Assessment method of multiple flood protection improvements in a water system governed by a storm surge barrier: The case of Ramspol Barrier

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Preface

This thesis, “Assessment method of multiple flood protection improvements in a water system governed by a storm surge barrier: The case of Ramspol Barrier”, is written for obtaining the Master of Science, in Hydraulic Engineering at the faculty of Civil Engineering and Geoscience of the Technological University of Delft. The research described in this report was conducted under the collaborated supervision of Rijkswaterstaat and TU Delft.

After nine years of studying in the field of Civil Engineering, the moment has come for this cycle of my life to come to a conclusion. I would like to express my gratitude to the people supported me through this process.

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Zoi Zikidou
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Summary

According to climate projections, it is highly likely that the level of the sea will continue rising. Moreover, the dominant wind direction in the North Sea and consequently in IJssel Lake is getting reverted to a more southwest direction and in the same location it is expected to have the highest increase of storminess according to the projections. The intensity of summer rainfalls increases, because of the rising of the global temperature which leads to more evaporation. Finally, the projections show a rise in the winter precipitation and as a consequence the peak river discharge of the main rivers in the Netherlands is expected to increase. There is still high uncertainty on the projections of future climate, but these effects of climate change, can lead to high water levels in IJssel Lake and threaten the safety of the dikes which are protecting the inland against flooding. Thus, action needs to be taken to prevent threatening situations.

Nowadays, the development of technology and engineering tools provides engineers with the opportunity to design and execute new, innovative and complex projects. However, the pool with the available structures and techniques is wide, and the selection of the appropriate solution every time is not an easy task to accomplish. Flood risk management programs need to develop effective strategies that can adapt to the uncertain impacts of climate change and socio-economic development. Computer models play a vital role in the decision-making process, assisting in various stages from risk assessment to implementation. In the early planning phases, when data and resources are often limited and uncertainty is high, it is crucial to identify robust flood risk management strategies. However, currently the modelling tools that can efficiently evaluate multiple strategies across various future scenarios considering climate and socio-economic factors, while also having low data requirements and resource constraints, are limited.

The assessment method which has been developed for the purposes of this thesis, is fast, reliable, flexible and can provide with more opportunities than the assessment of a specific water system. It depends on reliable calculations (Hydra-NL) and the application of simple formulas for estimating the water level reduction that each improvement is associated with. Lower water levels relate to lower flood risk, but for this stage of screening of many interventions the focus can be only in the reduction of water level without using more complex probabilistic calculations for the flood risk. This assist to have a fast first estimate of the influence of the different interventions to the water level and flood safety of the area. Because of the fast assessment some uncertainty is introduced and thus the reliability level is not as high as it would if analytical models would have been used. However, this uncertainty is treated by selecting the five most promising interventions. Moreover, except for the reduction of the water level, the method considers the decision-making aspects of cost and ecological impact which is a crucial consideration for such early stages of the assessment. For the assessment of the ecological impact of the interventions, a simple but holistic approach, the “ecological sign” has been developed. The method can consider at the same time hard and soft measures and provide comparative results. Additionally, this method provides the opportunity to the decision makers and researchers to intervene by adjusting the importance of the decision-making aspects. Finally, the same method can be used for similar water systems as represented. For water systems with different characteristics, other formulas can be used for estimating the reduction of water levels.

During northwest storms, the water level in IJssel Lake rises to the southern part of the lake. The mechanism behind that is the wind set-up, where the water levels rise due to the wind shear stress to the water of the lake, a phenomenon which is increasing further because of the syphon shape of the

Lake. Following, the high-water level in IJssel Lake, is getting pushed in Ketel and Zwarte Lakes and even influence the water levels upstream to the Zwarte Water River and the city of Zwolle. To prevent flooding in the West Overijssel area, a province in the Netherlands, in 2002 an inflatable storm surge barrier was constructed to separate Ketel from Zwarte Lake, the Ramspol Barrier. Initially it was expected that the barrier would close for protection reasons, once every two years. However, during the last decade, the barrier closed multiple times, even during summer, in the time period of a year. This might indicate a changed frequency of local climate and required closings of the barrier. When this happens, the water level in Zwarte Lake and Zwarte Water River rises, because the discharge of the river is getting accumulated behind the barrier. Consequently, the low-lying areas in the lake are inundated and the safety of the dikes along the lake and the river is threatened. Finally, a possible breaching of the dikes near the city of Zwolle, a city upstream to the Zwarte Water River, would cause tremendous damages.

For handling this situation twenty improvements for this complex water system have been designed, aiming to decrease the expected water level in the city of Zwolle, through the following improvement strategies:

a. Decrease of wind set-up phenomenon,
b. Lower the initial water level in IJssel Lake,
c. Create an outflow discharge from Zwarte Lake,
d. Increase the discharge capacity of Zwarte Lake,
e. Lower the initial water level in Zwarte Lake,
f. Raise the dikes along Zwarte Lake and Zwarte Water River,
g. Increase the discharge capacity of the river branches and
h. Increase the reliability of Ramspol Barrier.

The improvements which arose out of a brainstorming procedure, considering the above improvement strategies are:

1. Breakwater in IJssel Lake (a),
2. Afsluitdijk II in IJssel Lake (a),
3. Land reclamation in IJssel Lake (a),
4. Outflow channel at Ketelbrug (a),
5. Ramspol Barrier II at Ketelbrug (a),
6. Increase pump capacity at Afsluitdijk (b),
7. Installation of pump station at Marker Lake (b),
8. Deepening IJssel Lake (a),
9. Creating of a vegetation area in IJssel Lake (a),
10. Creation of a wetland area in IJssel Lake (a),
11. Changing the roughness of the bottom in IJssel Lake (a),
12. Installation of pump station at Ramspol Barrier (c),
13. Extension of Vollenhover channel to IJssel Lake (c),
14. Sizing up Zwarte Lake (d),
15. Succeed faster closure procedure at Ramspol Barrier (e),
16. Decrease of the closing limit of NAP + 0.5 m (e),
17. Raising the height of the dikes along Zwarte Lake and Zwarte Water River (f),
18. Widening the river branches of Zwarte Water River (g),
19. Creation of flood plains along the branches of Zwarte Water River (g) and
20. Increase the reliability of Ramspol Barrier (h).

The list with the available improvements for the water system is extensive, and thus an assessment method has been designed, initially for narrowing down in a fast and reliable way the twenty interventions to the most promising ones (assessment stage 1), and secondly for recommending a detailed assessment method for identify the most beneficial improvement (assessment stage 2).

1st stage of assessment

The first stage of assessment is a screening method of assessment and selection of the most promising for the water system improvements. The twenty improvements assessed through a combination of 3 decision making aspects, the water level reduction at Zwolle, the cost and the ecological impact that each improvement is associated with. To address the combined influence of the three aspects to the assessment, the grading and weighing technique has been used. Specifically, three combinations of weighing have been tested in order to check the sensitivity of the assessment on the weights. The uncertainty that a fast assessment and selection method introduces, has been considered for the aspects of the decrease of water level maximum and cost.

For assessing the aspect of the decrease of water level maximum of the improvements, the water level in the city of Zwolle (dike section "Vechtdelta_10-01_35_ZW_km0002"), for different return periods were calculated for the different improvements. The improvements which influence the wind set-up phenomenon in IJssel Lake and Ketel Lake, Improvements 1 to 9 handled by the wind set-up formula. The improvements which influence the discharge capacity of Zwarte Lake, Improvements 12 to 16, handled by a lake-level formula. The improvement which influences the discharge capacity in the river branches, Improvement 19, handled by the normal flow depth formula. Finally, for Improvement 17, rising the height of the dikes, which represents the current situation of water levels and Improvement 20, increased reliability of Ramspol Barrier, the results of Hydra-NL model (probabilistic model for assessing the safety of the dikes in the Netherlands) are used directly. Finally, the uncertainty handled, by addressing the level of uncertainty per improvement and applying an increase to the calculated water levels, respectively.

For assessing the aspect of cost, characteristic cost values per unit and rough dimensions of the improvements used, for calculating the total construction cost. The uncertainty handled through applying a lower and upper bound to the cost. For assessing the aspect of ecological impact, the concept of the "ecological sign" has been developed. Considering the impact of construction, maintenance and operation of each improvement, to the ecosystems in the water system, a value for the "ecological sign" has been derived.

Results of the first stage of assessment

The five improvements which scored the highest assessment value through the grading and weighing technique and are selected for the second assessment stage are:

1. Breakwater in IJssel Lake (1),
2. Outflow channel at Ketelbrug (4),
3. Sizing up Zwarte Lake (14),
4. Raising the height of the dikes along Zwarte Lake and Zwarte Water River (17) and,
5. Creation of flood plains along the branches of Zwarte Water River (19)

Recommended 2nd stage of assessment

The second stage of assessment, which is recommended for identifying the most beneficial improvement between those which are selected from the first assessment stage, is following the same approach with the first assessment stage but is a more detailed approach. Specifically, the usage of Hydra-NL, analytical cost estimation and ecological impact assessment is recommended.

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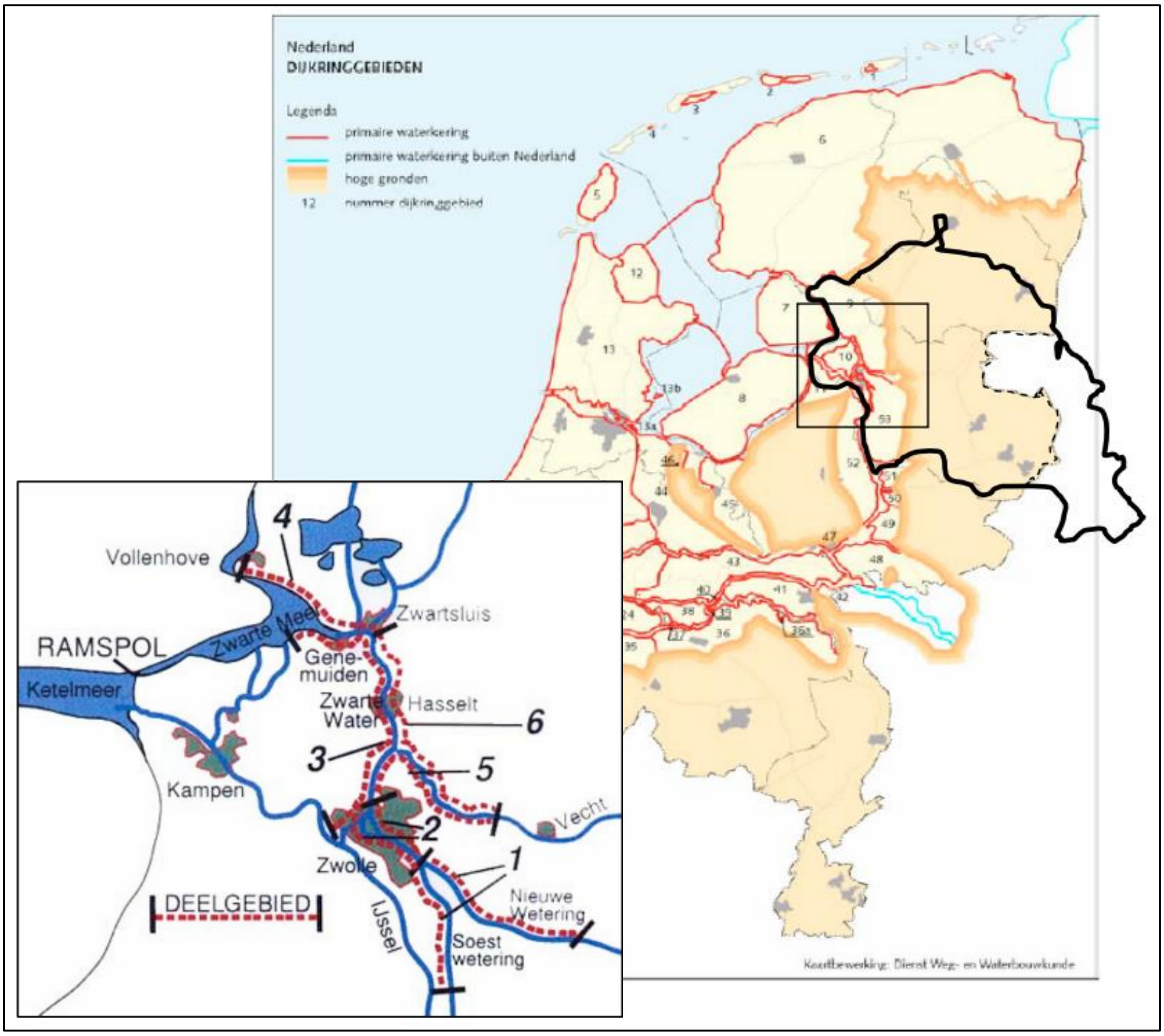
1. Introduction

1.1 Background information

In the Netherlands, flood protection is of significant importance, because a great part of the population lives below sea level. The hinterland is protected against the sea and the major rivers' water, by structures and strategies that reassure the citizens' safety. The low-lying areas are divided into dike rings. Each dike ring is surrounded by a continuous line of flood defences protecting the enclosed area against flooding. All the primary flood defences in the Netherlands are assessed every six years to be in accordance with the safety regulations. However, the changing climate threatens flood safety, by causing sea level rise, and possible more extreme storms, precipitation and river discharges. A thorough discussion for flood defences can be found in Appendix A.

