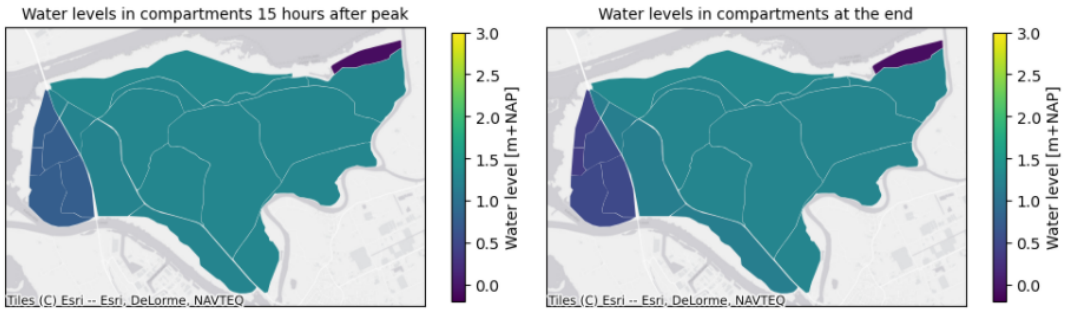


Figure 5.11: Water levels on the Kampereiland during the last hours of the simulation, in the storm dominated scenario KsrMp040Q0100U32D292 with a breach in the overflow resistant part of flood defense 225.

Due to the breach being present in the overflow resistant part of flood defense 225, the maximum water levels in the compartments to the west of the N50 are reached roughly 45 minutes earlier than in the case without breaching. The inflow into adjacent compartments starts 15 minutes earlier in compartments to the west of the N50. When traveling more towards the east of the Kampereiland, the compartments fill up to higher water levels and also inundate earlier than in the case of no breach. The first inflow is generally about an hour to an hour and a half earlier in comparison to the cases without a breach.

The results again show a big difference in the scenarios surpassing 37 m/s wind speeds. The width of the breach stays roughly the same, but as seen in the scenarios with no breach as well, the water inflow into the Kampereiland drastically increases in these cases. The combination of a breach in flood defense 225 and the peak water levels at the Ketelmeer lead to the Kampereiland being entirely flooded, with significantly higher resulting water levels in all compartments compared to the case with wind speeds of 32 m/s. The water levels in all compartments reach water levels which are nearly a meter higher than in the case of 32 m/s, as shown in Figure 5.12.

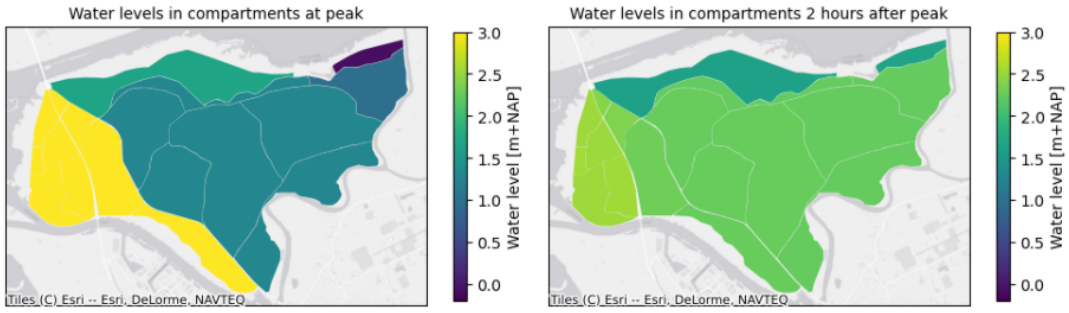


Figure 5.12: Water levels on the Kampereiland during the first hours after the maximum water level on the Ketelmeer, in the storm dominated scenario KsrMp040Q0100U37D292 with a breach in the overflow resistant part of flood defense 225.

The water level at Grafhorst increases significantly as well. Peak water levels occur near the breach, where the inflow of water is so substancial that it reaches the outside water level of the Ketelmeer. The peak water levels on the Kampereiland are lower in case of a breach in the non overflow resistant part of the flood defense. This has to do with the initiation of the breach happening later, while compartments along the overflow resistant part of the flood defense are already inundating because of regular overflow.

The width of the breaches vary from 125m to just over 150m for wind speeds up to 32 m/s. When very extreme wind speeds of 42 m/s occur, the water level at Grafhorst increases. The water levels in the western part of the Kampereiland follow this rising water level. This results in water levels in the western compartments that is higher than the water level on the Ketelmeer. This in return leads to outflow into the Ketelmeer, through the breach that is present. The outflow through the breach causes the breach width to increase, leading to a final breach width of roughly 200m.

To recap this section, the breach causes significant increases in rising velocities in the western part of the Kampereiland. The larger volume of water that flows into the Kampereiland causes all compartments to inundate up to their respective boundaries. Peak water levels are significantly higher in case of a breach, with maximum water levels of 0.5m +NAP higher than in the same scenarios without breaching (The peak water levels are more clearly visible in Appendix B.2.1). The wind speeds increasing to 37 m/s still massively increase water levels on the island, with maximum water levels being roughly a meter higher than in scenarios with 32 m/s wind speeds.

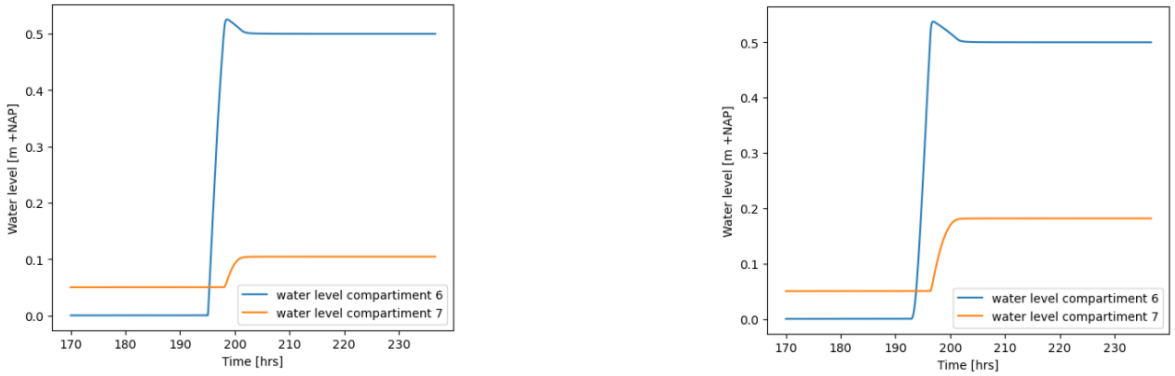
An upside of a breach being present is visible in Figure 5.11. Due to the presence of a breach, outflow of water is possible, leading to lower final water levels on the island, of roughly 1.25m +NAP (boundary height of the N50). In the western compartments this is outflow is more significant, resulting in water levels around 0.5m +NAP.

5.2.2. Discharge dominated scenarios

The breaches in discharge dominated scenarios are mainly fixed to the location in northern flood defense of the Kampereiland. This is because without higher wind speeds being present, water levels surpassing the crest height of flood defense 225 will never be reached.

A singular breach in the flood defense of 101 does not lead to substancial differences in comparison to the calculations without a breach. Breaching does not change the flooded compartments. The old sea dike at the southern side of the polder will still prevent the flooding of the rest of the Kampereiland, by containing the water. Compartments to the west of the breach compartment will inundate slightly more, leading to roughly a decimeter increase in water level in compartments 6 and 7. This is shown in Figure 5.13, where a comparison of the water levels in compartment 6 and 7 have been shown for the case without a breach, compared to with a breach.

The total inflow of water from the Zwarte Meer into the Kampereiland is very limited, because the water level is quickly equalized with the outside water level. Since this is barely higher than the lowest compartment boundary within compartment 10, the inundation is very limited overall. Figure 5.13 also shows this. The inundation just stops in the two compartments connected to the lowest compartment boundary of the breach compartment.



(a) No breach

(b) Breach

Figure 5.13: Water levels in compartments 6 and 7 with no breach and a breach, for 4000 m³/s discharge.

The breach widths are very similar to the breaches in the storm dominated scenarios. However, the breach growth is more consistent. During the storm dominated scenarios the breach growth initially happens, then flattens out and increases again after, due to larger outflow again. This has to do with that the water level rises faster during the storm dominated. The water level in the breach compartment quickly follows the outside water level, leading to little discharge through the breach.

To summarise, the flooding of the Kampereiland does not significantly change in case of a breach in the northern flood defense during a discharge dominated scenario. The water levels that occur of the Kampereiland are nearly the same as in the case without a breach.

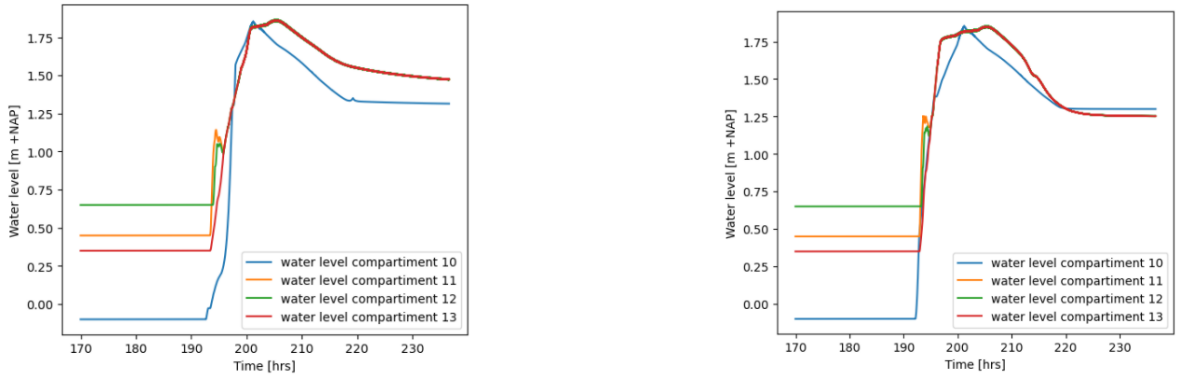
5.2.3. Extreme events

The extreme event scenarios do not lead to significant changes in the water levels on the Ketelmeer, compared to the storm dominated scenarios. This is due to the small impact that the discharge has on the water levels at this location. However, the water levels at the Zwarte Meer and Grafhorst do change significantly, due to the combination of high discharge and wind speeds. These high water levels have a longer duration but the difference between the maximum water level and the minimum water levels are smaller. These also cause breaches to grow more consistently.

During extreme events, the inflow order of the Kampereiland can change due to the lake level of the IJsselmeer. Due to a higher base value, the water levels at the Zwarte Meer and at Grafhorst can surpass the

local crest heights roughly 8 hours prior to the peak storm setup reaching flood defense 225 along the western boundary of the Kampereiland. This leads to inflow from the northern and southern side of the island, prior to inflow due to the storm from the western end. These higher lake levels only cause earlier inflow during a lake level of 0.9m+NAP. While staying below this value, the peak of the storm dictates the inflow of the Kampereiland. This results in west to east inflow of the Kampereiland.

Rising velocities of the water level in the different compartments are still heavily dictated by inflow over flood defense 225. This is enhanced by the breaching in this flood defense. Water levels rise faster when inflow from west to east occurs. This is the case for the entire island. Breaches in flood defense 225 cause peak water levels to be reached earlier in the compartments on the Kampereiland. This is shown in Figure 5.14. These are compartments that are located to the east of the N50 causeway. In case of a breach along the western border of the Kampereiland, the peak water level is reached roughly 4 hours earlier than in the case of no breaching, while the moment of initial inundation is the same.



(a) No breach

(b) Breach

Figure 5.14: Comparison of times reaching peak water levels in compartments in the center of the Kampereiland

The maximum water levels reached in the compartments to the west of the N50 are higher than those in the case without breaching. However, final water levels on the Kampereiland are about 25 cm lower in case of a breach. This follows from the excess water that can flow out through the breach after the outside water levels reduces. In the case of no breaching, during extreme events, final water levels on the Kampereiland are 1.55m+NAP. This is as expected since this is the lowest outside boundary present, near Grafhorst. However, the compartment boundaries are almost all lower than this flood defense, leading to redistribution of the water levels in compartments, after the outside water levels drop. Water flows out of the system, towards the west, resulting in final water levels of 1.25m+NAP to the east of the causeway N50 (see B.2.3).