<u>Area of interest</u>

In this study the case of Ramspol Barrier will be considered (See Map 1). In 2002, to protect West Overijssel province in the Netherlands against flooding due to high water at the IJssel Lake, an inflatable storm surge barrier was constructed, the Ramspol Barrier. The solution of the inflatable barrier was chosen because otherwise 115 km of dikes along the river branches and the lake should

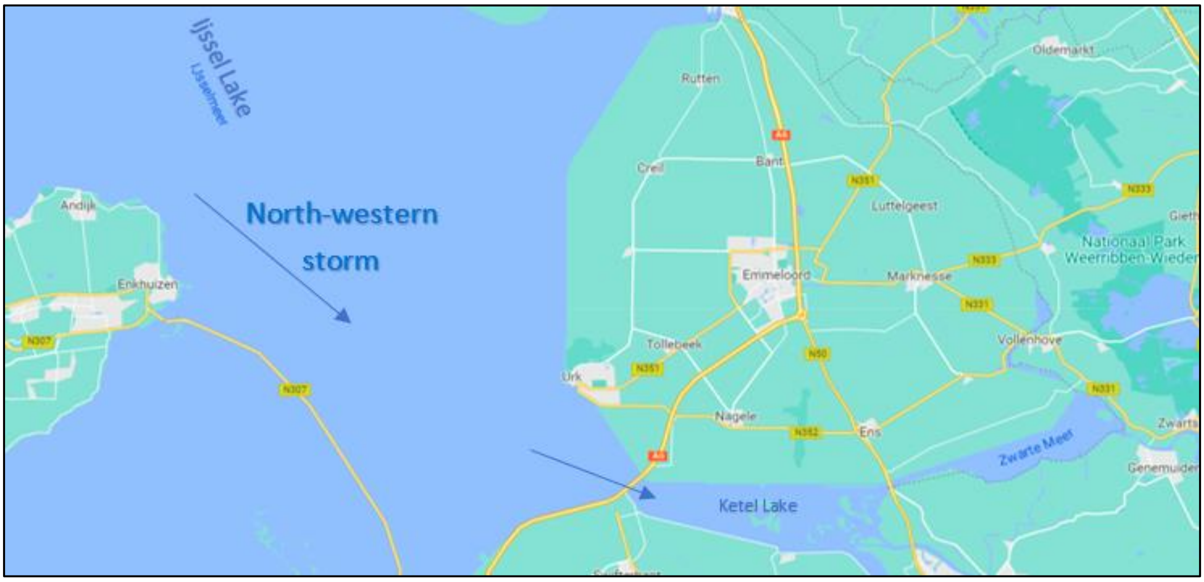


Map 1 From the "Wet op de waterkering", showing the dike-ring areas. The marked area surrounded by the black continuous line represents the river Overijsselse Vecht catchment area. The insert shows the area of interest around the city of Zwolle [2]

have been raised in order to have sufficient height to protect hinterland against water [1]. Before that, an extreme storm event in the IJssel Lake would subsequently cause frequent flooding of the surrounding low-lying areas. After the construction of the barrier, during its closing stage, the discharge from Zwarte Water River is getting accumulated behind it leading to high water levels. However, the flood risk is lower than it would have been with an unprotected barrier.

1.2 Problem definition

During intense northwest storms, the water level at the southern part of IJssel Lake is rising, because of wind set-up phenomenon which leads to rising of the water level due to the wind shear stress to a water body. In IJssel Lake this is further escalated because the dominant wind direction (northwest) comes in alliance with the longest shore to shore dimension (fetch length) and because of the lake's syphon shape, leading further to high water level in Ketel Lake and Zwarte Lake, where IJssel and Zwarte Water (Vecht) River are discharging (See Map 1 and 2).



Map 2 During strong and long-lasting northwestern storm the water level is rising at the bottom right corner of IJssel Lake

Ramspol Barrier is the first line of defence against storm induced high water threats from IJssel Lake and Ketel Lake [3]. With a measured water level at Ramspol Barrier NAP + 0.5 m, the barrier closes to protect the areas behind it from flooding. At the closed stage of the barrier, the blocked discharge of Zwarte Water River will be stored in Zwarte Lake, in Zwarte Water River branches and in case of emergency at the inundation areas in the Zwarte Lake side of Dike Ring 10. For extended closing time of the barrier and a high-water discharge of the river, the high-water level in Zwarte Water River will also influence areas further upstream at Vecht River, the city of Zwolle and Sallandse Weteringen [4]. This situation threatens the stability of the dikes and the flood safety of the city of Zwolle, which has a relatively high probability of failure. The safety level of the dike section under research has been calculated through Hydra-NL equal to 23842 years (failure mechanism 2% wave run-up). However, more mechanisms can lead to failure of the dike and thus the frequency can increase considerably. For the climate change scenarios G (Moderate) and W+ (Warmer), target year 2100 the return period of the dike failure increases significantly from 23842 to 120 and 45 years respectively (Hydra-NL). The city of Zwolle is an area of high economic value with an estimated damage in case of a dike failure of three billion Euro [5]. Thus, improvements need to be implemented, in order the area of interest to be sufficiently protected currently and in the future.

Additionally, complex water systems, such as the one under research, are already facing the influence of climate change. Multiple reports [31,32,33,34,35,36 and 37] indicate the following possible climate change effects:

- the increase in the intensity and frequency of extreme storm events
- the switching of the dominant wind direction,
- the increase of peak river discharges,
- the increase of the precipitation and
- the sea level rise.

Finally, while numerous models exist for quantifying flood consequences, such as HAZUS, effectively addressing the decision-makers' requirements in the initial stages of decision-making has been a challenge. Some flood risk screening models have been developed for specific cases, but their application is often limited to a single region and focused on a specific type of flooding, such as storm surges [81 and 82]. There is a clear need for risk models that integrate simple, fast, and widely applicable simulations with real-world decision-making processes. These desired models should possess several key characteristics, including the ability to (1) consider both pluvial and coastal flooding, (2) encompass both structural and non-structural measures, (3) incorporate economic and non-economic performance indicators, and (4) have a generic setup that can be easily adapted to other flood-prone regions globally. A model which is focused on those key characteristics is FLORES [83].

1.3 Research objective

The objective of this study is to develop an assessment method capable to handle many different improvements and highlight the most beneficial interventions for the water system under research, which is governed by the function of the inflatable storm surge barrier Ramspol, in order to improve the flood safety of the protected area, considering the influence of climate change to the water system.

The method must consist of 2 stages of assessment. The first stage must be capable of narrowing down, in a fast and reliable manner, the different improvements and pointing out the most promising ones. The second stage must be able to highlight the most beneficial improvement for the water system (supplementary objective).

1.4 Research questions

In line with the aforementioned research objective the following research and design questions were defined.

Research questions

How to assess a large number of improvements, which increase the flood safety of the area protected by a storm surge barrier against the effects of climate change, in terms of (1) decrease of water level maximum, (2) cost and (3) ecological impact, in a fast and yet reliable way?

Design question

What is the best strategy to adapt the flood protection system of the area behind the Ramspol barrier to climate change.

In order to provide an answer to the main research questions, research sub-questions are posed. The answer to each one of the sub-questions will support the answer to the main questions.

1. *How does climate change affect the flood safety of the area of interest?*
2. *Which interventions in the water system can improve the flood safety of the area of interest and how?*
3. *How to quantitively estimate the decrease in water level maximum?*
4. *How to roughly estimate the implementation cost of the improvements?*
5. *How to qualitatively estimate the influence of the interventions to the ecology?*
6. *How to handle the uncertainty which is being introduced?*
7. *How to combinedly assess the three decision making aspects and select the most promising improvements?*
8. *Which are the benefits that the designed assessment method is providing with?*

1.5 Report structure

In this chapter the structure of the report as it is indicated in the related Figure 1, will be explained.

Chapter 2 of the report will focus on the analysis of the system were the problems and the pressure parameters will be pointed out. The area of interest will be thoroughly presented and the water bodies which influence the flood protection in the area of interest, will be discussed. Additionally, an investigation will be conducted to determine the issues arise from the current situation and the effects of climate change. After understanding the function of the water system, the issues from the current situation and the climate change related threats, a list of requirements will be conducted, which will be further used during the brainstorming for designing the improvements.

Chapter 3 of the report will showcase the proposed improvements which have been designed through extensive brainstorming and consideration of the list of requirements. The proposed improvements will be categorised into 4 groups: the first group will aim to limit the wind set-up phenomenon in both IJssel Lake and Ketel Lake. The second group of improvements will aim to reduce the influence of river discharge in Zwarte Lake. The third group aims to reduce the water level by intervening in the cross section of Zwarte Water River in the area of Zwolle, and the fourth group concerns the increase of the reliability of Ramspol Barrier. The case of rising the height of the dikes will also be treated but it does not introduce changes in the water levels (represent the current water level situation).

Chapter 4 of the report will present the assessment method. The method consists of 2 assessment stages. The first stage considers a screening method to rapidly and reliably narrow down the 20 designed improvements in order to highlight the most promising ones. The second stage of assessment considers a detailed assessment method, which can be only applied to the selected improvements. The assessment consists of three decision making aspects:

1. The decrease of water level maximum,
2. The cost and
3. The ecological impact.

In chapter 5 of the report, the results from the calculation of the first stage of improvements will be presented and the most promising improvements will be selected.

In chapter 6 of the report, the assumptions made during the development of the assessment method and the calculation of the results will be discussed.

Finally, in chapter 7 of the report, the research question will be answered and recommendations for future research will be discussed.

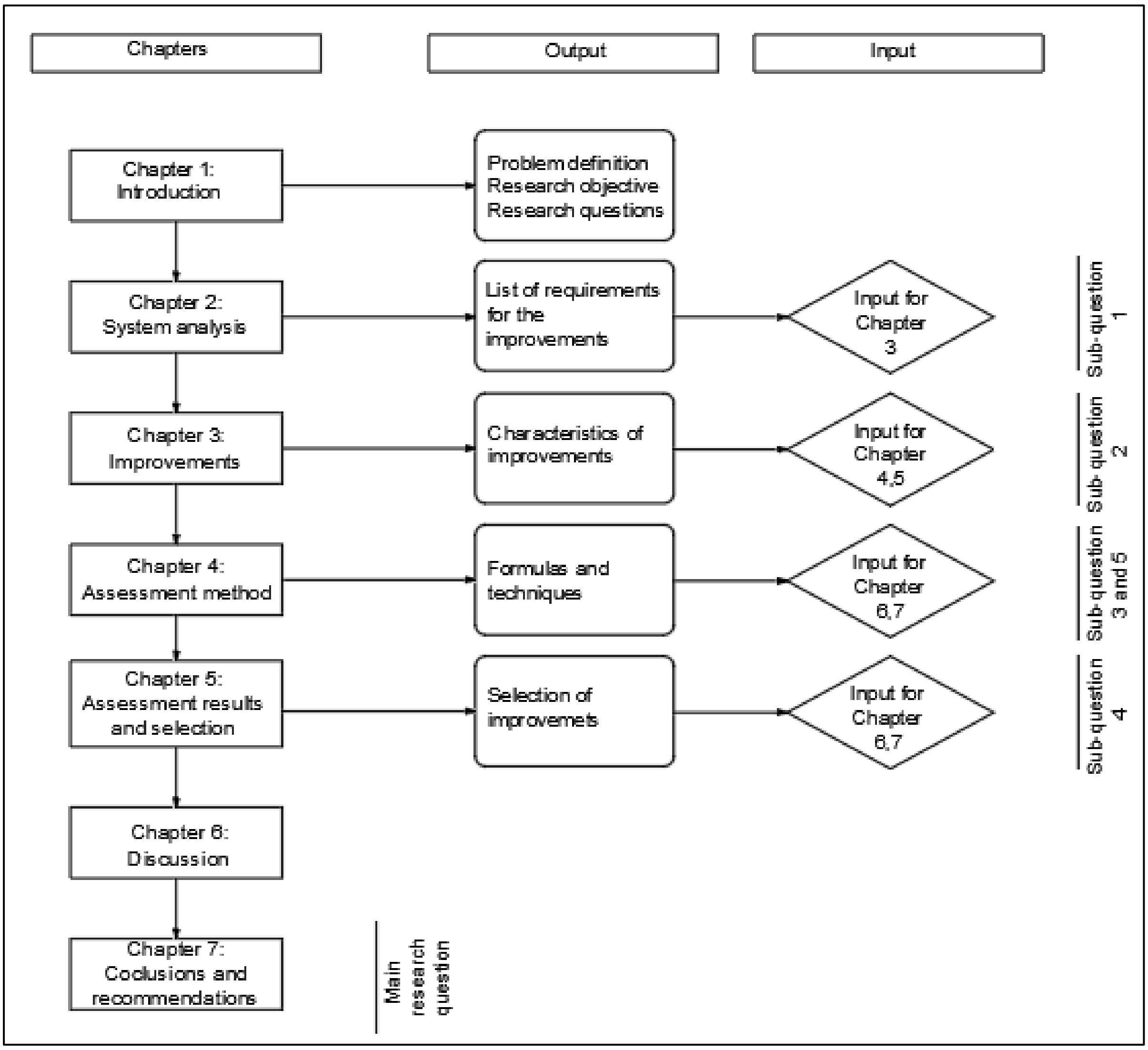


Figure 1 Chart showing the structure of the report according to the research approach

2. System analysis

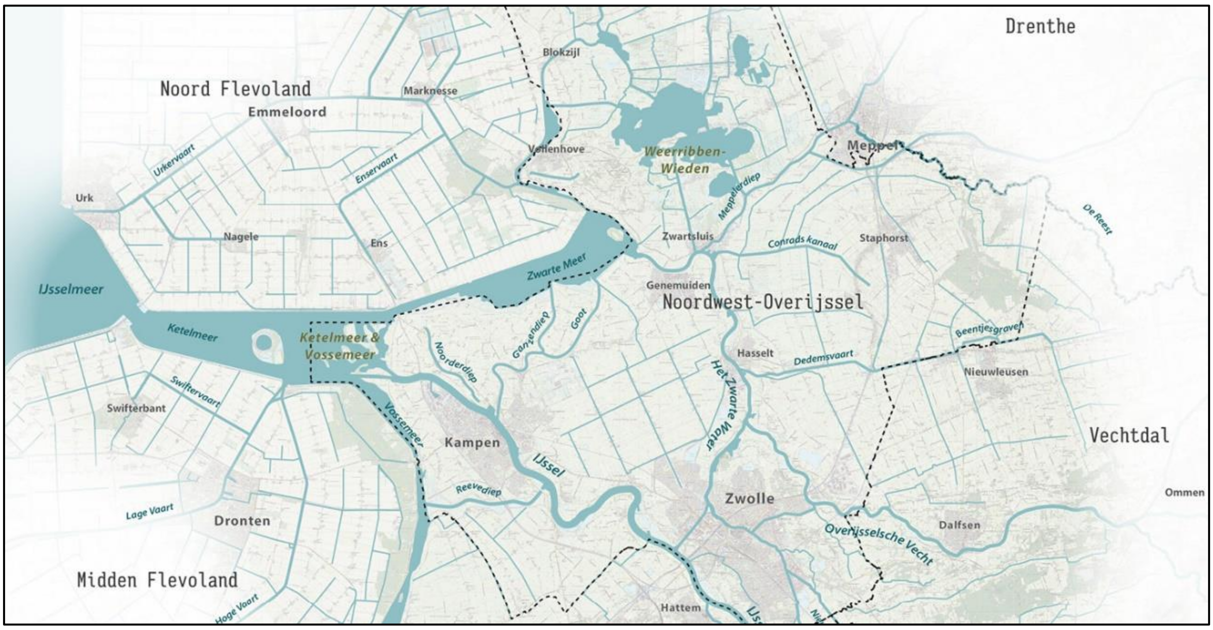
In this chapter an analysis of the water system under research has been executed.

2.1 Area of interest: Vecht and IJssel Rivers, IJssel Lake and Inflatable storm surge barrier Ramspol

The area of interest for this study is: IJssel and Vecht River Deltas, Ketel and Zwarte Lakes, Ramspol storm surge barrier and IJssel Lake. The Ramspol Barrier was constructed to protect the Overijssel area against high water levels due to storm events coming from IJssel Lake. Moreover, the discharge of IJssel and Vecht delta plays a significant role to the water level of Ketel and Zwarte Lake. Thus, all those water bodies together with the barrier structure (Ramspol) will be taken into consideration. In the following chapters the characteristics of the area of interest will be discussed.

2.1.1 The water system of Vecht and IJssel Rivers

There are two rivers discharging into IJssel Lake. Those two rivers are Vecht (Zwarte Water) and IJssel River. IJssel River flows directly into Ketel Lake. Vecht River first flows into Zwarte Water River, north from Zwolle and then flows into Zwarte Lake. The Vecht Delta covers the area of Overijsselse Vecht, between Dalfsen and Ommen, to Ramspol Barrier in Zwarte Lake (See Map 3).



Map 3 Water system of Vecht and IJssel Delta, Zwarte and Ketel Lake [6]

2.1.1.1 Vecht River

The Overijsselse Vecht enters the Netherlands east of De Haandrik and flows into the Zwarte Water near Zwolle, which then flows into the Zwarte Lake. The Zwarte Lake flows into the IJssel Lake via the Ketel Lake. The storm surge barrier of Ramspol is located between Ketel and Zwarte Lakes. More flood defence structures are located in the Zwarte River region. Those will be handled in the related Chapter 2.1.3.

For the Overijsselse Vecht, it is mainly the discharge that determines the normative water level. The wind has a minimal influence on the water level on the Vecht due to the lack of nearby large bodies of water. However, this changes further downstream near the Zwarte Water, where the system gradually transitions from discharge to wind dominated. When Ramspol Barrier is open, Zwarte Lake is mainly a wind dominated system. When Ramspol Barrier is closed, the influence of the wind is limited, and the discharge plays the most significant role in the height of the water levels [7].

2.1.1.2 IJssel Delta

In the Netherlands, the Rhine splits into three branches shortly after the border with Germany. At the Pannerdensche Kop, the Rhine splits into the Waal and the Pannerdensch Channel. The Pannerdensch Channel splits into Neder-Rijn and IJssel a little further on. The IJssel flows into the Ketel Lake via the IJssel estuary and then into the IJssel Lake.

2.1.2 The IJssel Lake

IJssel Lake is the largest freshwater lake in the Netherlands covering an area of eleven hundred square kilometres. It is located between the Houtribdijk (Lelystad - Enkhuizen), North Netherlands, the Afsluitdijk, Friesland, the Noordoostpolder and Flevoland. Since 1932 the Afsluitdijk (thirty-two-kilometre-long flood defence) has closed off the IJssel Lake (former Zuider Zee) from the Wadden Sea. During low tide, the water level in the Wadden Sea is lower than in IJssel Lake and water can be discharged from two sluices. Those sluices are located at Den Oever (Stevinsluizen) and at Kornwerderzand (Lorentzsluizen).

The balance of water in IJssel Lake depends on two main water movements. The input of water through the rivers flow in the Lake and the output of the water out through flowing from the two sluices (Stevinsluizen and Lorentzsluizen) at Afsluitdijk. The contribution of the rest input and output water parameters can be found in the following Figure 2.

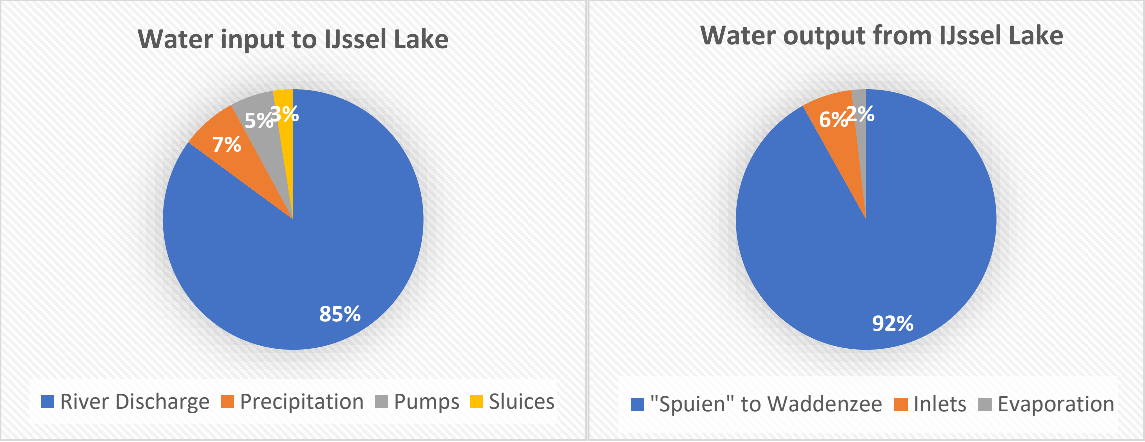
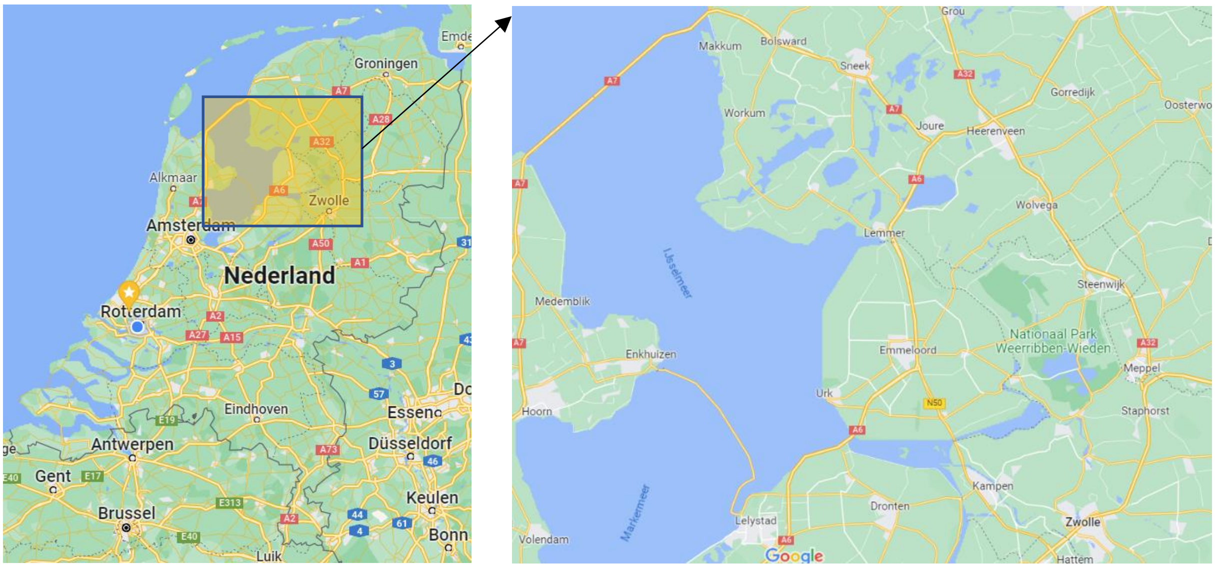


Figure 2 Water input and output for IJssel Lake

The IJssel Lake serves as a buffer for the water surplus. In periods of high-water supply, the level in the IJssel Lake rises. North-westerly winds cause higher water levels in the Wadden Sea. This makes draining more difficult and at the same time raises the water level in the southeast IJssel Lake because of the phenomenon of wind set-up. The IJssel Lake is used for navigation but also by water sport enthusiasts. In addition, the Lake provides freshwater supply for the province of Friesland.

2.1.3 Inflatable storm surge barrier Ramspol

Ramspol Barrier is an inflatable storm surge barrier in the IJssel Lake at northeast Netherlands (See Map 4). More specifically, it was constructed in 2002 and closes off Zwarte Lake from Ketel Lake during high water events. As far as the operation is concerned, the closure procedure starts for a measured water level of NAP + 0.50 m (at the barrier) and a flow direction towards the Zwarte Lake and takes almost an hour to be completed.



Map 4 Left: Area of interest in the Netherlands, right: Area of interest with IJssel Lake, Ketel Lake and Zwarte Lake, IJssel and Vecht Rivers and Ramspol Barrier

When the barrier is open, the fabric is stored in a sill which is installed at the bottom of the river (underwater) and when it is needed, the barrier is inflated with water and air. The solution of the inflatable barrier was chosen because otherwise 115 km of dikes along the river branches and the lake should have been raised in order to protect hinterland against flood [8]. Further, the inflatable approach gives the advantage of being invisible. Only during storm events leading to closure procedures, the whole barrier is visible (Figure 3).

Figure 3 Ramspol Barrier during closing state [9]

The main characteristics of Ramspol Barrier can be found in the following Table 1:

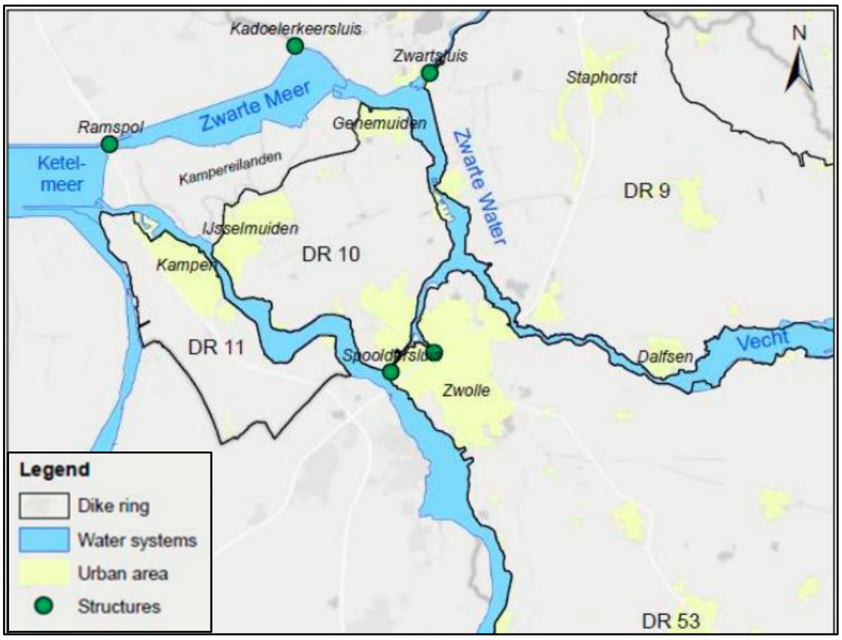
Table 1 Ramspol Barrier's characteristics [10]

Main function:	Navigation and water exchange
Length:	450 m
Cumulative span:	202 m
Width:	13 m
Design barrier height (probability of occurrence 1/10,000 years):	8.35 m
Retaining height	NAP + 3.55 M
Navigation openings:	52 m
Flow openings:	2 * 75 m
Sill level:	NAP/MPL - 4.65 m
Foundation type, depth:	Pile, 10 m (relative to the sill level)
Closing procedure:	60 min
Opening procedure:	180 min
Additional closings:	Test/inspection closures, calamities (e.g., oil spoil)

More information for the characteristics and function of Ramspol Barrier can be found in Appendix A. In Appendix B can be found information regarding the operation and issues of Ramspol Barrier, as indicated from the engineers operating at the barrier.

2.1.4 Other flood gates and dike rings in Vecht and IJssel Delta

The Vecht and IJssel Deltas consist of four Dike Rings 9, 10, 11 and 53. Except for Ramspol Barrier, more flood defence structures are responsible for the protection of those dike rings against high water levels from Vecht and IJssel River. An overview of the area can be found in the following Map 5.



Map 5 Overview of the water system IJssel and Vecht Delta, five main water structures and 4 dike rings in the study area [11]

2.1.4.1 Flood gates in Vecht and IJssel Delta

The area is protected against high water events from dikes and the storm surge barrier Ramspol. There are more floodgates in Vecht – IJssel Delta except for Ramspol Barrier. Those are: Kadoelersluis, the structures in Zwartsluis, Spooldersluis, a barrier in Zwolle and Ganzensluis [11].

The Kadoelerkeersluis

The Kadoelerkeersluis regulates the flood defence between the Zwarte Lake and the Kadoeler Lake. With a persistent north-westerly wind, the water from the IJsselmeer will be pushed towards the Ketel Lake and Zwarte Lake. In that case the water from Zwarte Water River cannot escape and the flow direction can even be reversed towards the river. This situation, causing high water levels in Zwarte Lake. However, the dikes in Kadoeler Lake are not designed to withstand that high water levels and thus, the gate is operating in cases needed. In normal weather, the lock is open and shipping traffic is possible. When the water level in Zwarte Lake exceeds NAP + 1.0 m, the Kadoelerkeersluis is closed, the Kop van Overijssel and therefore the area behind it is protected against flooding [12]. For opening and closing procedures equal time of an hour is required [13].

The Grote Kolksluis, the Meppelerdiepsluis and the pumping station Zedemuden in Zwartsluis

The exchange of water between the Zwarte Water and the Meppelerdiep channel is regulated by three structures, the Grote Kolksluis, the Meppelerdiepsluis and the pumping station Zedemuden, responsible for keeping safe against floodings the village of Zwartsluis. Because of these structures it is possible to discharge water in Vecht, even for water levels in Vecht higher than in Meppelerdiep. The Grote Kolksluis is a schutsluice (possible to move ships from one water level to another) located at the Zwartsluis, able to block the water flow between Meppelerdiep River and Zwarte Water River when is closed, in order to protect village Zwartsluis. The sluice closes for water levels between NAP – 0.5 m and NAP + 0.5 m, approximately 16 days per year due to too high or too low water levels. The Meppelerdiepsluis is a schutsluice located at the Zwartsluis also for blocking the water flow between Mappelerdiep and Zwarte Water River. The sluice closes for water levels between NAP – 0.5 m and NAP + 0.5 m, approximately 16 days per year due to too high or too low water levels. Meppelerdiepsluis has been recently (2017) renovated in order to meet the requirements of the water system. Finally, the pumping station Zedemuden, is getting used next to the Meppelerdiepsluis. When high precipitation is observed, the pumping station provides water drainage from the province of Drenthe via the Zwarte Water River and the IJsselmeer to the Wadden Sea [14].