To finalise this section the main findings are repeated. A breach in the extreme scenarios leads to higher water levels on the Kampereiland, as well as higher rising velocities of these water levels. The highest rising velocities occur with a breach in the overflow resistant part of flood defense 225. The maximum water levels on the Kampereiland take place roughly 4 hours earlier in case of breaching, compared to no breaching, but the final water levels are lower due to the outflow through the breach when outside water levels subside.

5.3. Two breaches

One of the uncertainties of the breaching is whether a singular breach or multiple breaches take place. To check the sensitivity of the flooding of the Kampereiland to this, the chosen scenarios of this thesis research have also been calculated for two breaches. As with the case of a single breach, the same three locations have been used. The way calculations have been performed with two breaches, is explained in section 4.1. This explains that two breaches have been schematised as a single breach with two times the total width of the breach. The factor 2 for the total width has been checked to give a respresentative discharge through the breach in subsection 4.2.2.

5.3.1. Storm dominated scenarios

As with the case of a single breach, all compartments are fully flooded due to breaching in flood defense 225 during a storm dominated scenario. The only exceptions to this are the scenarios with negative lake levels of -0.1m+NAP, combined with a wind speed of 32 m/s. These scenarios do cause inundation of the entire island, but not up to the crest height of the southeastern flood defense near Grafhorst. Maximum water levels in these scenarios are up to 2m+NAP in the compartments to the west of the N50, while they are roughly 1.5m+NAP in the center compartments of the Kampereiland. After the peak of the outside water levels has passed and redistribution of the water levels has finished, the compartments to the east of the N50 end with a water level of 0.75m+NAP.

In the majority of the storm dominated scenarios, the outside water level is higher than described above. This also results in higher water levels in the compartments. In all other scenarios calculated in this research, the Kampereiland fully fills up. Maximum water levels surpass 2.5m+NAP in the west. After the outside water levels drop, the entire island is still filled up to 1.25m+NAP. This again has to do with water flowing out again through the breach.

Compartments 1 through 7 all have maximum water levels well over 2m+NAP in case of a double breach. These are also accompanied by fast increasing of the water level, with rising velocities of roughly 1.5 meter per hour. However, once these compartments have filled up, they cause a reduction of the inflow into the compartments further to the east, due to the presence of the N50 causeway. This is clearly seen in Table 5.1. The water that flows in from the west all flows through compartment 6 and 7 (also see Appendix B.3.1 for the graphs of the water levels in each compartment), where the lowest part of the N50 is located. This reduces the flow towards the eastern compartments, which is seen in the rising velocity of the water level in these compartments. Where the rising velocity is significantly above 1 m/hr for the majority of the compartments to the west of the N50, this is far lower in the compartments further to the east.

Shortly summarising, the entirety of the Kampereiland fills up in nearly all scenarios where a double breach takes place. Water levels to the west of the N50 fill up very rapidly, with rising velocities varying from 1 to 1.6 m/hr. Since the compartment boundaries to the west of the N50 are relatively low, these compartments are completely filled quickly. The water propagates further to the east, but a reduction in rising velocities is found due to the reduced inflow into the Kampereiland.

5.3.2. Discharge dominated scenarios

Even with a second breach in discharge dominated scenarios, the flooding of the Kampereiland is still contained fairly well. The breaching compartment along the northern side floods and overflow to compartments towards the west follows (as can be seen in Appendix B.3.2). However, the combination of the old sea dike and the causeway of the road N50 contain this. The volume of water flowing into the island is insufficient to cause widespread flooding of compartments.

The results do not vary from the model results with the singular breaching. Water levels are the same as in the case with a single breach in the northern compartment. The water levels in the breach compartment are consistently the same as the outside water level, leading to barely any inflow of water at all. The only time inflow happens is while water flows over the western boundary to compartment 6 and 7. As explained in the case with a single breach (see subsection 5.2.2), the outside water level is barely higher than this western boundary. Therefore, the water inflow is very limited, resulting in no further inundation.

5.3.3. Extreme events

The difference between a singular breach and two breaches is very minimal in extreme scenarios. The entire island fills up rapidly, mainly from west to east. Even in the situation where the breach takes place along the northern side of the island, the main flooding still occurs from the west. The breach inflow shows an earlier inflow into the northern compartment, but this does not fill up fast enough to cause the flooding to spread before the western compartments have completely filled up.

The worst-case scenario calculated in this research is a scenario with a discharge of 3600 m^3/s and a wind speed of 37 m/s. The resulting outside water levels calculated by WAQUA are shown in Figure 5.15. These water levels surpass the crest height of the overflow resistant part of flood defense 225 by nearly a meter.

Table 5.1: The rising velocities and maximum water levels per compartment for a scenario with a discharge of 100 m³/s and wind speed of 32 m/s with a double breach in compartment 3.

Compartment nr	**Double breach comp 3**	
	Max wl [m+NAP]	Rising vel [m/hr]
1	2.62	1.14
2	2.57	1.52
3	2.42	1.11
4	2.12	0.69
5	2.37	1.59
6	2.52	1.55
7	2.48	1.19
8	1.58	0.20
9	1.48	0.36
10	1.50	1.07
11	1.13	1.33
12	0.94	0.08
13	1.23	0.28
14	1.08	0.20
15	1.68	0.69
16	1.08	0.32
17	0	0
18	1.23	0.33
19	1.28	0.48

This combined with a double breach leads to extreme water levels on the Kampereiland. In Table 5.2, the maximum occurring water levels in each compartment are shown per breach location. The rising velocity of the first 1.5m water level rise has also been added to the table. It is clear to see that the western part of the Kampereiland is most influenced by a breaching in the lower part of flood defense 225. This leads to higher rising velocities as well as higher maxima for the water level in the compartments. Further to east of the Kampereiland, the resulting water levels are much closer for the three different breach locations. Generally these compartments are larger and more time has passed before the water levels in these compartments start rising.

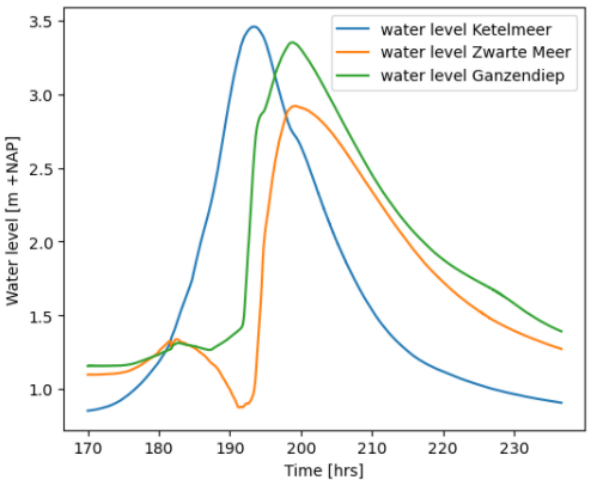


Figure 5.15: The outside water levels in scenario KsrMp040Q3600U37D292.

The compartments along the north and eastern boundary of the Kampereiland are more dependent on breaching from the north, due to the water levels in the Zwarte Meer. However, the water levels need to be very

Table 5.2: The rising velocities and maximum water levels in the worst case scenario per compartment.

Compartment nr	**Double breach comp 3**		**Double breach comp 9**		**Double breach comp 10**	
	Max wl [m+NAP]	Rising vel [m/hr]	Max wl [m+NAP]	Rising vel [m/hr]	Max wl [m+NAP]	Rising vel [m/hr]
1	**3.43**	**1.37**	3.21	0.94	3.14	0.94
2	**3.38**	**1.78**	3.13	1.28	3.12	1.28
3	**3.27**	**0.99**	3.00	0.74	2.92	0.74
4	**2.93**	**1.19**	2.69	1.01	2.63	1.01
5	**3.18**	**2.27**	2.94	1.65	2.87	1.65
6	**3.34**	**2.44**	3.15	1.50	3.16	1.48
7	**3.24**	**2.27**	3.09	1.41	3.10	1.39
8	**2.85**	**1.84**	2.75	1.20	2.77	1.21
9	**2.76**	1.01	2.68	**1.04**	2.71	0.82
10	**3.10**	0.047	3.09	0.03	3.09	**0.11**
11	2.71	0.37	2.70	**0.58**	**2.72**	0.56
12	2.50	0.52	2.49	**0.75**	**2.51**	0.73
13	**2.85**	0.60	2.83	0.64	**2.85**	**0.71**
14	**2.75**	0.64	2.74	0.57	**2.75**	**0.67**
15	**3.38**	1.67	3.37	1.78	**3.38**	**2.00**
16	**2.71**	1.34	2.70	1.70	**2.71**	**2.36**
17	**3.14**	**0.07**	**3.14**	**0.07**	**3.14**	**0.07**
18	2.85	0.71	2.84	0.76	**2.86**	**0.81**
19	2.91	0.96	2.90	1.19	**2.92**	**1.29**

extreme to cause the entirety of the Kampereiland to flood. As already shown in subsection 5.2.2, even in the most extreme discharge dominated scenario, the Kampereiland barely inundates.

In conclusion, an extra breach in case of extreme scenarios still leads to a fully flooded Kampereiland. The resulting water levels on the island are extremely high, especially near the breaching location (see Appendix B.3.3), where water levels exceed 3m +NAP. In a number of compartments the rising velocity is higher than 2 m/hr, meaning that there is little time to react and evacuate.

6

Discussion

In this chapter, the use of the model results are further reviewed. This includes the impact of assumptions that are made. First, the model results are discussed further. After this, the influence of assumptions are treated.

6.1. The model results

While the Kampereiland is meant to inundate during high water scenarios, it is good to know to what degree that inundation takes place. As the WAQUA simulations to date have used numerous simplifications and assumptions, the outcomes only give rough estimates of flood propagation on the Kampereiland. These simplifications and assumptions mainly relate to the lack of detailed breach analysis and using a simplified compartment structure.

The results of this thesis research fill the gaps created by these simplifications and assumptions and can be used to create a more comprehensive picture of the flooding of the Kampereiland. It now includes the influence of breaching along the northern and western flood defenses of the Kampereiland, in multiple different scenarios of high water. Breaching during storm induced high water is a subject of research, which has been extensively evaluated in this thesis. The effects of breaching during a storm shows that the flooding is widespread, but also reduced due to the compartment structure present.

In this, the Kampereiland floods completely in scenarios with wind speeds of 37 m/s and higher. The flooding from the western side of the Kampereiland is more critical than that from the northern side, both with and without breaches. In very extreme cases, breaches in the northern flood defense 101 lead to more extreme results for the compartments located more in the southeast part of the Kampereiland. This is all information that can be put to use to make evacuation plans, to inform the people who live on the island and for policy makers to further improve the safety against flooding in the area of the IJssel- and Vechtdelta.

From the results found in this thesis research, the flood defense protecting IJsselmuiden (flood defense 10-2) will most likely not be threatend due to increasing loads when the Kampereiland floods. This flood defense has a height of just over 3m +NAP. This is only reached by water levels on the Kampereiland in the most extreme scenarios calculated. Considering that the allowable failure probability of flood defense 10-2 is 1/10000 per year and the probabilities of reaching these water levels on the Kampereiland follow from water levels with a return period of over 1/30000 years along flood defense 225, it is expected that flood defense 10-2 will not be threatend, even in case of breaches in flood defense 225 along the western side of the Kampereiland. However, it is noted that wind setup might cause higher water levels further to the southeast of the island, during western winds. This might cause higher water levels than calculated.

6.2. Influence of the assumptions

Every assumption that is made has an influence on the results of the research. To narrow down the scope of the research, assumptions are a necessity. The impact of the assumptions are elaborated upon in this subsection.

Modelling the flow

The spacial variations of the model used for this research are strongly simplified. Every compartment fills up equally across the entire ground level. This means that the flow within a compartment is not fully accurate. A more precise flowpattern is found in the existing WAQUA model. The more precise determination of the flow pattern is important for a number of reasons. This will not only allow for tilted water levels in the compartments while these fill up, but also take the effect of the water level set up due to the wind into account. The tilting of the water surface due to the wind results in higher water levels in eastern direction. This would lead to earlier inflow in compartments located more towards the east, while water levels are lowered in the west of the compartment. This influences the time that there is either free or submerged flow into an adjacent compartment. It is expected that the winds from the west lead to a reduction of the submerged inflow and cause compartment boundaries to overflow at an earlier stage. However, the compartment boundaries also provide shelter to the wind. How these two effects will compare to each other can be gauged by making the compartment structure in the WAQUA model more precise. This is also recommended in the next chapter for future research (see Section 7.2).

Breaching of the compartment boundaries on the Kampereiland

Another assumption that was made in this research is that compartment boundaries inside the Kampereiland do not breach. This assumption was made based on a report on making flooding calculations in the Netherlands [4]. Since the compartment boundaries are mainly roads and old flood defenses with faint and well covered grass slopes, these are assumed to have significant strength against overflow, thus they do not breach. However, a full breaching analysis has not been performed in this thesis research. To give an idea into the impact of a breach within a compartment boundary, some calculations have been made in which the height of a compartment boundary has been lowered (see Appendix A). This has been done specifically for the old flood defense along the southern boundary of the Willem Meyer- and Stikkenpolder. In doing this, suddenly the Kampereiland would fill up to 1.3m+NAP. This shows that discharge dominated scenarios could very well become a larger threat than so far has been shown in this research.

Uncertainties in breaching

There are some aspects of the breaching process which are assumed in this thesis research. One of these is the assumption that the breach occurs when the outside water level exceeds the crest height of the flood defense. The moment of breaching is hard to predict. In practise, two different moments in time are generally used. The initiation of a breach is either assumed to occur when the outside water level exceeds the crest height, or at the maximum outside water level. The first option is used in this thesis research, which is assumed to lead to higher water levels on the Kampereiland. This is due to earlier inflow and a higher water level difference between the outside water level and inside the breach compartment. In case of breach initiation at the peak outside water level, overflow over the flood defense will already have started prior to the breach. This will cause lower inflow, smaller breach widths and shorter duration of inflow through the breach compared to earlier breach initiation. It is therefore assumed that the made assumption leads to a more critical situation.

The number of breaches that take place is something that cannot be precisely predicted. When a breach occurs, it often leads to more weak points in the flood defense, leading to higher probabilities of more breaches. In this research, no more than 2 breaches occur at the same time. The influence of another breach is expected to increase water levels on the Kampereiland, especially near the breaches. However, if the water level would increase to match the outside water level, then inflow would be reduced significantly. Since the highest outside water levels in the most extreme case are just over 3.5m +NAP, similar water levels on the Kampereiland will be found near the breaches. The higher the number of breaches is, the more likely it is that this will be the trend that follows on the Kampereiland.

The locations of the breaching is something that is still uncertain. Three locations are chosen to do the analysis. This is done to show the impact of the different breach locations and how it affects the water levels on the Kampereiland. Ofcourse breaching at other locations could occur as well. However, the results do show that

due to earlier inflow into the Kampereiland at locations that have been made overflow resistant, the impact of breach at higher elevated flood defenses is reduced. What this means is that a breach in the overflow resistant part of flood defense 225 has a bigger influence on the water levels and rising velocities in the Kampereiland than a breach along the higher part of this flood defense. It is expected that this is the same for other locations along the northern side of the Kampereiland. If a breach would occur along the south eastern boundary of the Kampereiland, it will most likely be influenced by very high water levels due to storm scenarios. These scenarios cause peak water levels along the western side of the Kampereiland first, meaning that in those cases, the island will already be flooded before water levels in the Ganzendiep would lead to overflow or breaching (with breach initiation as assumed in this thesis research).

7

Conclusions and recommendations of future research

In this chapter, the results found in chapter 5 are used to answer the research questions posed in chapter 1. The formulated sub-questions are answered first. At the end of this chapter, the main research question is answered. Following this, recommendations for additional research are given.

7.1. Conclusion

The main research question in this report is stated as:

How does the Kampereiland flood during high water scenarios, while taking the uncertainties in the breaching process and compartmentalisation into account?

To answer this, the sub-questions that have been formulated are answered. All these answers together form the answer to the main research question posed.

What are the relevant flooding scenarios for the Kampereiland?
The relevant flooding scenarios are reviewed in chapter 3. The different stochastic variables that contribute to the resulting water levels at both the western boundary (flood defense 225) and the northern boundary (flood defense 101) of the Kampereiland have been analysed and plotted against each other. From this, it follows that the wind is the most important parameter in causing overflow into the Kampereiland. The discharge plays a relatively larger role for inflow from the north compared to the location along the western side of the island. This results in three main scenarios that cause inflow into the Kampereiland.

The first of these is the wind dominated scenarios. The water levels in these scenarios are predominantly caused by wind setup and result in high water levels on the Ketelmeer. Water levels that surpass the crest height of flood defense 225 are found from wind speeds of 27 m/s and up. The discharge has nearly no impact on the resulting water levels here, whereas the lake level on the IJsselmeer does influence this. The design point for this location (western boundary of the Kampereiland) for water levels exceeding the crest height follow from low lake levels with high wind speeds of 37 m/s. However, higher lake levels and low wind speeds also result in water levels surpassing the crest height. A span of stochastic combinations is therefore made for different combinations of low discharges, varying high wind speeds (from 27 m/s and higher) and varying lake levels between -0.1m+NAP and 0.9m+NAP.

The discharge dominated events consist of higher discharges with low wind speeds below 16 m/s. These cause water levels in the Vechtdelta to increase, leading to flooding from the northern side of the Kampereiland. The water level increases are of a longer duration and increase more gradually than that of the storm dominated scenarios. These are used to determine the influence of flooding of the Kampereiland from the north.

Finally, in the extreme event of a combination of high wind speeds and discharges, water levels at both the western and northern sides of the Kampereiland increase. This is used to understand the water levels that are reached on the Kampereiland in a worst case scenario.

What is the compartmentalisation structure on the Kampereiland?
To determine the compartmentalisation structure on the Kampereiland, higher elevated line elements are used. The Kampereiland is historically created by land reclamation. Because of this, the historic flood defenses and higher boundaries that were originally at the outside contours of the island are now present further inland on the island. These higher elevated line elements are now mainly roads and old flood defenses that are present on the Kampereiland. Using these, the final compartment structure is as shown in figure 7.1.

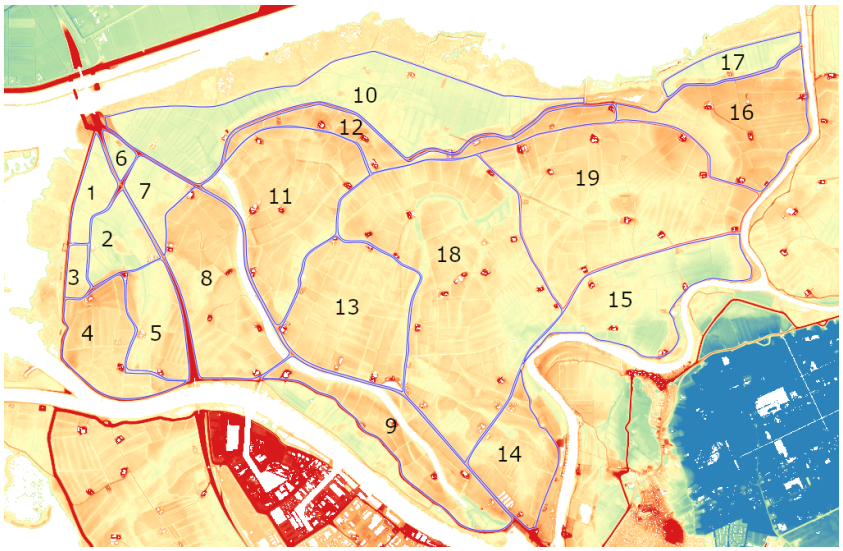


Figure 7.1: The numbered compartment structure of the Kampereiland.

This compartment structure takes only the main boundaries into account. Small trenches and waterways are not accounted for. This is done based on the assumption that this will only have a small impact on the inundation time of the island, as stated in a research of the inundation of the Land van Maas and Waal [7].

What are the uncertainties in the breaching process and compartmentalisation structure?
There are numerous uncertainties in the breaching process. These are:

- When is a breach initiated?
- Where does a breach take place?
- What width does the breach have?
- How many breaches occur?
- Do the compartment boundaries breach?

The detailed analysis of all the failure mechanisms is outside of the scope of this research. However, to still add these uncertainties into the research, a sensitivity analysis has been performed by varying a number of the uncertainties listed above. The breach initiation is fixed at the point in time when the outside water level exceeds the crest height of the outside boundary. The locations of the breaches have been analysed in three different locations with varying crest heights, hinterland compartment sizes and different dominant forcing types (storm and discharge).

The breach width is determined every time step by the use of the breaching formulation defined by Verheij and van der Knaap [27]. By the use of this breaching formulation the water level difference is taken into account in every time step. Therefore breach growth continuously gets adjusted based on the water level

inside and outside of the breach. The final breach widths of single breaches is between 100 and 200 meters in most scenarios. The breach growth is faster in case of storm dominated scenarios compared to the discharge dominated high waters. This is due to the larger difference in water levels which is found. However, the breach growth process lasts longer in cases of discharge dominated scenarios, since high water duration is present for a longer period of time.

The number of breaches has also been varied, running the model for either no breaches, a single breach or two breaches. In the literature study it was determined that consecutive breaches generally occur near the initial breach. Two breaches have therefore been modelled in the same location. This is done by determining a factor with which the breach width is multiplied to get a representative discharge through the double breach. This representative discharge is then equal to the discharge through two separate breaches in adjacent compartment boundaries.

Finally, an assumption is made that the compartment boundaries do not breach. This assumption follows from the literature study of this research, where compartment boundaries are generally wide and well compacted and thus are less likely to breach [4]. Considering that most of the boundaries are roads, this is assumed to be the case and therefore no breaches occur. As explained in chapter 6, some scenarios have been ran where some specific compartment boundaries have been lowered. This showed that for example a breach in the old flood defense, would lead to the Kampereiland flooding in discharge dominated events, whereas this would not occur without this breach. More information on this is given in Appendix A Some boundaries have been lowered to get an idea of what would happen when the boundary would be lower, to see the impact of what a breach would be like.

The uncertainties in the compartment structure are mainly related to what counts as a boundary and what does not. In this thesis research, the total number of compartments has been limited using the main boundaries present. This is justified according to the research done with the inundation of the Land van Maas and Waal [7]. The main boundaries cause the large majority of the stoppage of the water flowing to other parts of the island. However, this does not mean that there is no further influence by using a more detailed compartment structure. The implication of having used a simplified compartment structure has been that inflow reduction over compartment boundaries was less, the final inundation depth was reached faster and the rising velocities of water levels are higher.

How does a breach during overflow impact the flooding of the Kampereiland, in a storm scenario?
The storm dominated scenarios are more critical than the discharge dominated scenarios. The wind is the most dominant parameter and this is reflected by the results explained in chapter 5. In the case of no breaching, the critical scenarios are found when water levels exceed the crest height of the entire (both the overflow resistant and non-overflow resistant parts) flood defense of 225. This is at 3m+NAP. These are only reached in case of wind speeds of 37 m/s and higher. Breaches in flood defense 225 speed this up, meaning that inundation takes place across the entire island even during wind speeds of 32 m/s. In addition to this, the start of inundation of the more eastern compartments is roughly an hour earlier.

The breach location is most critical in the overflow resistant part of the flood defense. This has to do with the moment of breach initiation. Due to the height of the overflow resistant part of flood defense 225, the compartments behind this location will already be inundating, prior to the breaching of the non overflow resistant part of the flood defense.

How does a breach during overflow impact the flooding of the Kampereiland, in a high discharge scenario?
The flooding of the Kampereiland during discharge dominated scenarios only occurs at the northern side of the island. In case without breaching, the volume of water flowing into the island is not enough to make the water levels in the northern compartments overflow into adjacent compartments. This is due to the presence of the old flood defense which has a crest level of 1.85m+NAP. This compartment boundary contains the flooding. This is still largely the case during breaching of flood defense 101. The water level in the breach compartment (compartment 10) equalises the outside water level in the Zwarte Meer. This water level is not high enough to flow out of the compartment, causing the water to no longer flow into the Kampereiland.

Using the defined compartmentalisation structure, how does the flooding of the Kampereiland propagate through the island?
When flooding in a storm dominated scenario takes place, the western compartments fill up first. This then flows over the northern part of the N50 into compartments 6 and 7. Following this, the inundation progates towards the south. Depending on the wind speed used in the scenario, the center of the Kampereiland completely fills up (from wind speeds of 37 m/s and higher) or not (for wind speeds up to 32 m/s).

In discharge dominated scenarios, the flooding starts from the north, then flows towards the western areas in the cases where it is not fully contained in the first compartment. In all scenarios, this is contained in compartment 10, 6 and 7.