Spooldersluis

Spooldersluis is a schutsluis between the IJssel River and the Zwolle IJssel Channel in the municipality of Zwolle. Located west from the city of Zwolle, it separates the IJssel and Vecht River systems and protects the hinterland against high water level of IJssel River.

Ganzensluis

The Ganzensluis in Kampen is a schutsluis that connects the Ganzendiep with the IJssel River. The Ganzensluis was built in 1938 and is part of the Ramspol storm surge barrier. When the barrier at Ramspol is closed, the gate functions as a floodgate.

Barrier Zwolle

Finally, there is a flap barrier near Zwolle. This barrier is located between the old centre of Zwolle and the highway A28 and its function is to protect the inner city of Zwolle and the Salland hinterland during high water levels on the Zwarte Water and the Vecht. The barrier operates when the water level rises above NAP + 1.0 m [15] and the flow of the Zwarte Water River is directed towards the centre of Zwolle. The closing frequency of the flood gate in Zwolle is once every two years [16]. After the construction of this barrier the status of the underlying dikes along the Asllandse Weteringen has changed from primary flood defences to regional (secondary) flood defences.

2.1.4.2 Dike rings and dike stretches in Vecht and IJssel Delta

Each part of the Netherlands that can be flooded by the sea or one of the main major rivers is divided into dike rings. The IJssel and Vecht Deltas contain four dike rings. Those are the dike rings of: 9 Vollenhover, 10 Mastenbroek, 11 IJsseldelta and 53 Groot-Salland (See Map 5). The characteristics and flood risks for each one of the above-mentioned dike rings, (VNK, 2014 [17]), can be found in the following Tables 2 and 3 respectively.

Table 2 Dike ring characteristics [17]

Dike ring	Dike length (km)	Protected area (ha)	Population
9 Vollenhover	46.0	58,200	88,600
10 Mastenbroek	47.5	9,540	32,000
11 IJsseldelta	32.4	13,700	47,800
53 Salland	83.0	40,900	205,500

Table 3 Dike ring flood risks [17]

Dike ring	Flood probability (1/time period)	Economic risk per year (million)	Avg. damage per flood (million)	Casualties risk per year	Casualties per flood
9 Vollenhover	1/100	6.3	440	0.2	13.0
10 Mastenbroek	1/240	3.2	780	0.1	20.0
11 IJsseldelta	1/260	3.1	810	0.1	35.0
53 Salland	1/110	26.4	3000	0.5	60.0

Vollenhover: Dike Ring 9

The largest part of the area which is protected from Dike Ring 9 is in Overijssel province and a small part of it is in Drenthe province. The flood defences protect the Kop van Overijssel area against flooding by the Overijsselse Vecht River, the Zwarte Lake and the Zwarte Water River. An important aspect of Dike Ring 9 is the medieval Stenendijk levee near Hasselt. This retaining wall has a length of a kilometre and is the oldest brickwork flood defence structure in the Netherlands. The structure was built and maintained by the locals and each one of them was responsible for a part of the retaining wall. Consequently, the wall is a patchwork of different types of brickwork. In the early 19th century, the levees at Zwartsluis and Hasselt breached because of the combined effect of storm conditions and poor maintenance [17].

Mastenbroek: Dike Ring 10

The medieval polder between the IJssel River and Zwarte Water River in Overijssel province is being protected from Dike Ring 10. The levee Kamperzeedijk, (constructed before the 14th century), which belongs in this dike ring, is also one of the oldest flood defence structures in the Netherlands. This levee is the border with Kampereiland area, which was regularly flooded by the Zuider Sea in the past and still is getting flooded during Ramspol's barrier flood procedures. In 1825 the Kamperzeedijk failed in many positions during a storm surge and one of the most severe floods in Mastenbroek polder took place [17].

IJsseldelta: Dike Ring 11

Dike Ring 11 is in IJssel Delta, protecting an area which belongs partially to Overijssel province and partially in Gelderland. In 1926 after a levee breach at Zalk the biggest part of the area was flooded. Since then, the area was regularly flooded by the Zuider Sea and thus the properties of the locals were already sufficiently protected and the damage was limited. The following years, the navigation channel of IJssel River was deepened and a high-water channel was dug. This high-water channel transects

Dike Ring 11, and the river is connected with the Dronter Lake. Those measures have been taken to guarantee flood protection in the future [17].

Salland: Dike Ring 53

Dike Ring 53 protects the Salland region from high water levels by the IJssel River, the Zwarte Water River and the Overijsselse Vecht River. The protected area is mainly rural and contains some large cities as Zwolle and Deventer. With the downstream direction of the river, the elevation of the area is getting lower, meaning that if the levees along IJssel River breach the lower lying areas around Zwolle will get flooded. In addition, for extreme high water of IJssel and Overijsselse Vecht Rivers at the same time, then the city of Zwolle will be threatened as well. In January of 1926 there was a major flood event in the IJssel valley, but this area did not get flooded [17].

Each dike ring consists of dike stretches and ring sections. A ring section is part of the dike where the flooded area and the impact (damage and casualties) are nearly independent from the exact location of the breach. Ring sections are used for flooding simulations. For dikes ring 9, 10, 11 and 53 there are respectively 9, 16, 4 and 13 ring sections determined. Additionally, the dike ring is divided into dike stretches for the derivation of failure probabilities. A dike stretch is a part of the dike where the characteristics regarding strength and loads are nearly homogeneous. Dike Rings 9, 10, 11 and 53 are separated into respectively 51, 55, 44 and 72 dike stretches [17].

2.2 Current situation and climate change scenarios (City of Zwolle)

In the following Figure 4, it can be seen the return period of water levels for the current situation. Also, the water levels for two climate change scenarios and two different target years can be found. Finally, it can be seen the water levels for different probabilities of failure of the Ramspol barrier. The graph has been produced, by using the Hydra-NL model.

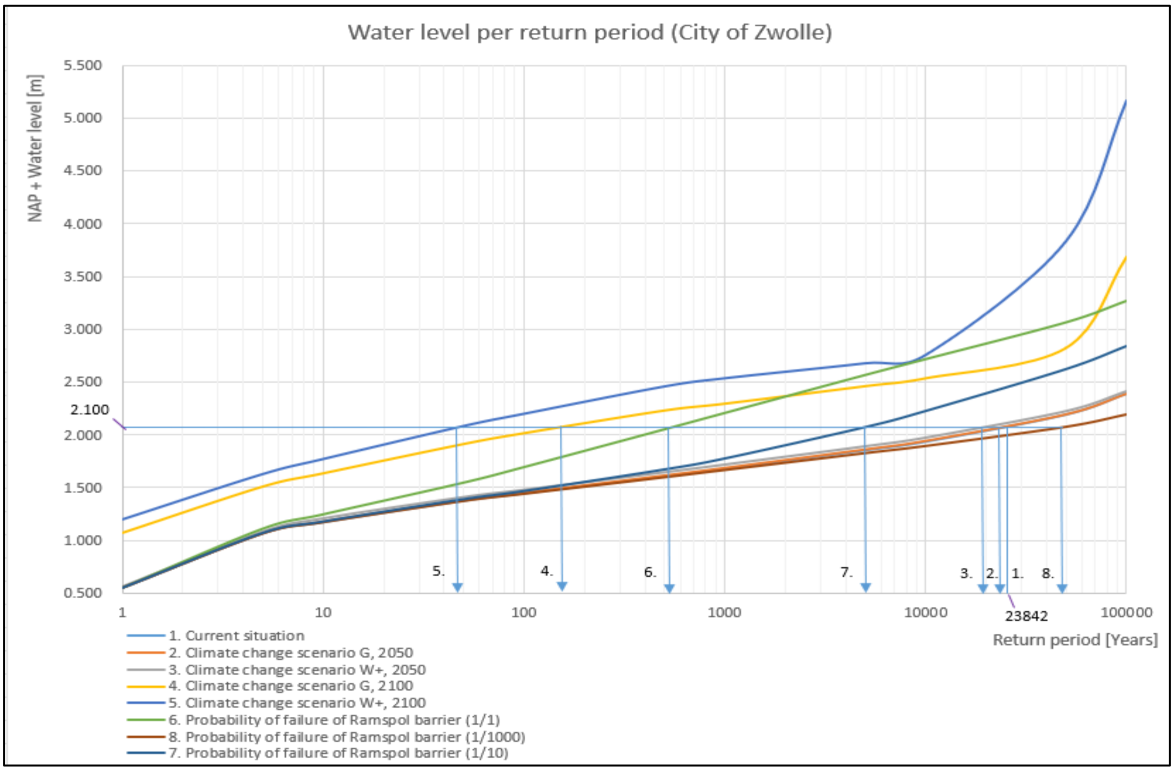
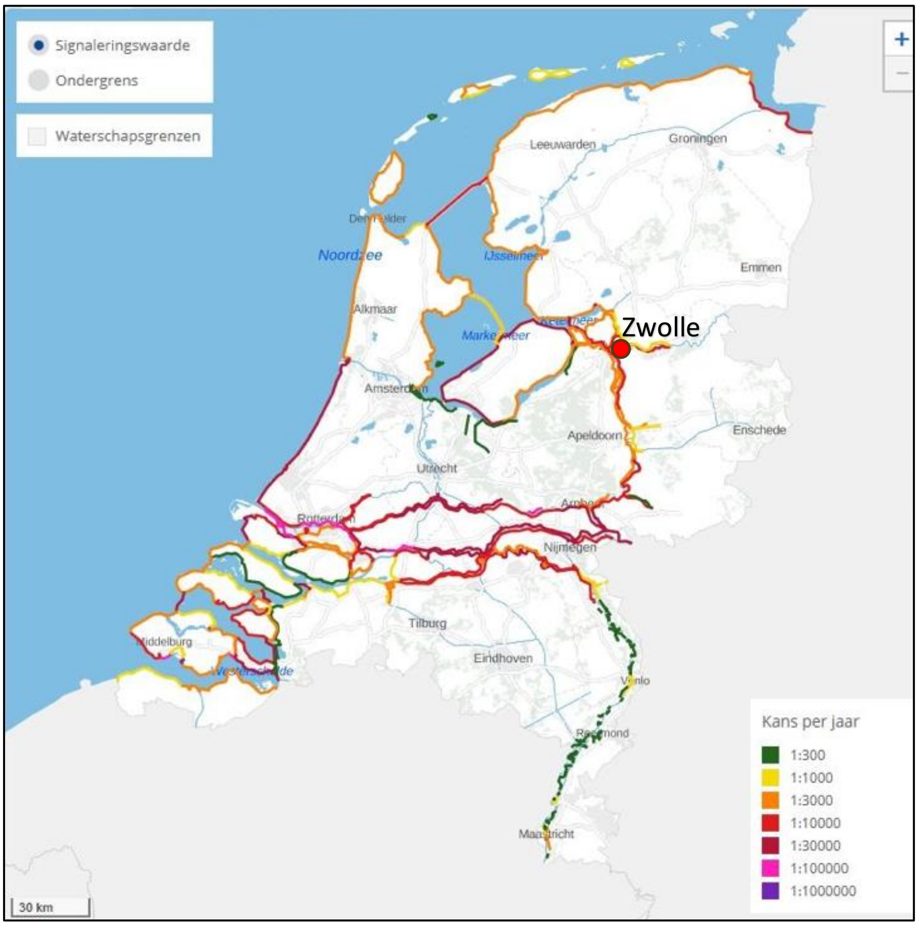


Figure 4 Water level per return period (Zwolle – dike section Vechtdelta_10-01_35_ZW_km0002) for the current situation, two climate change scenarios for two target years and for different probabilities of failure of Ramspol barrier (Hydra-NL)

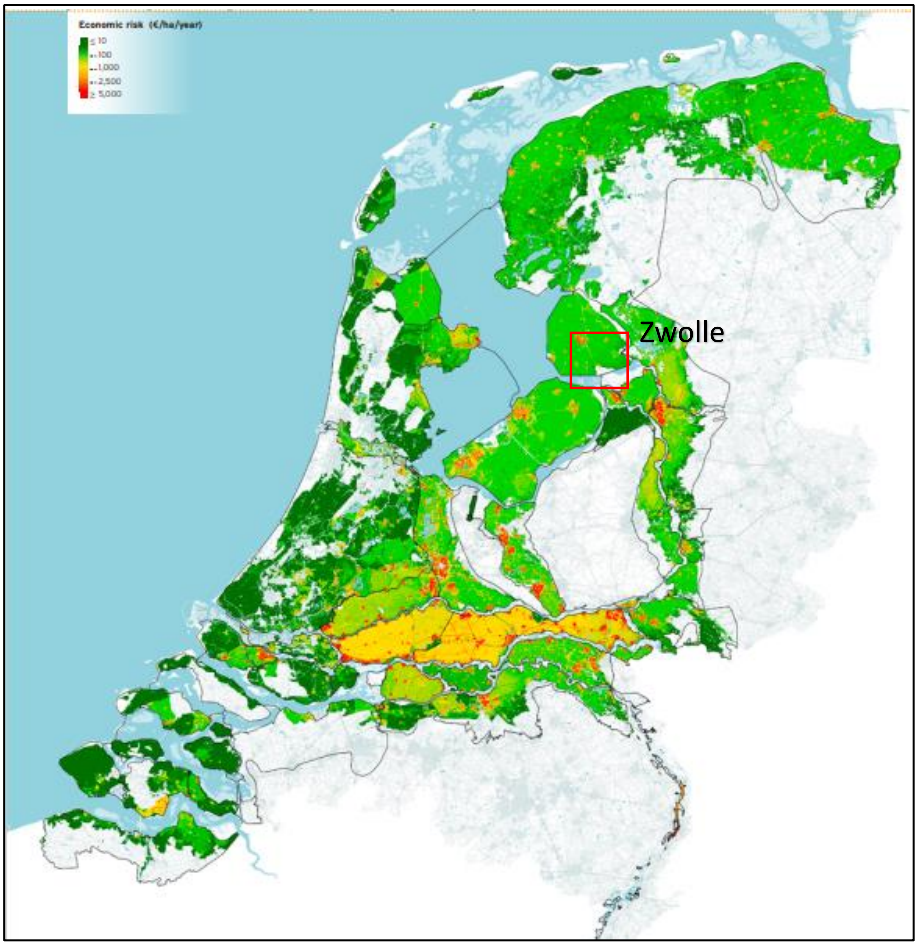
It has been calculated by using Hydra-NL that for the current situation (light blue line), the dike fails for return period of 23842 years and a water level of 2.1 m. It can be seen that the climate change scenarios G (Moderate) and W+ (Warmer) for 2050 (orange and grey lines), give similar water levels with the current situation. The model is taking into account only the increase of river discharge. Moreover, for the target year 2100 the model shows a great increase of water levels. In that case the model takes into account except from the increase of river discharge, also the lake level rise. It can be seen that for the climate change scenarios G (Moderate) and W+ (Warmer), target year 2100 (yellow and blue lines), the return period of the dike failure decreases significantly (from 23842 to 120 and 45 respectively). A climate change analysis of the effects of climate change which are influencing the water system under research can be found in Appendix C. For the case of an always failing barrier (green line), the return period of a failing dike is also decreasing considerably (from 23842 to 520). On the same way, for a probability of failure of Ramspol barrier 0.1 and 0.001 the return period of the dike's failure is getting decreased and increased respectively. However, the failure point of the dike corresponds only to the failure mechanism 2% wave run-up and thus in reality it can be assumed failure of the dike for even lower water levels, and thus failure for lower return period (higher frequency).

Map 6 for the national safety standards for the primary flood defences shows that the flood defences near the city of Zwolle, have safety standards between 1/10000 to 1/30000. This means that currently, the flood defences in the area are slightly meet the requirements, and they will not suffice for the future. More information regarding the assessment of flood defences and flood risk in the Netherlands and assessment approach and methods can be found in Appendix A.



Map 6 National safety standards for primary flood defences [20]

The city of Zwolle is an area, the flooding of which would cause high economical damage and thus, its protection is of high necessity. This can be seen in the following Map 7 where the economic risk is high near the area of interest (See red rectangular).



Map 7 Economic risk in the Netherlands, area of interest in red rectangular [23]

3. Design of the improvements

3.1 List of requirements and design process

Based on the research done, a good representation has been established on the current issues of the existing storm surge barrier Ramspol and the questioning levels of protection it can provide for the area of interest against flood. Additionally, by taking into account the projected trends in climate change, a list of requirements was conceived. These requirements are the result of the research done and the understanding of the area's characteristics. The list of requirements has been conducted in order to be used as a guide for designing solutions which could lead to decrease of water levels in the water system.

List of requirements

The improvement must …

1. … be able to respond to the climate change trends (severe storm events, high river discharges and sea level rise)
2. … efficiently lower flood risk level of the areas protected from Ramspol Barrier
   2.1 … be able to limit wind set-up which lead to high-water levels
   2.2 … be able to lead to lower water levels at Zwarte Lake, Zwarte Water River and Zwolle
   2.3 … be able to lead the excess water out of Zwarte Lake
   2.4 … be able to increase the reliability of the flood defence system

Based on the list of the requirements improvements have been designed, which are aiming to decrease the flood risk in the area of interest, city of Zwolle. A comprehensive list of 20 potential improvements for the water system under study has been generated through a brainstorming process. Many of the improvements discussed in this chapter are not new and have been previously covered from other studies (e.g., RWS Waterdienst December 2009, Quirijn Lodder).

3.2 Improvements

Based on the analysis conducted, in order to enhance the flood safety of the area of interest, improvements have been designed. The proposed improvements can be classified into four distinct categories based on their influence on the water system. The four types of improvements must:

1. Mitigate the wind set-up phenomenon.
2. Reduce the water levels in Zwarte Lake.
3. Create additional space for water discharge in river branches.
4. Enhance the reliability of the Ramspol Barrier.

3.2.1 Mitigating the wind set-up phenomenon

Wind set-up is a phenomenon that occurs when intense winds blow across the surface of a body of water, causing the water level to rise on the upwind side and lower on the downwind side. This can result in a significant increase in the water level near the shore, leading to coastal flooding and erosion. The magnitude of the wind set-up effect depends on several parameters, including the depth of the water body, the wind speed and direction, the roughness of the bottom of the water body and the distance over which the wind can blow without obstacles (known as the fetch). Other factors that can influence wind set-up include the shape of the coastline and the presence of obstacles such as islands or reefs. Coastal areas with steep slopes or narrow bays may also be more vulnerable to wind set-up.

The understanding of these parameters and their influence on wind set-up can help to design and implement effective mitigation strategies.

Specifically, a beneficial wind direction, high wind speed, long fetch, small depth, and large roughness parameter can enhance the wind set-up phenomenon. The following improvements are based on changing those parameters in a way that would decrease the rising of water level because of wind set-up.

3.2.1.1 Improvements limiting the "fetch" length

One critical parameter that influences the wind set-up is the fetch length, which is the distance over which wind can blow over water without obstructions. In IJssel Lake, when the wind blows from a northwest direction, the long fetch distance and the narrowing near Ketel Lake cause the water to pile up, resulting in a higher water level (wind set-up). This effect is particularly enhanced near Ketel Lake, leading to closure of Ramspol Barrier, in order to prevent flooding and protect the surrounding areas. The longer the fetch, the more wind energy is transferred to the water surface, resulting in a larger lake state and more significant wind set-up. Therefore, a number of improvements has been designed in order to limit the fetch distance.

Improvement 1: Limiting the fetch length with breakwaters

This improvement recommends the limitation of the fetch length from 54 km to 10 km. Limiting the fetch length to only 10 km is one approach to mitigating wind set-up in IJssel Lake. This improvement suggests the installation of structures, such as breakwaters strategically placed to limit the length of water over which wind can blow without obstruction. By reducing the fetch length, the transfer of energy from wind to water is also reduced, thus reducing the potential for wind set-up and associated impacts.

In terms of navigation, sail ways can be incorporated into the design of the structures, allowing vessels to pass through to one or both sides of the structures. This would ensure that navigation remains possible while still limiting the fetch length and reducing the development of wind set-up. The shape of the structures can vary (Figure 5) depending on the specific design objectives and environmental conditions. For example, breakwaters can be designed as a series of staggered blocks or as a single continuous structure. These breakwaters can be curved or straight.

Figure 5 Improvement 1: Limiting the fetch length with breakwaters and Improvement 2: Dividing IJssel Lake with a structure "Afsluitdijk II"

Improvement 2: Dividing IJssel Lake with a dike "Afsluitdijk II"

This improvement recommends the division of IJssel Lake into two lakes. In that way the fetch length decreases from 53 to 24 km, which has a major influence on the set-up phenomenon (Figure 5).

Currently, the longest fetch length in IJssel Lake is 53 km, which can result in a significant build-up of water level due to wind set-up. By dividing the lake into two separate water bodies as suggested, the fetch length will be reduced to 24 km and thus the associated wind set-up will also be reduced.

The division of the lake can be made with a dike similar to Afsluitdijk which is the dike between Wadden sea and IJssel Lake. The barrier would need to be carefully designed to allow for water flow between the two halves, while still reducing the potential for wind set-up. This could be accomplished by incorporating gates or other mechanisms to regulate water flow. In addition, dividing the lake could also provide other benefits. For example, it could improve water quality by separating agricultural and urban runoff from recreational areas. It could also provide opportunities for diverse types of water-based activities and ecosystems, such as freshwater wetlands or fish habitats. However, there are also potential drawbacks of dividing the lake. For example, it could impact navigation and water transport, and create the need for construction of new channels or gates. It could also disrupt the local ecosystem, particularly if the barrier prevents the natural movement of fish and other aquatic species.

Improvement 3: Reclamation land

Creating a reclamation land (Figure 6) inside IJssel Lake is one approach to limit the fetch length and reduce the influence of wind set-up. This would involve building a new landmass within the lake, which would effectively reduce the length of the fetch and limit the build-up of water level due to wind set-up. The reclaimed land could then be used for various purposes, including residential areas or recreational spaces.

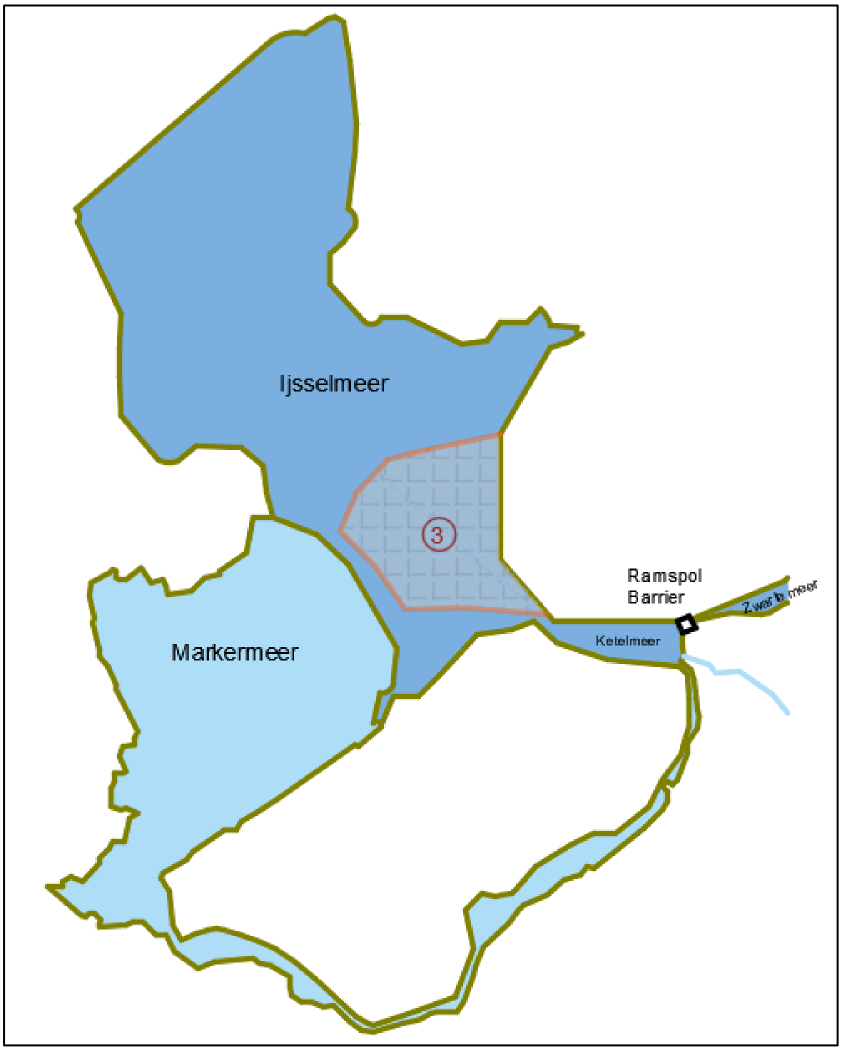


Figure 6 Improvement 3: Reclamation land

Improvement 4: Outflow channel

As it can be seen in Figure 7, this improvement concerns a protected channel which can carry the discharge of the outflowing rivers into Ketel and Zwarte Lakes, further into IJssel Lake. Within this channel the discharges of Vecht River flowing to Ketel Lake through Zwarte Lake and the discharge of IJssel River flowing directly to Ketel Lake, will finally flow to the middle of IJssel Lake. The channel influences positively the area of interest in two ways. First, since the discharge of the rivers flows directly away from Ketel Lake, no high-water levels will be observed because of the resistance to the river discharge from the IJssel Lake flow. Secondly, the wind set-up phenomenon which is developed in IJssel Lake will no longer influence Ketel Lake and Ramspol Barrier.

Figure 7 Improvement 4: Outflow channel

Improvement 5: Construction of a second storm surge barrier at Ketelbrug

The improvement being proposed involves the construction of a new storm surge barrier at Ketelbrug (Figure 8). By using another barrier at Ketelbrug, the area where the water discharge from IJssel and Zwarte Water River can be accumulated will be larger, which also implies higher water discharge capacity.

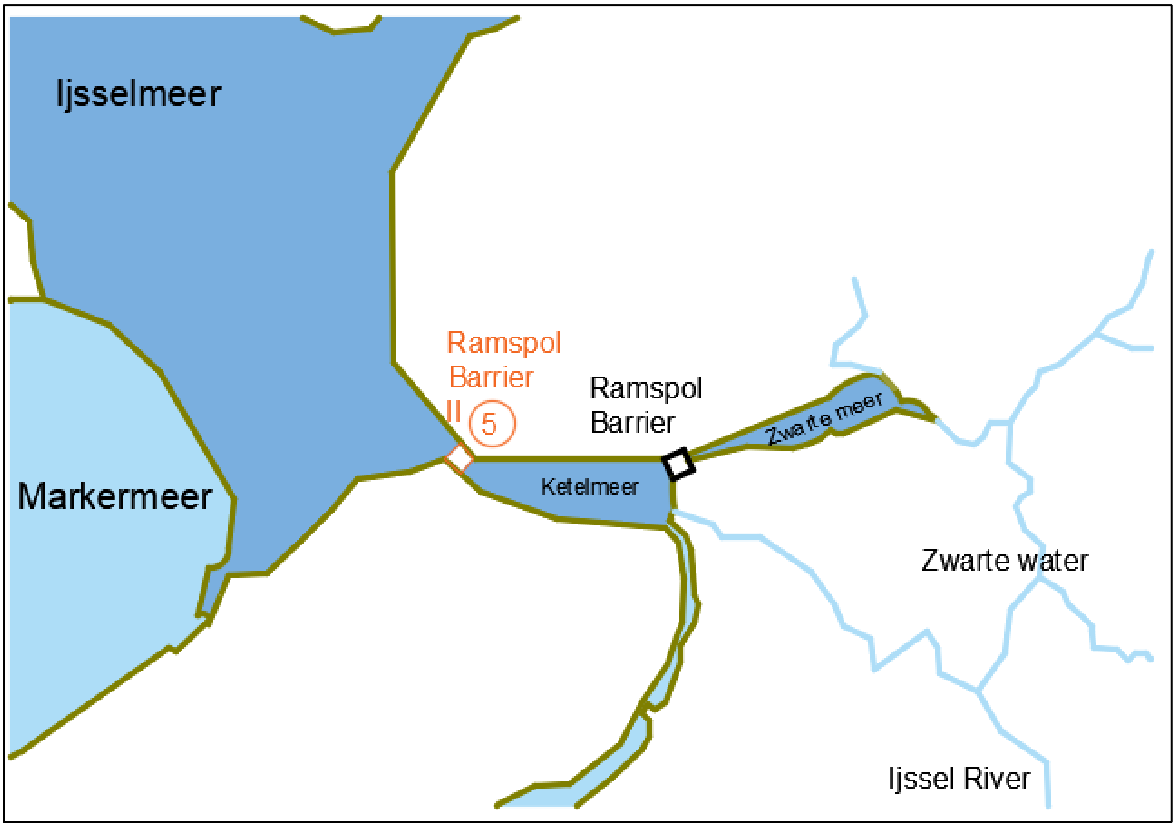


Figure 8 Improvement 5: Construction of a storm surge barrier at Ketelbrug

3.2.1.2 Improvements influencing the water level in lake IJssel

Currently, 81% of the water flows in IJssel Lake comes from IJssel River and 92% of the water flows out from two sluices in Afsluitdijk. However, during northwest storm events, a big amount of the water of the lake is concentrated to the south leading to lower water levels to the north. At the same time, a northwest storm can influence Wadden Sea in the same way, leading to high water levels in the Wadden side of Afsluitdijk. In that case the water can no longer flow outside of the Lake though the sluices. For that reason, and in order to cope with the sea level rise, pumping stations in the Afsluitdijk were installed and were ready for use at the beginning of 2022. By increasing the pump capacity of Afsluitdijk, more water would be pumped out in case of emergency in order to decrease the water level in the lakes.