How does the Kampereiland flood during high water scenarios, while taking the uncertainties in the breaching process and compartmentalisation into account?
In most cases, the flooding of the Kampereiland takes place due to a storm driven high water. From this, the western part of the Kampereiland floods, leading to all compartments to the west of the N50 causeway to fill up. This then overflows along the northern part of the N50 causeway into compartment 6 and 7, from where water flows into the center compartments of the Kampereiland. In cases without a breach where the wind speeds are below 37 m/s, only a few decimeters of water ends up in the center compartments. Once wind speeds become 37 m/s or higher, the flooding of the Kampereiland drastically increases.

In discharge driven events, the flooding of the Kampereiland is contained very well due to the presence of the old flood defense and the N50 causeway. Since outside water levels are quickly equalizes with the water level in the compartments that flood first, the inflow is reduced.

Extreme events show a similar results as the storm driven scenarios. The majority of the water flows in from the west initially, where rising velocities of the water levels in the compartments are high. These increase further with breaching, where breaching at location 1 in the overflow resistant part of flood defense 225 is most critical for the western compartments. This leads to rising velocities varying from 1 to 2.5 m/hr. For the eastern compartments, the rising velocities are more critical with breaching in compartment 10, where rising velocities of 2 m/hr also occur in the compartments 15 and 16. In general, the rising velocities in the western part of the Kampereiland are more critical than those in the east.

7.2. Recommendations

A combination of studies performed in regards to the IJssel- and Vechtdelta will bring the modelling of this complex delta to a higher level, providing a more comprehensive understanding of the entire delta. Recommendations of further studies are given in this section.

When the newest WAQUA model is completed with the compartment structure in more detail, the effect of the compartment boundaries on wave and wind setup can be determined more precisely. The water flow is modelled in more detail in WAQUA, where postitional coordinates make it possible to add the tilting of a local water level to the calculations. Combining this with the breach analysis done in this research, a total image of expected water levels can be determined. This combination makes it possible to understand the effects of breaching, while accurately modelling the water flow at the same time. The combined results lead to a better understanding of the flooding of the Kampereiland.

Another aspect which still needs to determined is whether the flood defense of 225 satifies the safety standards that are assigned to it in the Waterwet. In this, a more detailed failure probability of the flood defense 225 can be determined. Currently, the water levels for which flood defense 225 should overflow start at water levels with return periods of roughly 1/1000 years. However, this does not include the probability of failure of this flood defense. In addition to this, making a failure probability calculation of the two largest compartment boundaries on the Kampereiland (the N50 causeway and the old flood defense along the south side of the Willem Meyer- and Stikkenpolder) will give insight into the strength of these boundaries. Once the failure probabilities are known, the probabilities of the flooding events can also be determined in more detail.

To further improve the statistical analysis of the flooding of the Kampereiland, more scenarios can be calculated. This in combination with the failure probabilities of the flood defenses can then be added in Hydra-NL.

By doing so, the probabilities of occuring water levels in the different compartments on the Kampereiland can be determined by the use of Hydra-NL. This is not possible based on the total number of scenarios which have been calculated in this research, due to the time limitations for this thesis research. Running calculations on multiple computers at the same time would reduce the total required time as well.

The water levels determined in this research can be used to gauge the loading on the flood defense of 10-2, along IJsselmuiden. This flood defense has a crest height of just over 3m +NAP. In most cases, these heights are not reached in the compartments of the Kampereiland. In cases that lead to water levels with return periods less frequent than 1/50000 this could become a serious threat. Especially when this is accompanied by a double breach. Other than in these extremely rare cases, it is not expected that the water levels along flood defense 10-2 will surpass the crest height. A more detailed study into the loading of flood defense 10-2 at Grafhorst can be useful to check this hypothesis.

Bibliography

[1] Allecijfers. Allecijfers kampereiland, 9 Febuary 2021. URL https://allecijfers.nl/buurt/kampereiland-kampen/.

[2] Met andere woorden. Ons water in nederland, nieuw nationaal waterplan 2016-2021, 2015.

[3] J. Buisman. *Extreem weer!* Uitgeverij van Wijnen, 1e edition, 2011.

[4] K. de Bruijn and K. Slager. Leidraad voor het maken van overstromingssimulaties, 2018.

[5] E. de Bruine. The influence of compartmentalisation on the flooding of central holland, 2006.

[6] Waterschap Drents Overijsselse Delta. Versterking regionale waterkerering langs buitenpolders kampereiland- stikkenpolder en willem meyerpolder, 2018.

[7] A.W. Hesselink, G.S. Stelling, J.C.J. Kwadijk, and H. Middelkoop. Inundation of a dutch river polder, sensitivity analysis of a physically based inundation model using historic data, 2003.

[8] B. Kolen, R. Slomp, W. van Balen, T. Terpstra, M. Bottema, and S. Nieuwenhuizen. Learning from french experiences with storm xynthia, 2010.

[9] A. Kors and W. Rozier. Impactanalyse ijssel-vechtdelta scenario's en advies handelingsperspectief, 2020.

[10] Algemeen Hoogtebestand Nederland. Algemeen hoogtebestand nederland, 4 May 2021. URL https://ahn.arcgisonline.nl/ahnviewer/.

[11] Overheid.nl. Waterwet. URL https://wetten.overheid.nl/BWBR0025458/2021-01-01/#BijlageIII.

[12] Rijkswaterstaat. Stormvloedkering ramspol, . URL https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/stormvloedkeringen/stormvloedkering-ramspol.aspx.

[13] Rijkswaterstaat. Ruimte voor de rivieren, . URL https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/ruimte-voor-de-rivieren/index.aspx.

[14] Rijkswaterstaat. Ruimte voor de rivieren programma afgerond, . URL https://www.rijkswaterstaat.nl/nieuws/2019/03/ruimte-voor-de-rivierprogramma-afgerond.aspx.

[15] R. Slomp. Flood risk and water management in the netherlands, 2012.

[16] N. Slootjes and D. Wagenaar. Factsheets nromering primaire waterkeringen, 2016.

[17] L. Stenveld. Waterveiligheid kampereilanden, 2016.

[18] J. Stijnen, R. Daggenvoorde, S. Boersen, J. ter Hoeven, and J. Tigchelaar. Quick-scan veiligheidsanalyse - waterveiligheid langs de benedenloop van de ijssel, 2019.

[19] J. Stijnen, R. Daggenvoorde, and J. ter Hoeven. Amoveren roggebotsluis, 2019.

[20] Stowa. Ruimte voor de rivieren programma afgerond. URL https://www.stowa.nl/deltafacts/waterveiligheid/beoordelen-waterkeringen/nieuwe-normering-van-waterveiligheid.

[21] TAW. Grondslagen voor waterkeren, 1998.

[22] M. ten Voorde. Bresgroei bij dijkdoorbraken uit het verleden, 2004.

[23] Ministerie van Infrastructuur en Milieu. Peilbesluit ijsselmeergebied, 2018.

[24] Rijkswaterstaat Ministerie van Infrastructuur en Milieu. Natura 2000 beheerplan ijsselmeergebied 2017-2023 ijsselmeer, 2017.

[25] Rijkswaterstaat Ministerie van Infrastructuur en Milieu. Natura 2000 beheerplan ijsselmeergebied 2017-2023 ketelmeer and vossemeer, 2017.

[26] Rijkswaterstaat Ministerie van Infrastructuur en Milieu. Natura 2000 beheerplan ijsselmeergebied 2017-2023 zwarte meer, 2017.

[27] H. Verheij. Aanpassen van het bresgroeimodel in his-om, 2003.

[28] Paul Visser. Breach growths in sand-dikes, 1998.

[29] Helpdesk Water. Begrippen helpdesk water, . URL https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/begrippen/.

[30] Helpdesk Water. Model applicaties, . URL https://www.helpdeskwater.nl/onderwerpen/applicaties-modellen/applicaties-per/watermanagement/watermanagement/waqua/.

[31] Informatiehuis Water. Overzicht normen dijktrajecten waterveiligheidsportaal, . URL https://waterveiligheidsportaal.nl/#/nss/nss/current.

A

Breach in compartment boundaries

One of the assumptions in this thesis research is that only the flood defenses on the Kampereiland can breach. The compartment boundaries on the island itself are assumed not to breach. To give an impression of the effects of a breach in such a compartment boundary, the model has been run with a reduced height of one of the major compartment boundaries on the Kampereiland, which contains most of the flooding in discharge dominated scenarios.

The old flood defense along the southern side of the Willem Meyer- en Stikkenpolder is an important compartment boundary. The height of this old flood defense is the reason that discharge dominated events are very well contained in the most northern compartments, as was shown in Figure 5.6. Reducing the height of this boundary has a significant effect on the occuring water levels on the Kampereiland. This is especially the case for the compartments to the east of the N50 causeway. To compare, the same image is shown, but now with the height of the old flood defense reduced by 50% (see Figure A.1).

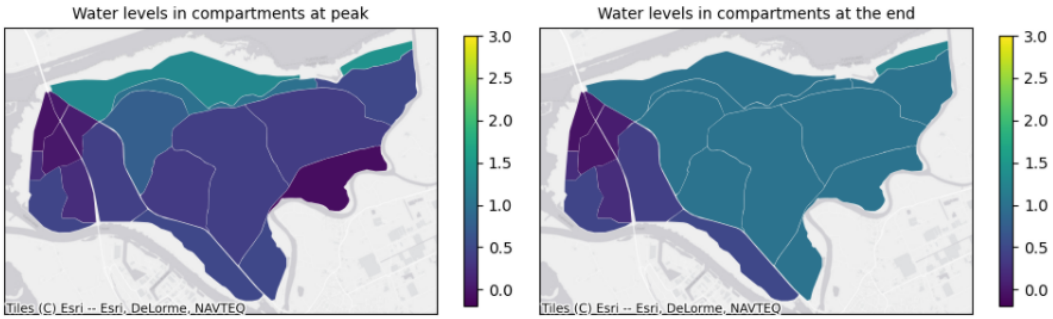


Figure A.1: Water levels on the Kampereiland at the maximum water level of the Zwarte Meer and at the end of the calculation, in the discharge dominated scenario KsrMp040Q4000U16D292 without a breach and a reduced height of the old flood defense.

A clear difference is seen in the water levels on the Kampereiland. The flooding is far more widespread. Of course, this is not the same as a breach in this boundary, since that would be a smaller gap. However, it does clearly show the impact of the higher compartment boundary in the system, especially in combination with discharge dominated water levels which tend to be significantly lower than the storm dominated water levels that occur.

B

Model output

In this Appendix, the water levels in all compartments are shown for the scenarios specifically elaborated on in Chapter 5. The graphs show the increase of water levels over the entire time series, per compartment.

The heights of the respective boundaries of the compartment are shown with grey dashed lines. When a boundary is also an outer boundary of the Kampereiland, this is dashed in red. Lastly, the ground level in an compartment is shown with a black dashed line.

The water levels of the compartments to the west of the N50 are shown in green, while the water levels in compartments to the east of the N50 are plotted in blue.