This measure could help to directly lower the water level in the lake and reduce the risk of flooding. A lower water level in IJssel Lake implies smaller depth and the phenomenon of wind set-up would be increased. Thus, it is important to investigate if this increase in wind set-up is smaller or bigger than the decrease of water level of IJssel Lake, because of the extraction of water through the pump stations.

Improvement 6: Increase pump capacity at Afsluitdijk

The water reaches IJssel Lake from the whole basin and flows out from sluices at Afsluitdijk. For adjusting the lake to the effects of climate change, as sea level rises, pumps have been installed at Afsluitdijk, in order to assist the out-flow of water from the Lake. By increasing the capacity of the pump stations (Figure 9), even lower water levels can be achieved in case of emergency. This initial lower water level would also lead to lower water level at Ketel and Zwarte Lake. Even though the smaller depth of the lake would slightly increase the phenomenon of wind set-up, this increase would be of lower importance.

Improvement 7: Pump installation to Marker Lake

Pumping water from IJssel Lake to Marker Lake (Figure 9) would lead to a decrease of water level in IJssel Lake. Since Marker Lake dike, located in the south of IJssel Lake, where the impact of wind set-up is higher, the influence of the water extraction through the pump station could imply a direct decrease of water levels in the most threatened from high water levels areas.

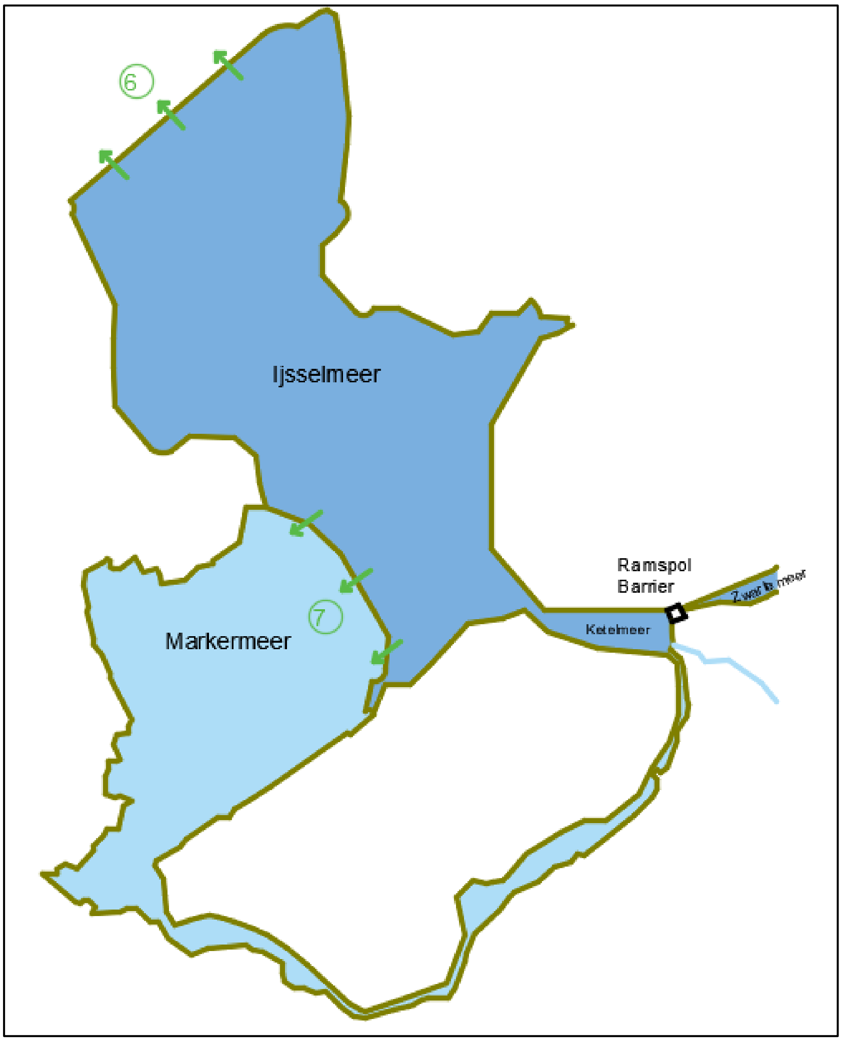


Figure 9 Improvement 6: Increase pump capacity at Afsluitdijk and Improvement 7: Pump installation at Marker Lake

3.2.1.3 Improvements influencing the depth of the lake

Improvement 8: Deepening the IJssel Lake to the south

Another parameter influencing the wind set-up phenomenon is the water depth. The depth and the wind set-up are 2 inversely proportional values. This is because deeper water has more volume to distribute the wind energy, resulting in a smaller rise in water level. This means that for a deeper lake, the wind set-up will be smaller for a given wind speed and drag coefficient. Therefore, by deepening the IJssel Lake (Figure 10), the expected wind set-up near the area of interest would be reduced.

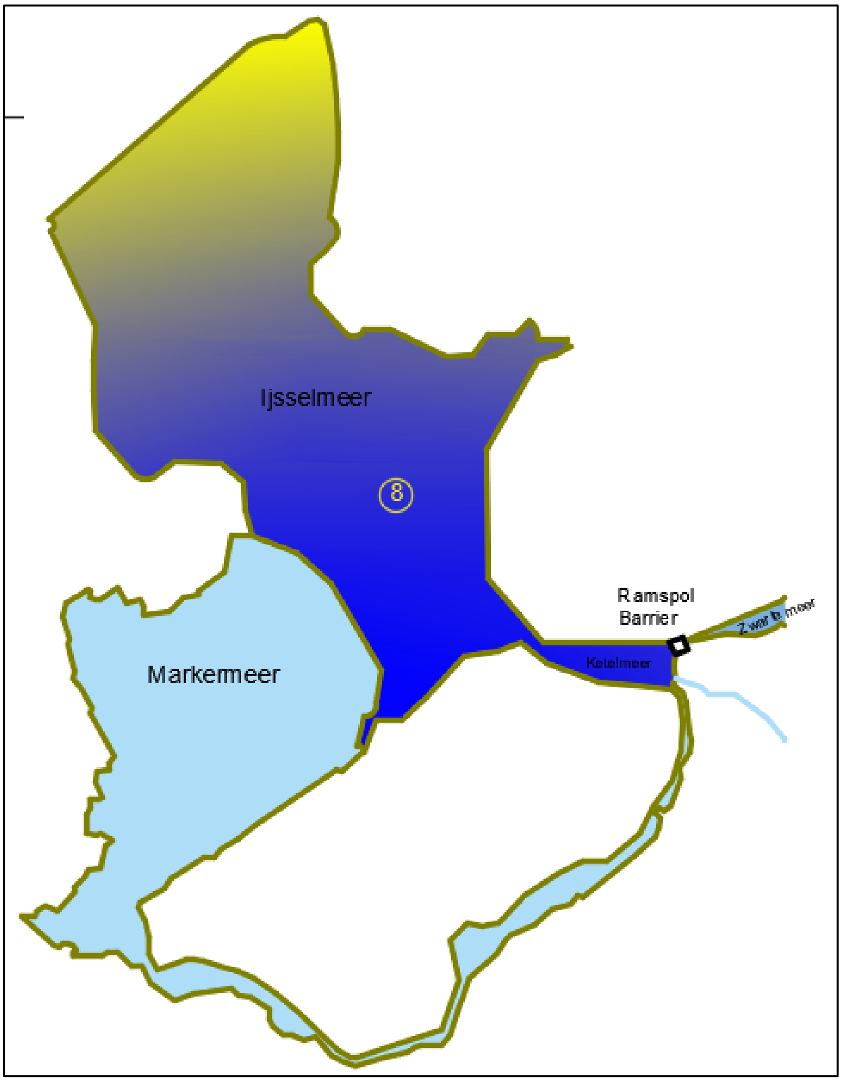


Figure 10 Improvement 8: Deepening IJssel Lake to the south

3.2.1.4 Improvements influencing the bottom of the lake

Improvement 9: Vegetation area

IJssel Lake is a large body of water that has been subject to numerous interventions to manage water levels, prevent flooding, and support various economic activities such as agriculture, navigation, and recreation. One way to improve the health of the lake and mitigate the impact of wind set-up is to create vegetation areas. There have been several initiatives to create vegetation areas in IJssel Lake. For example, the Dutch government has launched a project called "Building with Nature" that seeks to create natural solutions to water management challenges. As part of this project, vegetation areas have been created along the edges of IJssel Lake to absorb wave energy and improve water quality.

Creating a vegetation area (Figure 11), is following the approach of creating a reclamation area (Improvement 3), however in that case the created area will be provided to nature and the ecosystems. By creating a vegetation area, the fetch length can be limited since the vegetation area represents a disturbance to the wind direction. At the same time, vegetation contributes to the dissipation of wave energy.

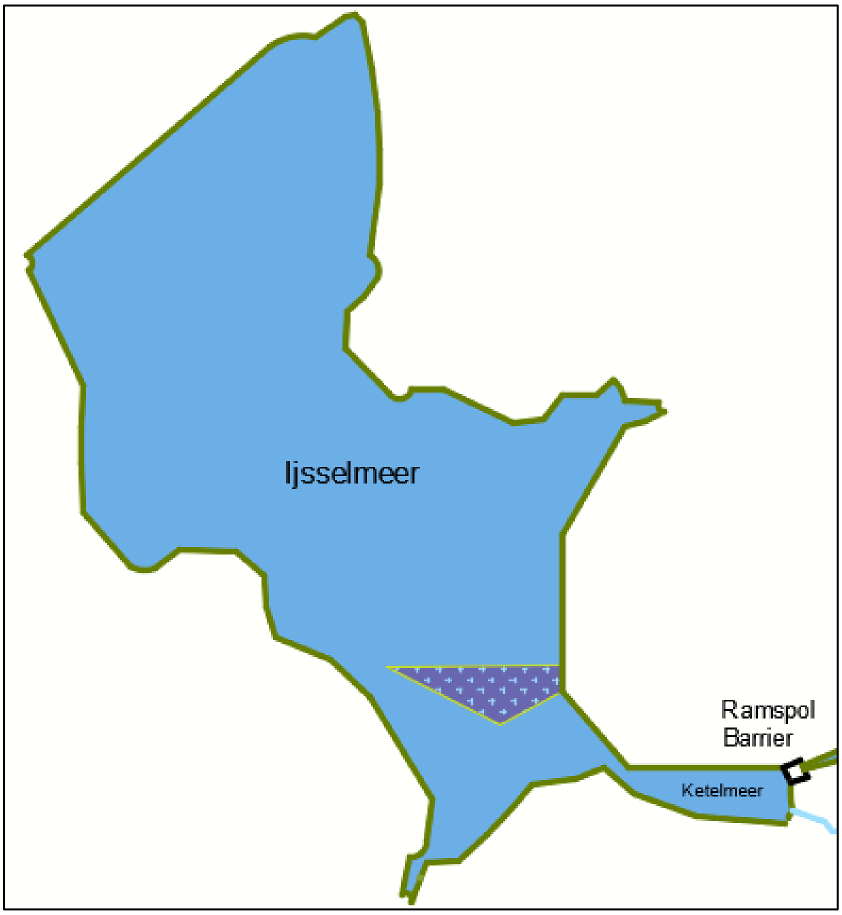


Figure 11 Improvement 9: Vegetation area, Improvement 10: Changing the bottom roughness 11: Wetland Improvement

Improvement 10: Changing of bottom roughness

The roughness of the bottom can affect the velocity profile of the water column. In a smooth bottom, the velocity profile of the water column is more uniform, and water moves more quickly near the surface, while in a rough bottom, the velocity profile is more complex, and water moves more slowly near the bottom. This means that a rough bottom can reduce the wind stress acting on the water surface, and therefore reduce the wind set-up.

By altering the roughness of the bottom of an area in IJssel Lake, it is possible to influence the development of waves and reduce the impact of wind set-up. One technique for altering the roughness of the bottom of IJssel Lake is using artificial reefs or structures. These structures can be designed to obstruct the water flow and create eddies and turbulence that disrupt the development of waves. The reefs or structures can be constructed using a variety of materials, such as concrete, rock, or even recycled materials like old tires or fishing nets.

By strategically placing these structures in areas of the lake that are most susceptible to wind set-up, it is possible to reduce the impact of this phenomenon and protect the surrounding areas from flooding and erosion. In addition, these structures can provide habitat for fish and other aquatic organisms, improving the overall health of the lake ecosystem.

Improvement 11: Wetland

Creating a wetland, low lying area, is following the approach of creating a reclamation area, however in that case the wetland is provided to nature and the ecosystems. The wetlands can absorb the wind-wave energy and stand as a natural obstacle to the development of the wind set-up phenomenon. Wetlands have more benefits for the water systems since it can improve the overall health of the lake.

3.2.2 Reducing water levels in Zwarte Lake

Zwarte Lake is a considerable small and shallow lake located in the Netherlands and is connected with the IJssel Lake. The low-lying areas near Zwarte Lake are vulnerable to flooding. In fact, during high water events some of the low-lying areas are inundated in order to prevent flooding of other areas. The flooding in the lake is getting triggered by the storm surge from the North Sea. When this happens, the Ramspol Barrier closes to prevent high water levels in Zwarte Lake. At the same time, the water level in Zwarte Lake can rise because of high precipitation, high river discharge and the development of wind set-up into Zwarte Lake.

By reducing the water level in Zwarte Lake, the flood risk of the dikes associated with the lake will be decreased. This can be achieved either by reducing the initial water level of Zwarte Lake, or by increasing the water capacity in the basin.

Improvement 12: Pump water out of Zwarte Lake through Ramspol Barrier (outflow discharge)

Pumping water out of Zwarte Lake (Figure 12) through a pumping installation at the Ramspol Barrier would, at a constant rate, lower or maintain the water level in the lake. More specifically, by pumping water from Zwarte Lake into Ketel Lake the volume of water which is getting accumulated behind Ramspol Barrier will be decreased and as so the increase of water level in the lake.

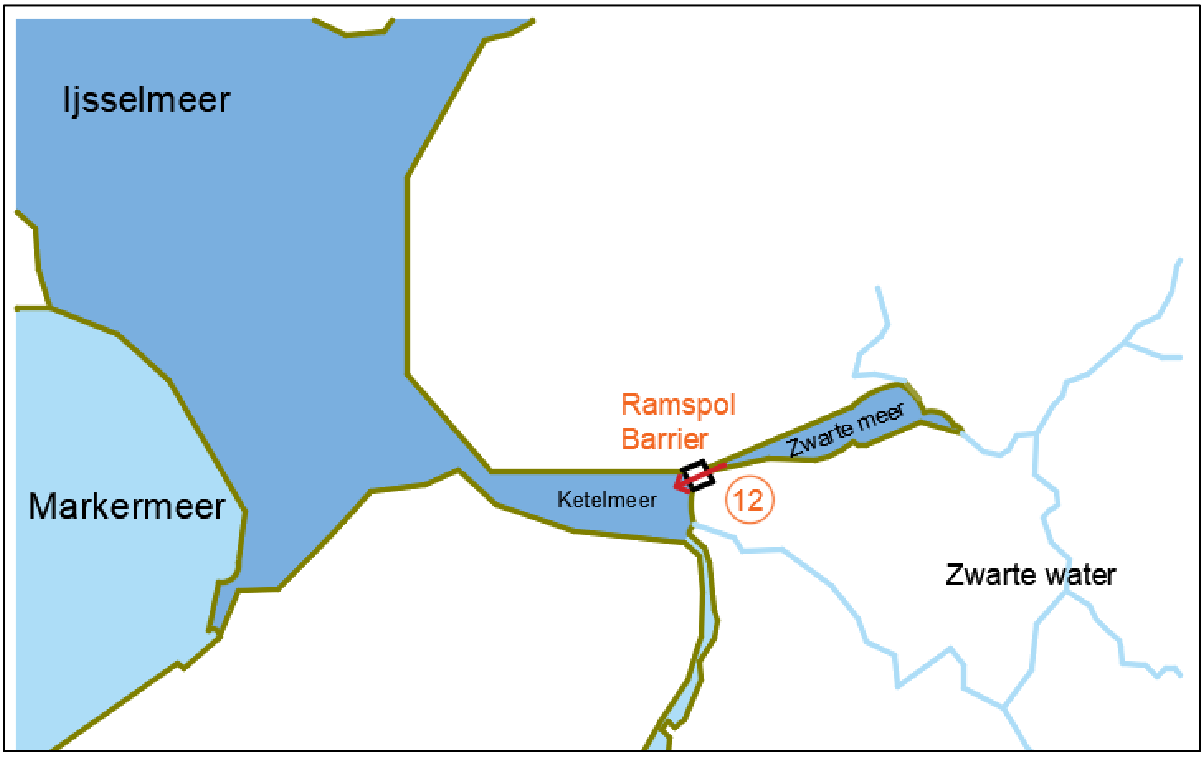


Figure 12 Improvement 12: Pump water out of Zwarte Lake through Ramspol Barrier (outflow discharge)

Improvement 13: Extension of Vollenhover channel to IJssel Lake (outflow discharge)

This improvement, proposing the connection of Zwarte Lake with IJssel Lake, through a channel. An extension of the Vollenhover channel to connect the Zwarte Lake directly with the northern part of IJssel Lake, would influence the water level in Zwarte Lake. The inflow of water in Zwarte lake from Zwarte Water River, could be partially balanced out by the water outflow through the extension of

Vollenhover channel. The channel which was designed is an extension of Vollenhover channel and can be seen in the following (Figure 13). Its main function is to relief Zwarte Lake of excess water load. The installation of a pumping station can be also a part of the improvement.

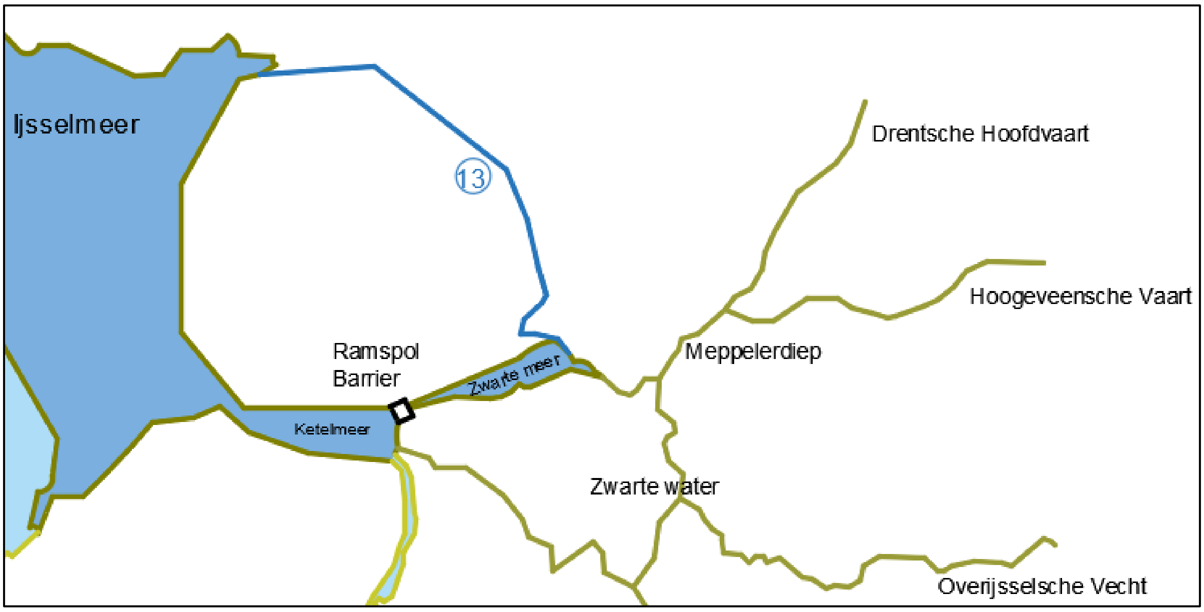


Figure 13 Improvement 13: Extension of Vollenhover channel to IJssel Lake (outflow discharge)

Improvement 14: Size-up Zwarte Lake

Sizing up the Zwarte Lake (Figure 14), is an improvement which is focussing on providing more space for the water discharge reaching the Zwarte Lake from Zwarte Water River. Currently, flood plains exist in Zwarte Lake. By extending the floodplains or sizing up Zwarte Lake, a lower water level can be achieved. In that way the discharge capacity of the lake can be increased, means lower water level in the lake and consequently lower flood risk.

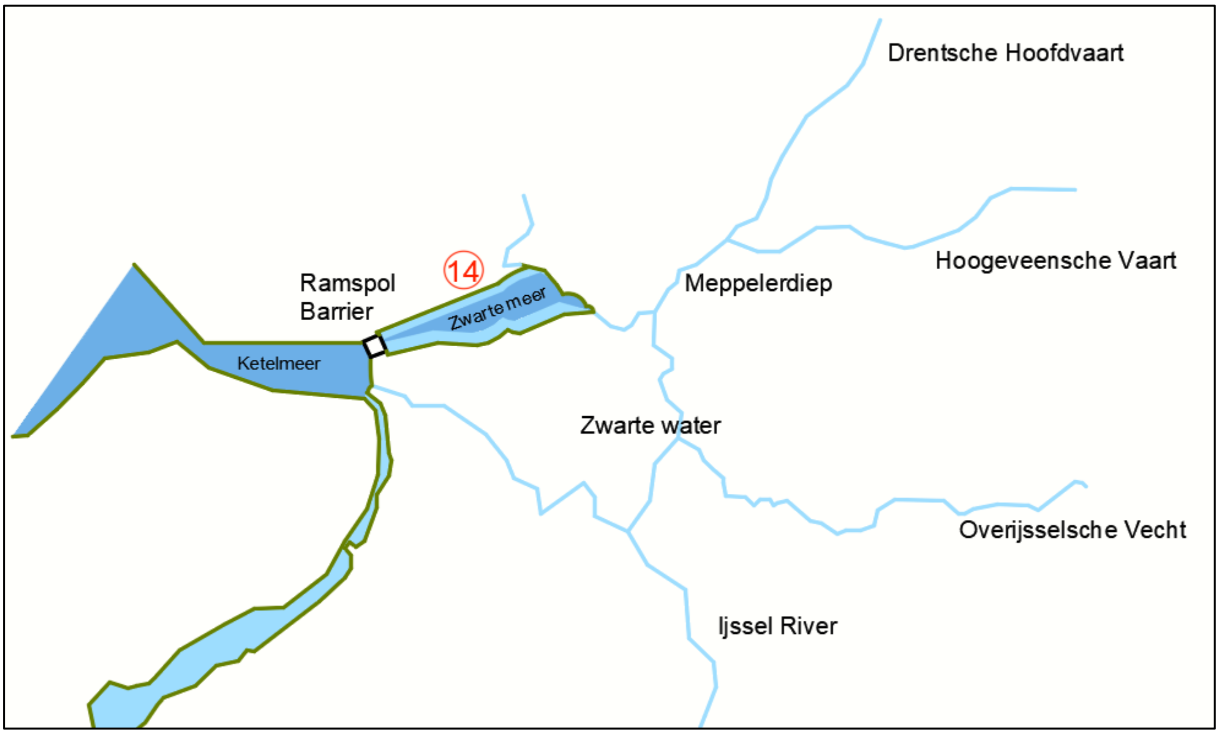


Figure 14 Improvement 14: Sizing up Zwarte Lake

Improvement 15: Faster closure procedure of Ramspol Barrier

In the current situation, the closure procedure of Ramspol Barrier starts when the water level to the barrier has been measured equal to NAP + 0.5 m and takes 1 hour. However, during the process of closing, the water level can rapidly rise to both sides of the barrier. That means that by the time that the barrier is completely closed, the water level in Zwarte Lake is considerably higher (NAP + 0.6 m). If the closing procedure lasts less than an hour, then the lake would have more time until reaching high water levels.

Improvement 16: Closing of Ramspol Barrier at a lower water level

If the closing procedure at the Ramspol Barrier were to start for a lower water level than NAP + 0.5m, it would mean that the barrier would be closed earlier in response to rising water levels in the IJssel Lake. This could potentially help to limit the rise in water level in the Zwarte Lake by preventing more water from entering the lake. Also, in a case of a long-lasting storm event, this lower initial water level in Zwarte Lake is providing with more water capacity in Zwarte Lake.

However, it is important to note that closing the barrier too early could also have negative consequences. For example, if the barrier is closed too soon and the water level in the IJssel Lake continues to rise, it could lead to higher water levels on the other side of the barrier, which could pose a risk to other areas. Moreover, closing the barrier for a lower water level means also more frequent closing procedures and thus more limitations to the navigation.

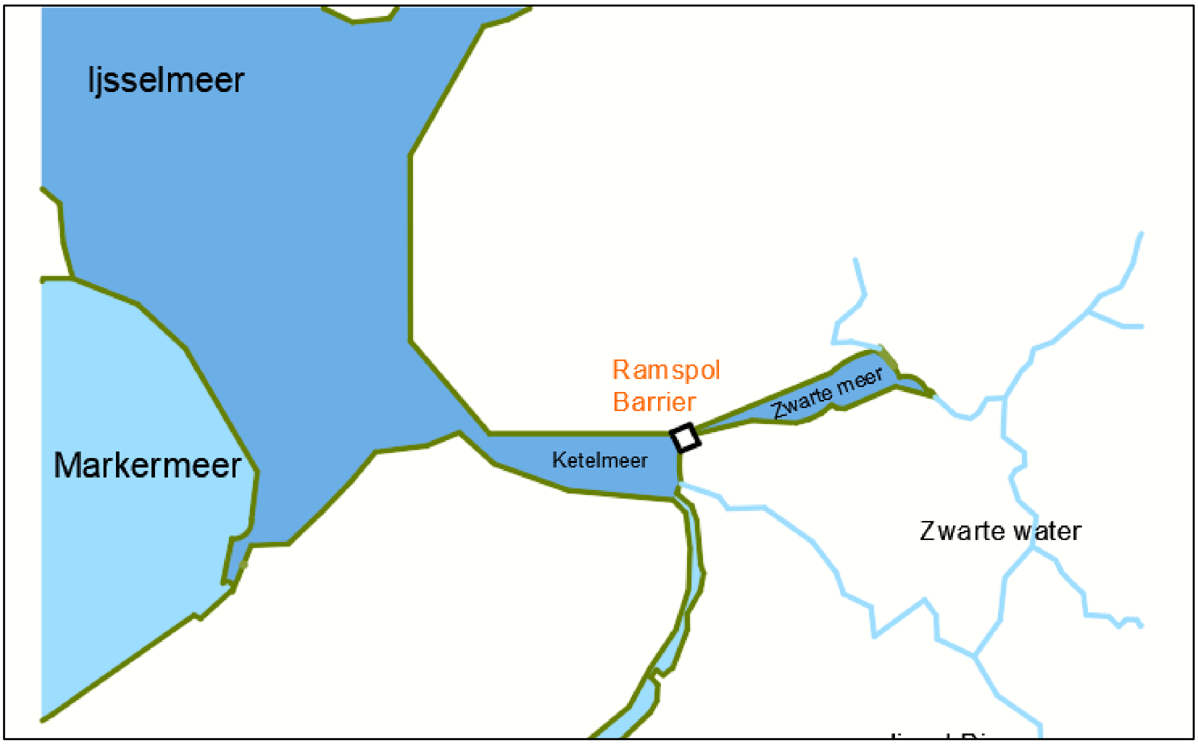


Figure 15 Improvement 15: Faster closure procedure of Ramspol Barrier and Improvement 16: Closing of Ramspol Barrier at a lower water level

3.2.3 Creating additional space for water discharge in river branches

The improvements belong in this category, aim to increase the capacity of the river system to accommodate higher water volumes and reduce the risk of flooding in the area of interest. This could be achieved by either increasing the height of the existing dikes, or by one of the “Room for the River” approaches. There are several measures which can be taken to mitigate the floods which belong to the “Room for the River” approach. The purpose of this approach is to provide enough room for the river to flow even in high discharge situations, without inundating the surrounding areas. The measures that can be applied depend on the location of the river in question. Key measures of the “Room for the River” program include:

- Deepening the main river channel
- Temporary water storage areas
- Creation of a secondary channel
- Dike relocation
- Creation of floodplains (Improvement 19)
- Lowering groynes
- Reinforcing dikes (Improvement 17)

Another room for the river concept is the river widening. Instead of creating more space by using higher vertical structures for the river, this approach is a horizontal expansion of the rivers.