B.1. Water levels over entire time series without breaching

B.1.1. Storm dominated

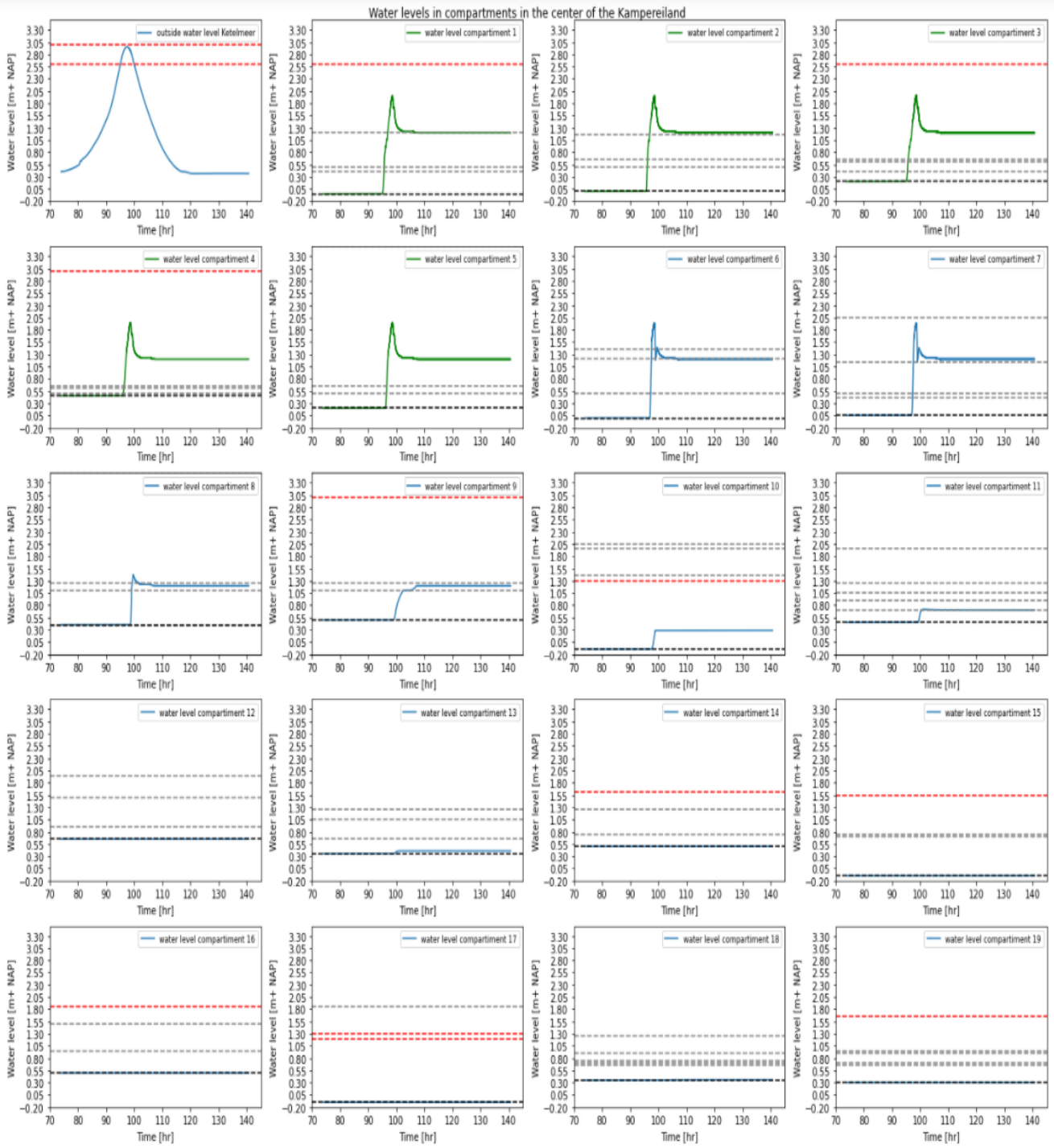


Figure B.1: KsrMp040Q0100U32D292 without breach.

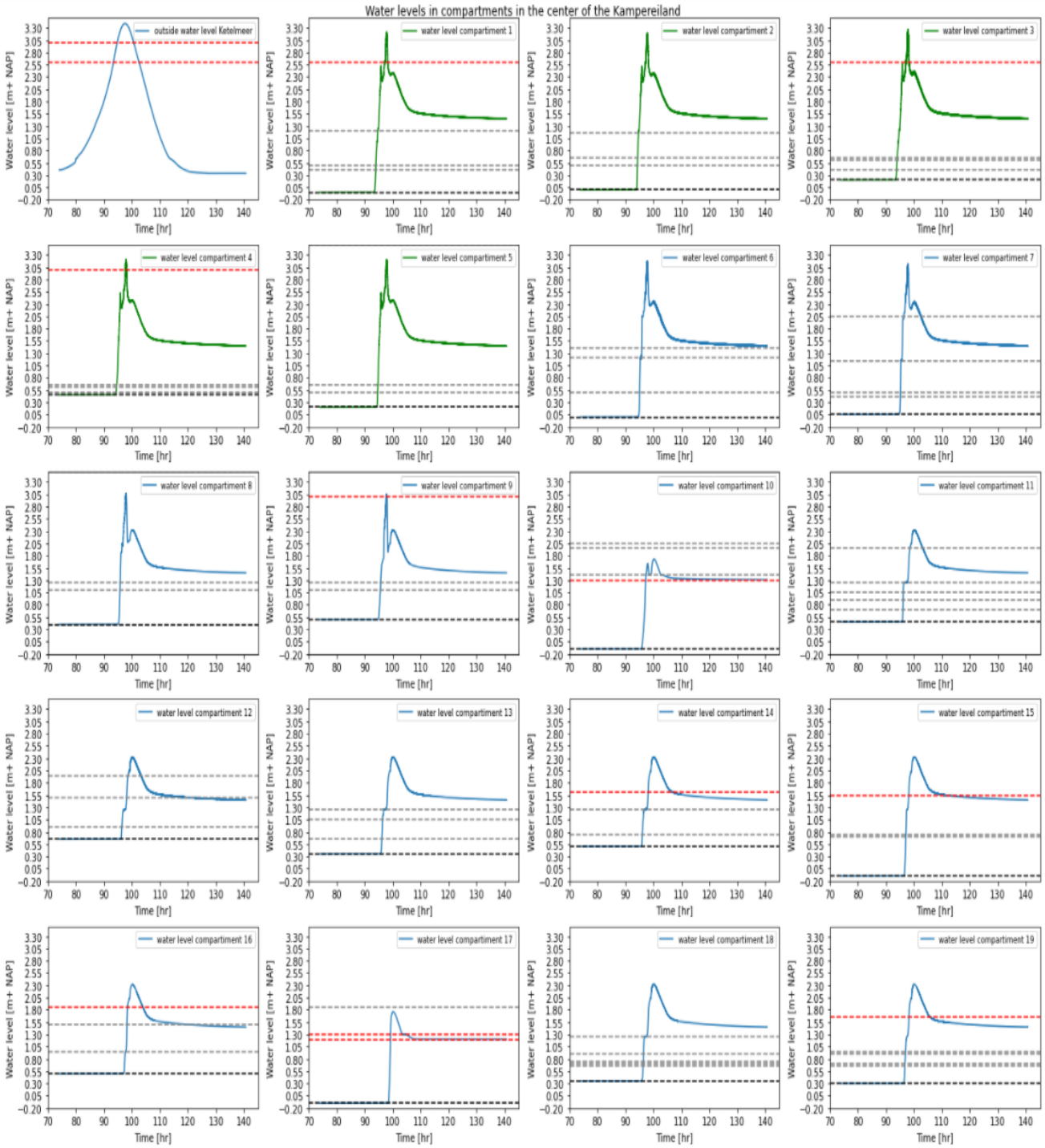


Figure B.2: KsrMp040Q0100U37D292 without breach.

B.1.2. Discharge dominated

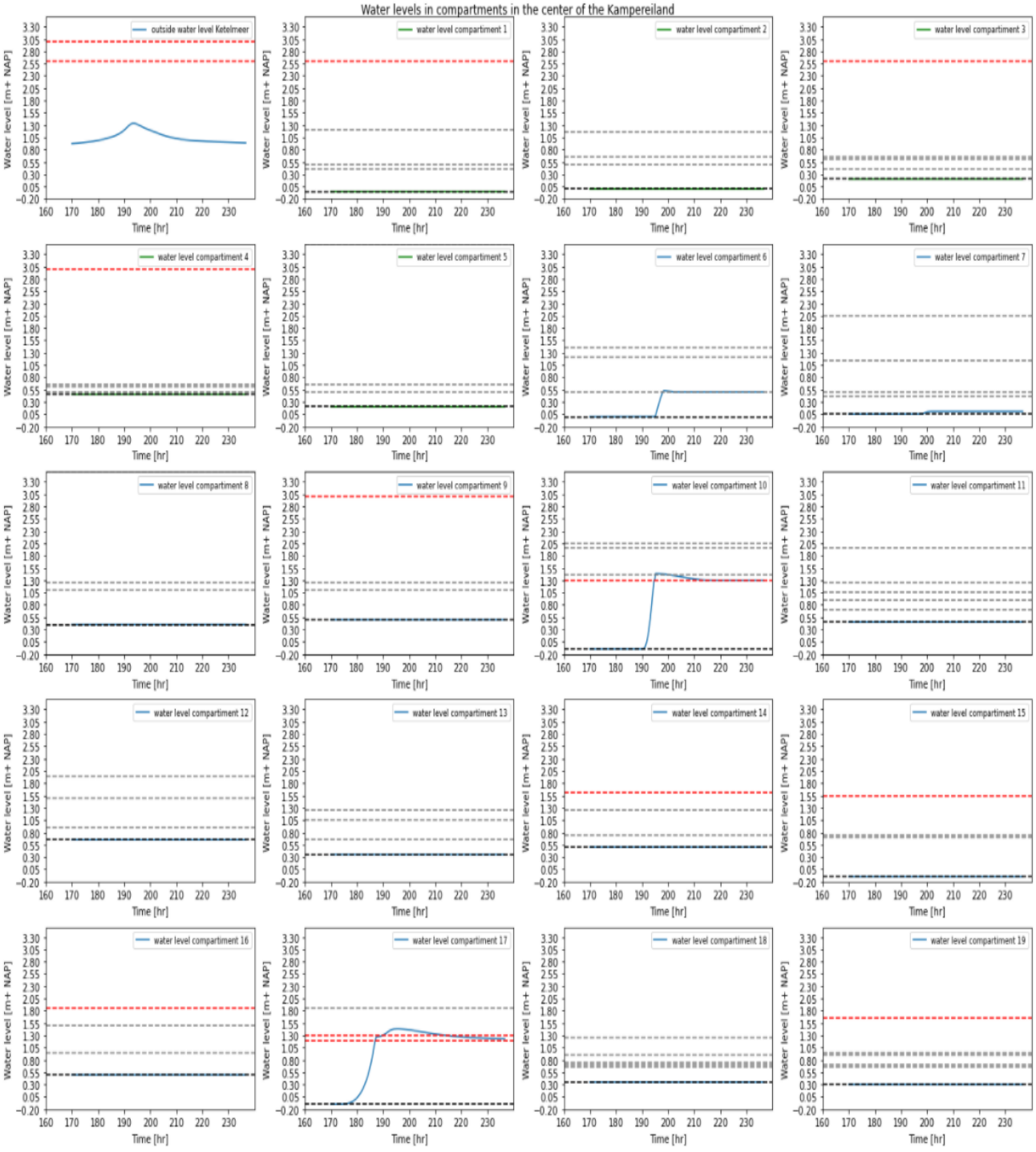


Figure B.3: KsrMp040Q4000U16D292 without breach.

B.1.3. Extreme event

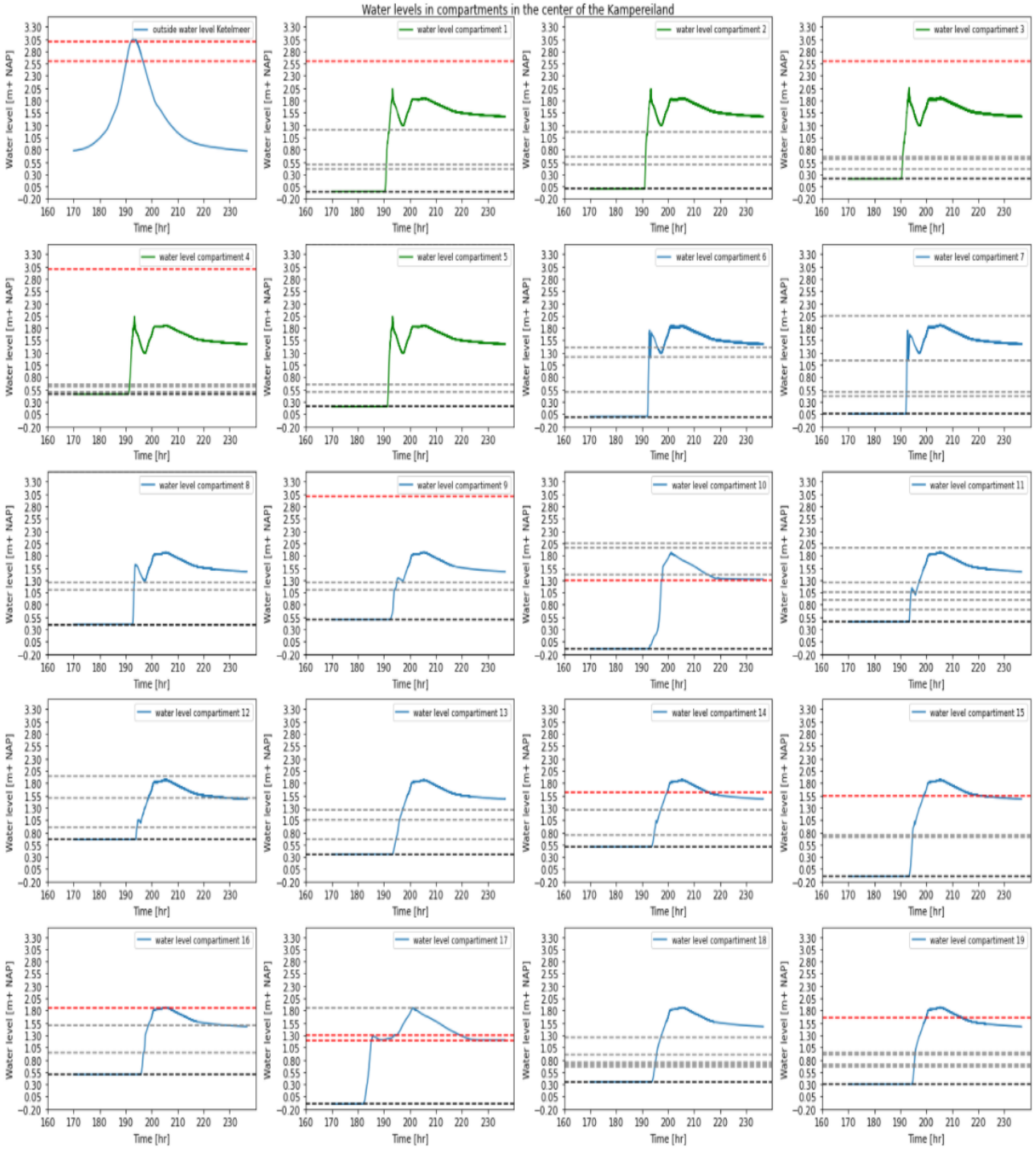


Figure B.4: KsrMp040Q3200U32D292 without breach.

B.2. Water levels over entire time series with one breach

B.2.1. Storm dominated

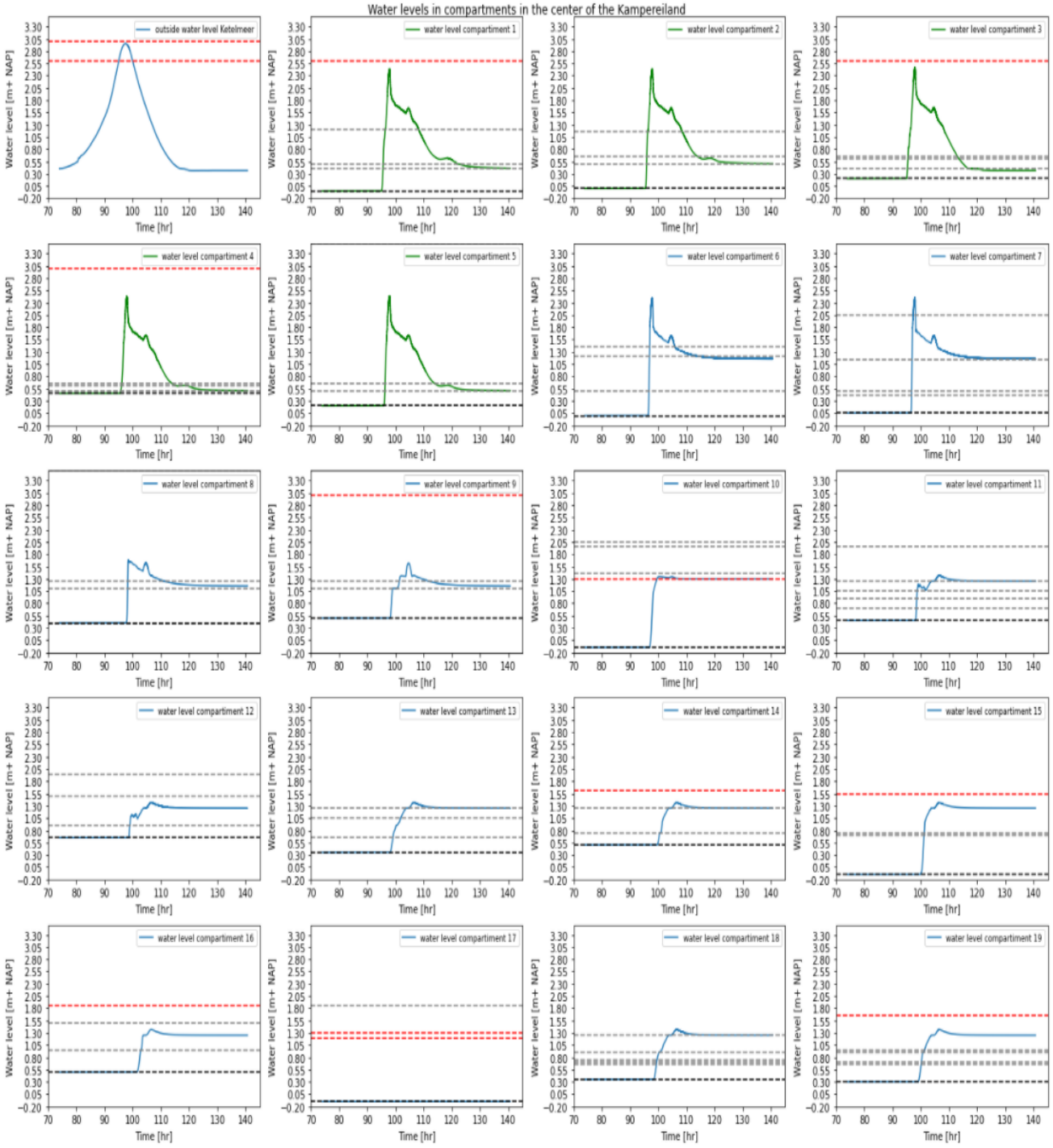


Figure B.5: KsrMp040Q0100U32D292 with one breach in compartment 3.

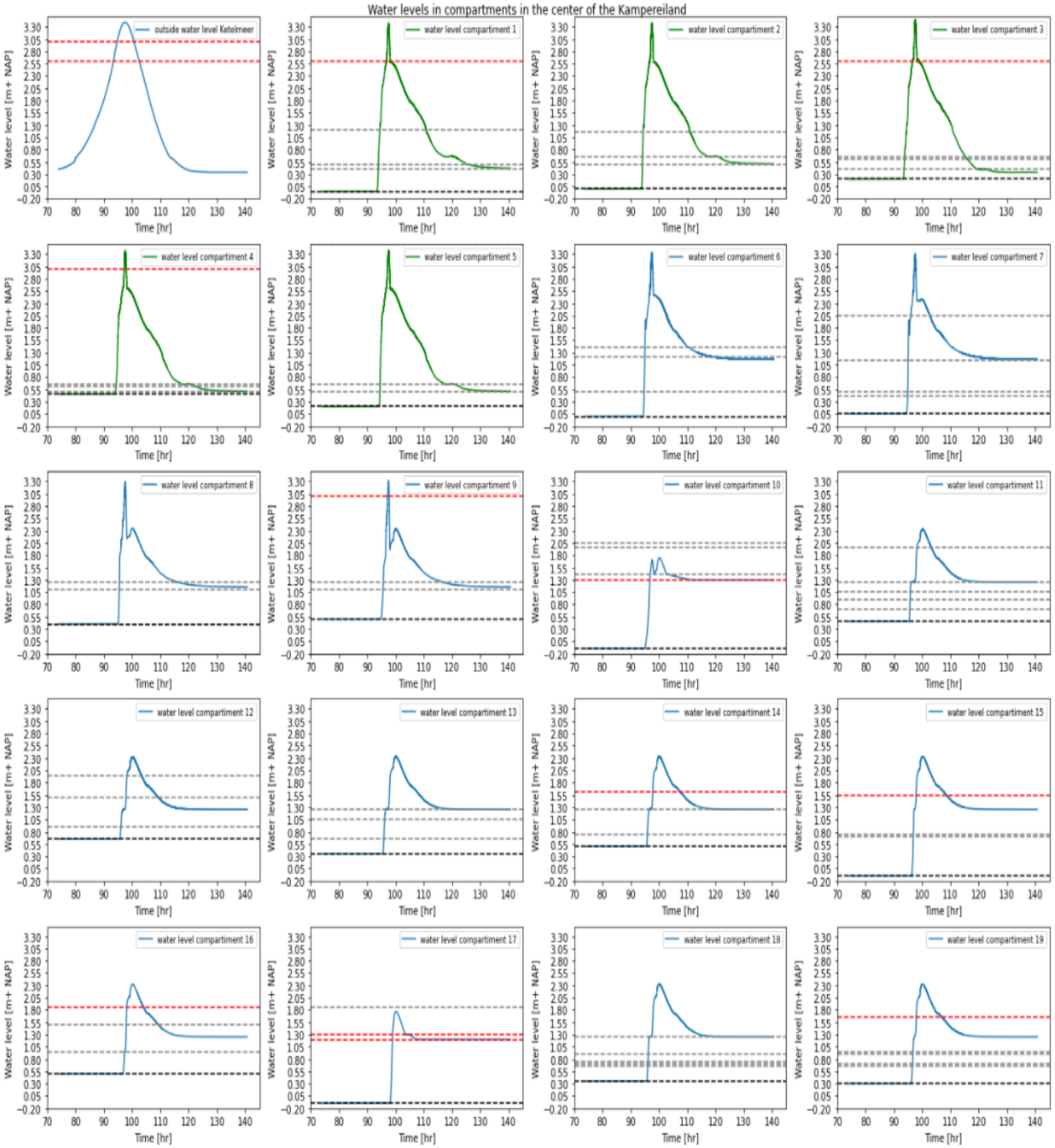


Figure B.6: KsrMp040Q0100U37D292 with one breach in compartment 3.

B.2.2. Discharge dominated

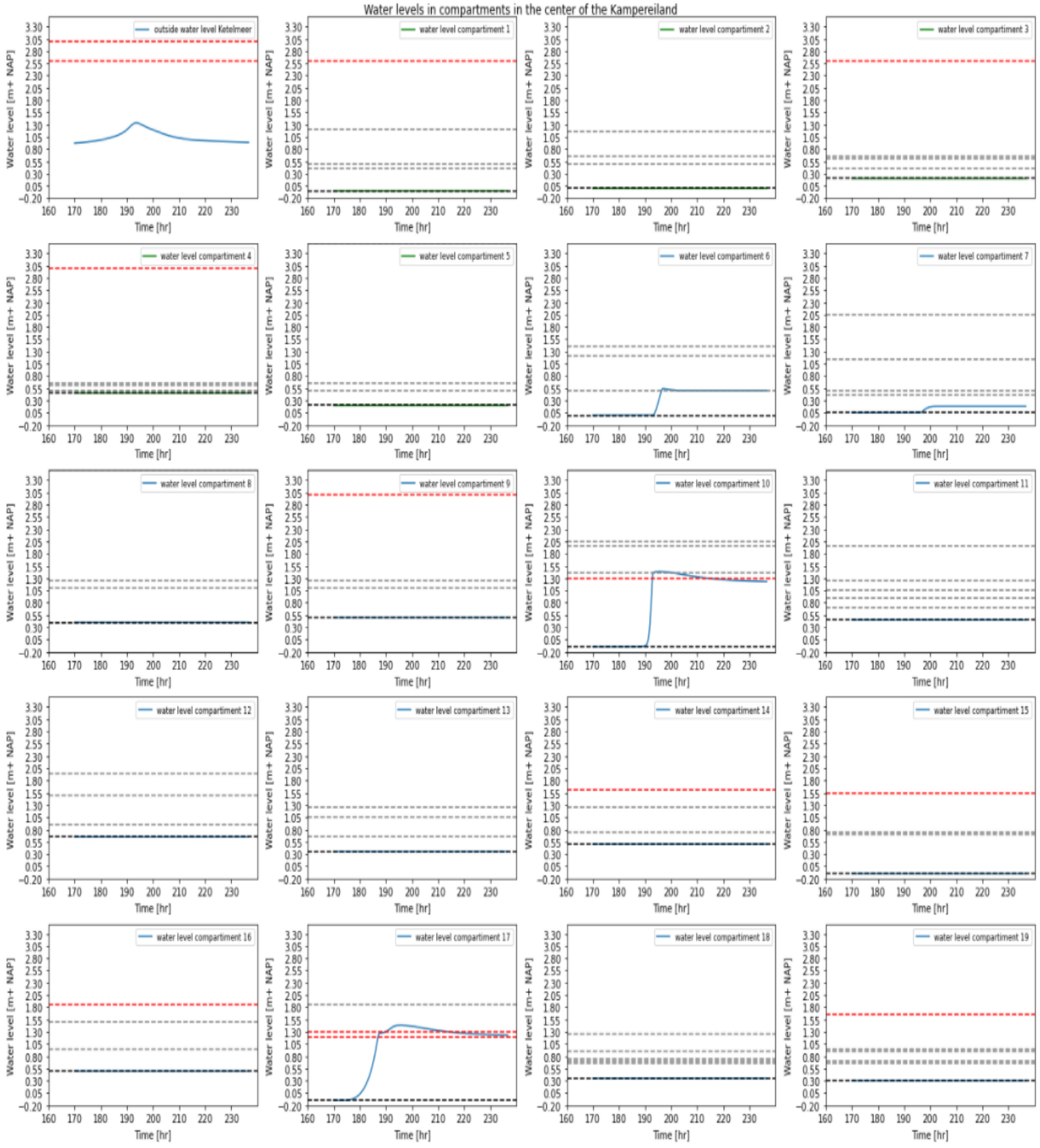


Figure B.7: KsrMp040Q4000U16D292 with one breach.

B.2.3. Extreme event

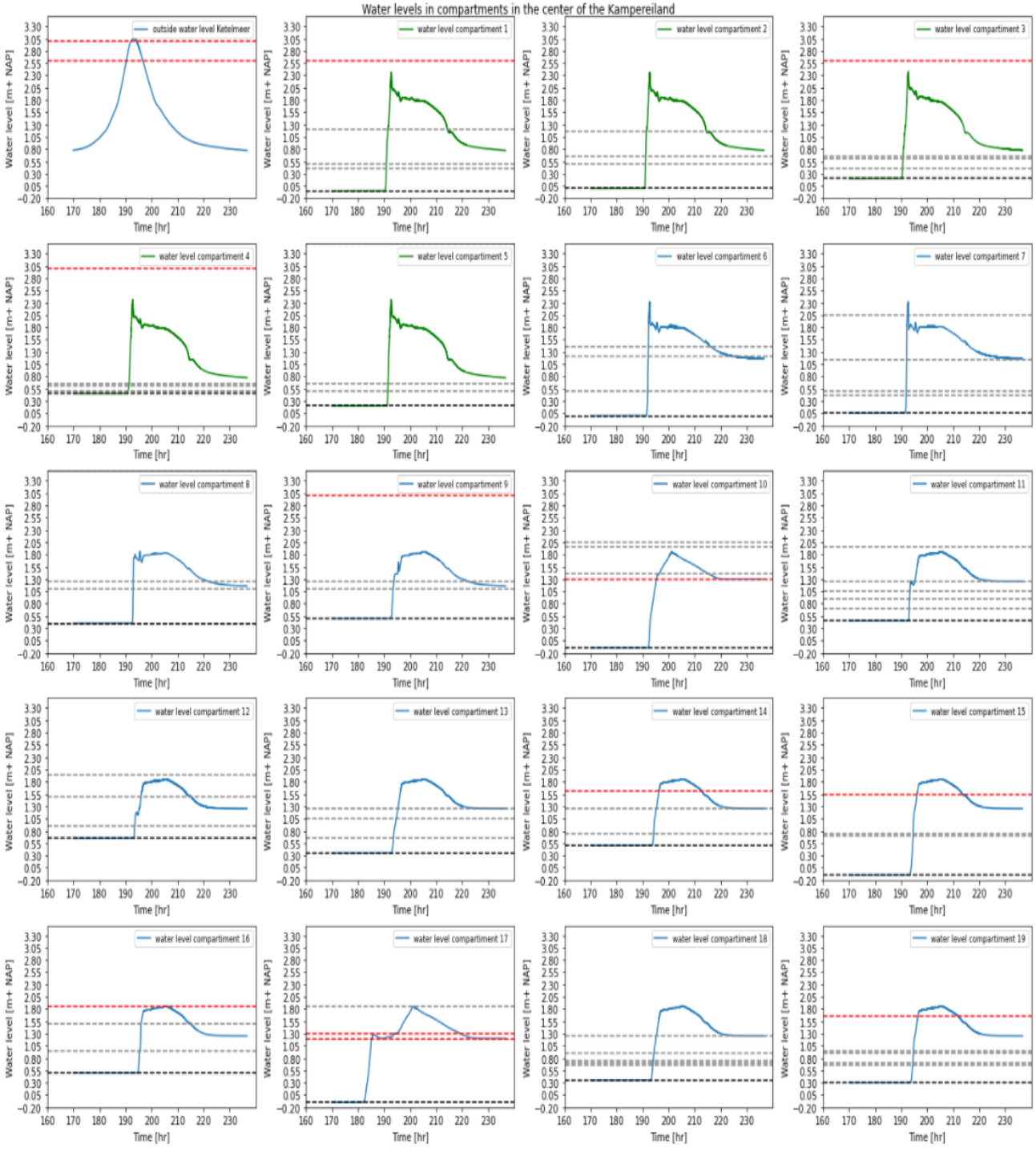


Figure B.8: KsrMp040Q3200U32D292 with one breach.

B.3. Water levels over entire time series with two breaches

B.3.1. Storm dominated

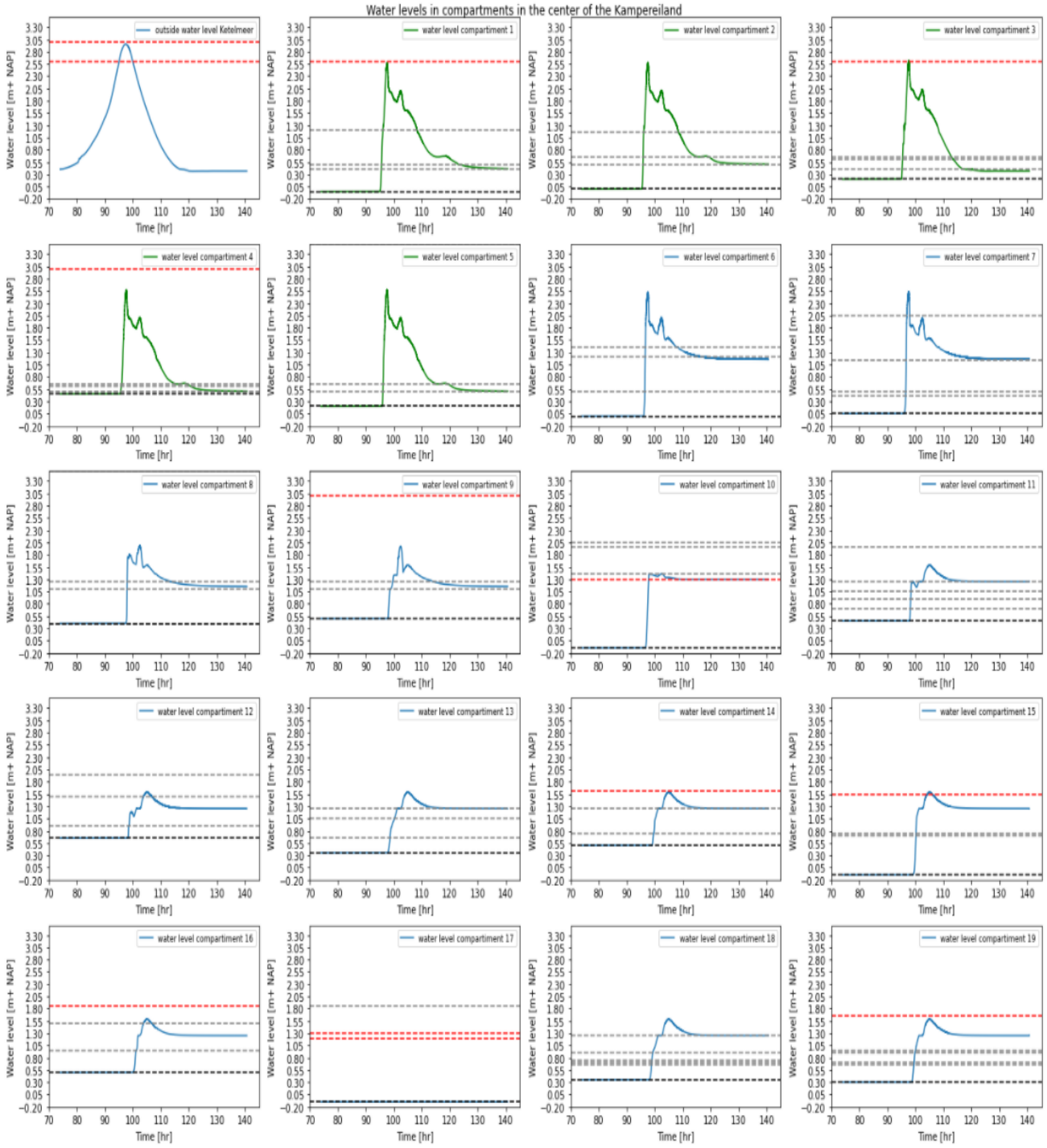


Figure B.9: KsrMp040Q0100U32D292 with two breaches in compartment 3.

B.3.2. Discharge dominated

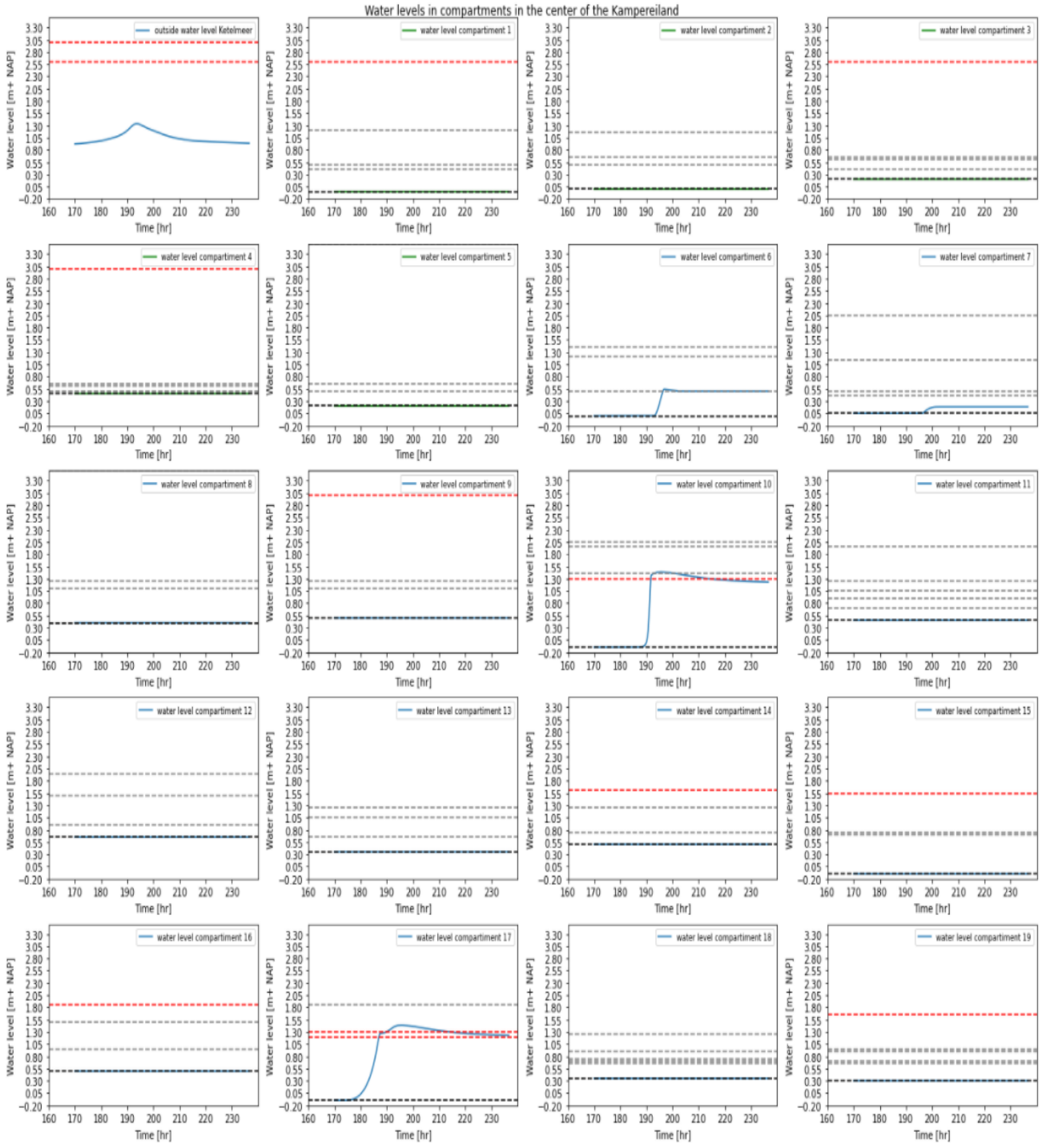


Figure B.10: KsrMp040Q4000U16D292 with two breaches.

B.3.3. Extreme event

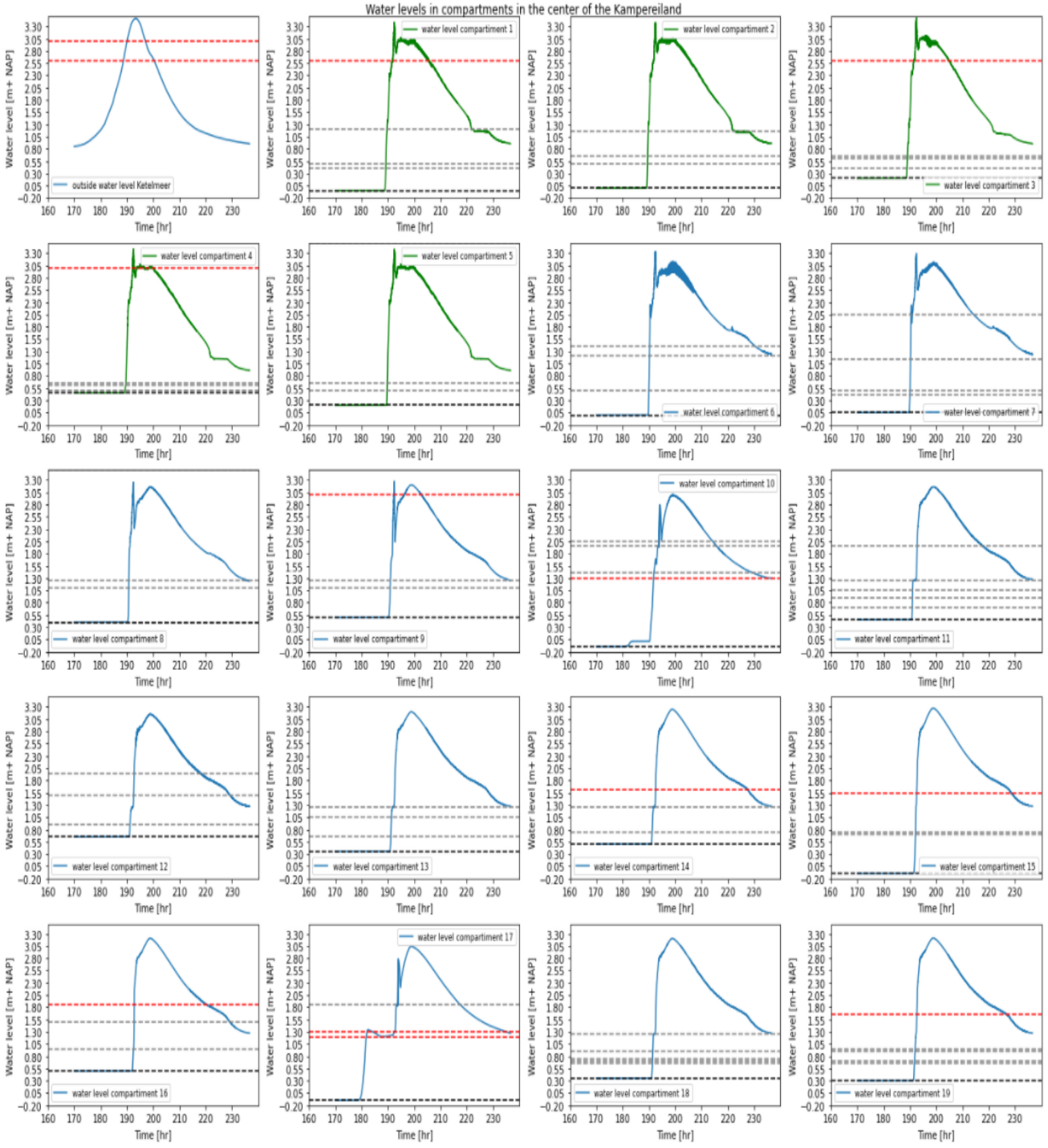


Figure B.11: KsrMp040Q3600U37D292 with two breaches in compartment 3.

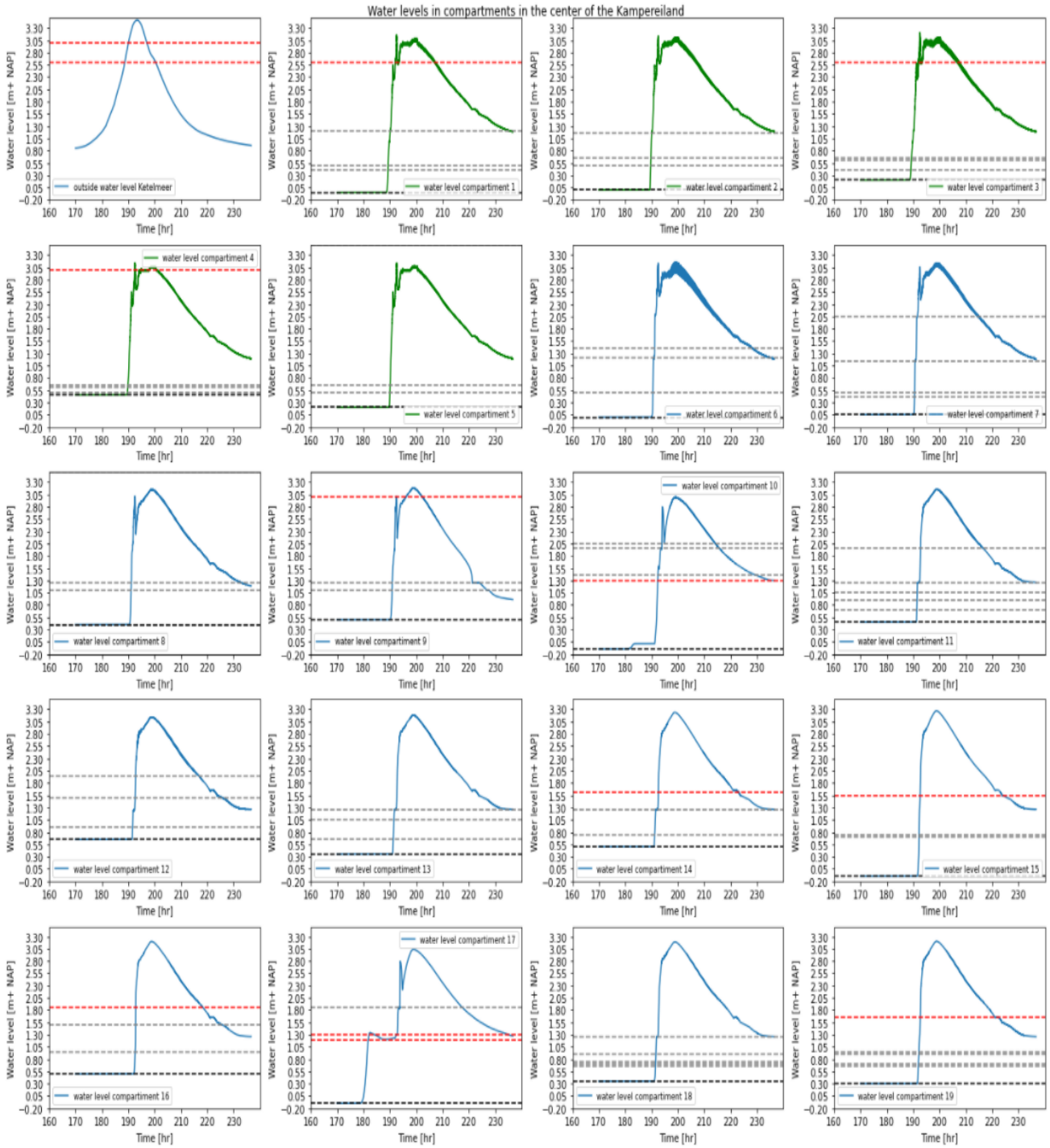


Figure B.12: KsrMp040Q3600U37D292 with two breaches in compartment 9.

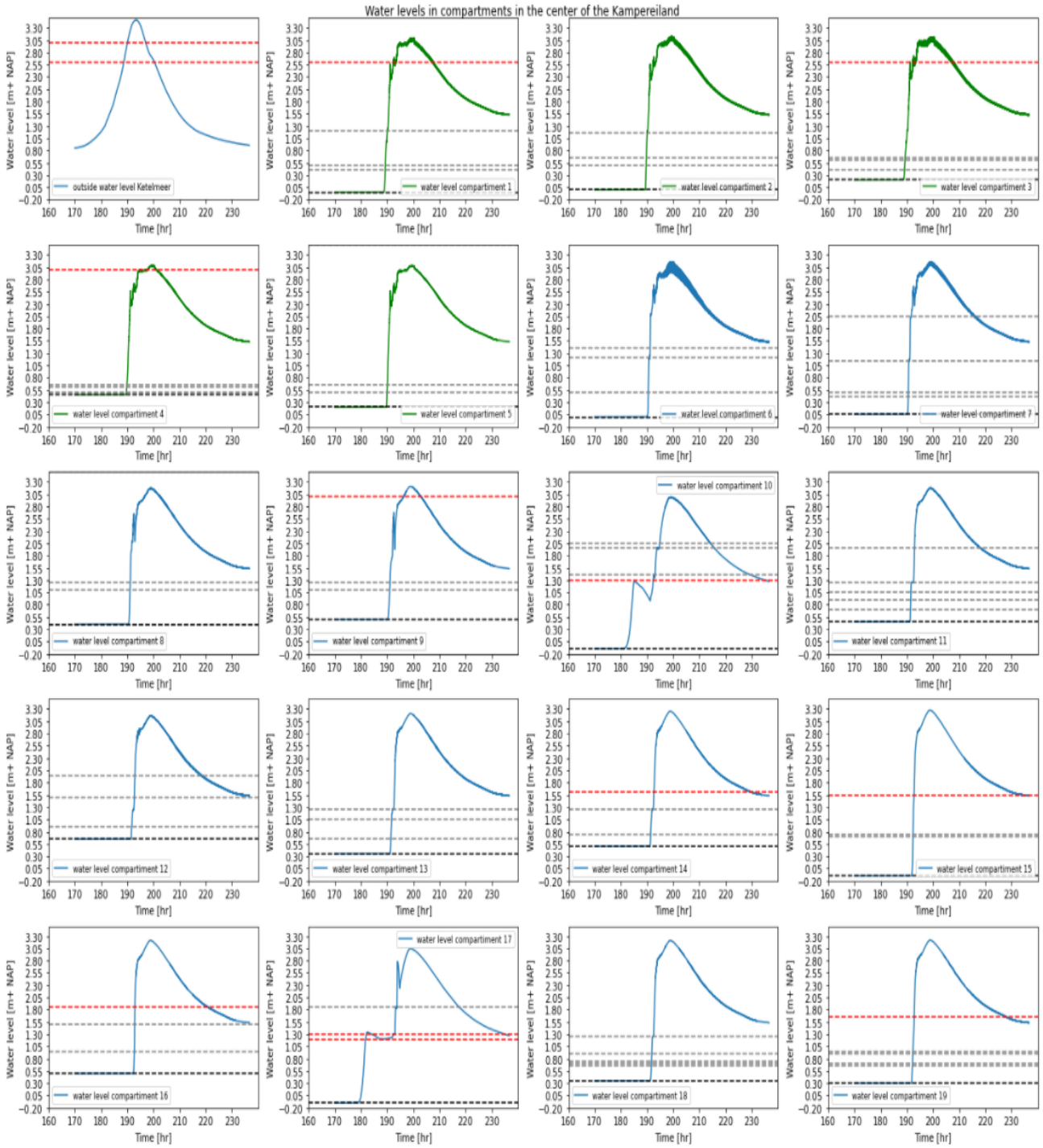


Figure B.13: KsrMp040Q3600U37D292 with two breaches in compartment 10.