Improvement 17: Increase the height of the dikes

This improvement considers the rise of the height of the dikes (Figure 16). This approach aims to increase the flood protection level by increasing the height of the existing dikes. This is necessary in order for the dikes to be able to withstand higher water loads.

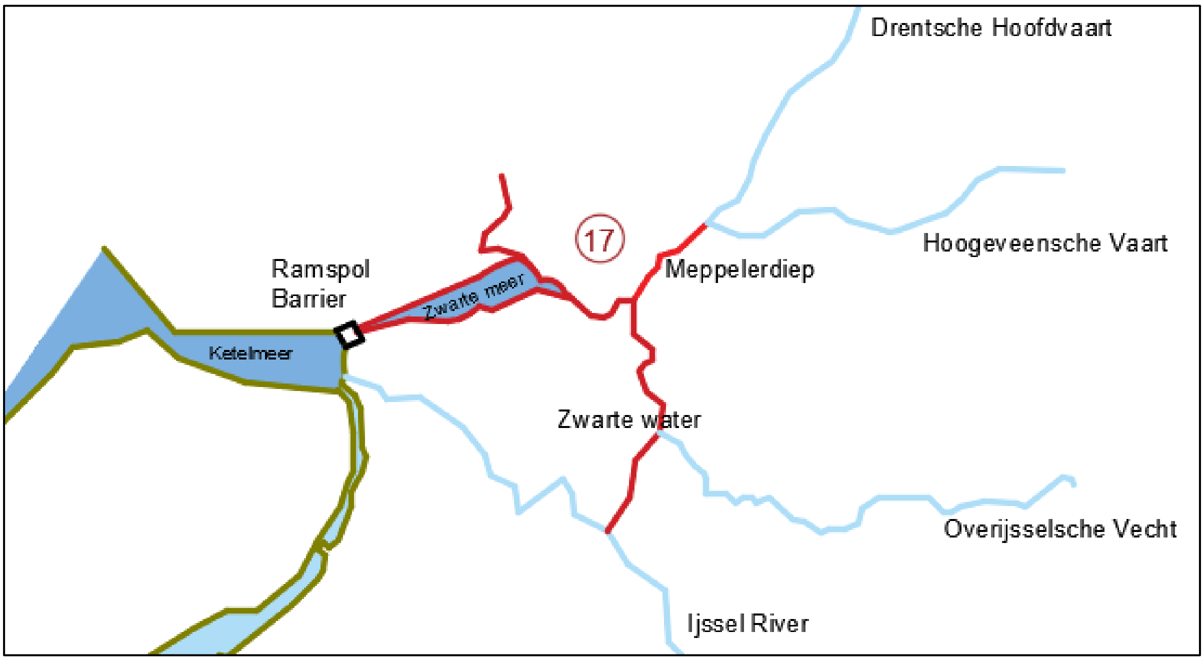


Figure 16 Improvement 17: Raising the dikes

When the area of interest experiences high water discharge from the Vecht river, the stability of the dikes along the river branches is called into question. Some of these structures are old and have only been maintained to meet regulations since their construction. However, with climate change causing higher river discharges, the reliability of the dikes is threatened. More specifically, the dikes of Zwarte Water, Mappelerdiep, Overijsselsche Vecht and Vollenhover channel, river branches and the dikes around Zwarte Lake would achieve a higher protection lever against flood if they were higher. This Improvement specifically suggests raising the dikes in Zwarte Lake, Zwarte Water River, Meppelerdiep, and Vollenhover channel to improve the flood safety of the area (Figure 16). It is not advisable to raise the dikes further upstream to the river, as the area that is most affected by the high-water levels in Zwarte Lake is the region near the lake itself.

Improvement 18: River widening (room for the river approach)

This improvement concerns the widening of the river branches close to Zwarte Lake (Figure 17). This involves creating more space for the river to spread out during high water levels, which means lower water levels in the river branches and thus the flood risk is being reduced. This can be achieved through measures such as removing obstacles, dredging the riverbed, and/or relocating infrastructures such as roads or buildings.

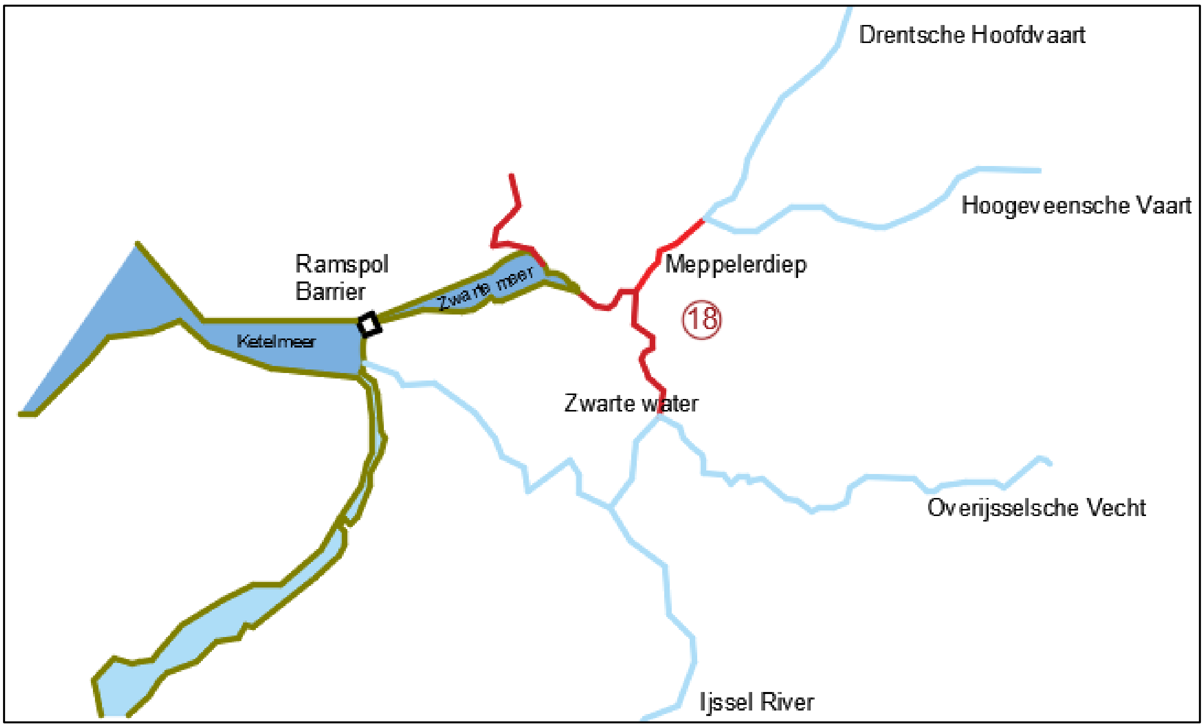


Figure 17 Improvement 18: River branches widening

Improvement 19: Extension of the flood plains (room for the river approach)

A similar approach with Improvement 18: River widening, is the creation of wider and lower floodplains along the river branches. By creating floodplains along the river, the main channel of the river will remain the same but more room will be given to the river in order to handle large water discharge, when this is necessary.

3.2.4 Increase the reliability of the Ramspol Barrier

Improvement 20: Increase the reliability of Ramspol Barrier

The barrier's reliability is a measure of its ability to operate as intended and effectively prevent flooding during high water events. In fact, improving the reliability of the barrier would mean decrease of the flood risk, especially for high return periods when multiple closings of the barrier are considered. If the reliability of the Ramspol Barrier were to increase, it would mean that the barrier is less likely to fail or malfunction during a flood event. The probability of failure for each storm surge barrier differs. This is happening because of their uniqueness.

3.2.5 Combination of Improvements

By combining multiple improvements for the water system, a more effective solution could occur.

4. Assessment method

Nowadays, the deep understanding of the complex physical water processes and the innovative techniques, assist in the development of numerous solutions for the engineering problems. The decision of the most favourable improvement for each water system is not easy to make, considering the uniqueness of the water systems and the large array of possible interventions. As discussed in Chapter 4, a total of twenty improvements have been designed in order to increase the reliability of the flood protection system behind Ramspol Barrier. However, in the early stages of decision making, it is important for the engineers to have reliable tools in hand, to rapidly assess and narrow down the possible solutions, a procedure which is called screening. In that way, only the most promising solutions will be further investigated and modelled, considering that the detailed assessment is usually a costly and time-consuming procedure and requires the collection of data.

The selection method which is proposed in this study consists of 2 stages of assessment (Figure 18). The first stage is a rapid assessment and selection (screening) method, aiming to point out the most promising improvements. The second stage is a more detailed method, aiming to highlight the most beneficial improvement for the water system. In both assessments, first stage (screening) and second stage (detailed), the proposed improvements will be assessed considering three main important decision-making aspects. Those aspects are: (1) the decrease of water level maximum, (2) the cost, and (3) the ecological impact of the improvements. Finally, the uncertainty that a rapid decision-making method introduces, will be also considered.

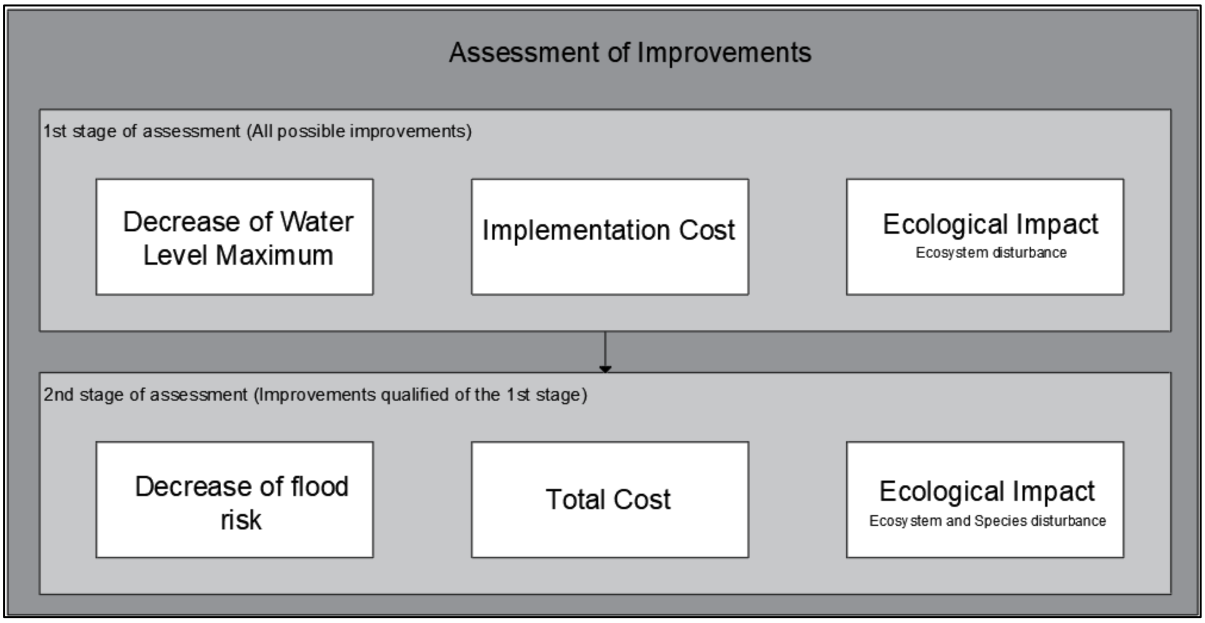


Figure 18 Structure of the selection method

This study has its focus on the creation of a rapid selection method. Thus, only the first stage of assessment will be executed. A method recommendation will be provided for the second stage of assessment, but this will not be handled from this thesis.

4.1 First stage of assessment

In the first stage of assessment, from twenty interventions which have been designed, only the most prevailing will be selected in order to further be investigated in a more detailed assessment (second stage of assessment). Following, the developed method will be discussed.

4.1.1 Screening method

The screening method that was developed has its foundation on three decision making aspects: (1) the reduction of water level maximum, (2) the cost and (3) the ecological impact. The first assessment stage must provide reliable and still rapid results. To succeed this, for assessing the influence of a measure on the expected water level the decrease in water level maximum will be estimated. For the assessment of the cost, the implementation cost will be calculated. Respectively, for the qualitative estimation of the ecological impact, the influence of the interventions on the ecosystems will be identified.

Grading and weighing of the assessment aspects

By calculating the influence for the three aspects explained above, a number of interventions will be more beneficial for the decrease of water level maximum, the cost or the ecological impact. In order to approach the interventions which are more beneficial for the combination of the three aspects, a grading and weighing method will be used. In this study, the aspect of the ecological impact could be used in order to eliminate those improvements, which have a very negative impact on the ecosystems. However, an eliminating technique in a rapid screening method, could lead to the elimination of an improvement which is beneficial for both the decrease of water level maximum and cost aspects. Considering the high uncertainty of the first stage of assessment, this could possibly have as a consequence the elimination of an improvement which in the second stage of assessment would not give “very negative” but “negative” impact for the ecosystems. Thus, it has been decided to use a “grade and weight” technique.

First, after the estimation (quantitatively or qualitatively) of the influence of the improvements, a grade will be given in the range of 1 to 9 for each assessment aspect. The grade of 1 shows a low/negative impact whereas a grade of 9 shows a large/positive impact. For the decrease of water level maximum, a grade=9 will be given for the interventions which cause the highest water level decrease and a grade=1 for the lowest water level decrease. An intermediate grade will be given for the intermediate values of water level decrease, using the linear interpolation technique, for calculating the intermediate values. For the cost aspect, a grade=9 will be given for the lowest cost intervention and a grade=1 for the highest cost (Table 4). Finally, for the ecological impact aspect, a grade=9 will be given for the lowest “ecological sign” and a grade of=1 for the highest “ecological sign” (Table 5).

Table 4 Grading for the assessment aspect cost (per cost range)

Grade	Cost
1 - 2	50,000 – 10,000
2 – 3	10,000 – 5,000
3 – 4	5,000 – 1,000
4 – 5	1,000 – 500
5 – 6	500 – 100
6 – 7	100 – 50
7 – 8	50 – 10
8 – 9	10 – 0

Table 5 Grading of the assessment aspect, ecological impact (per "ecological sing")

Grade	Ecological sign (Net value)
1	-7
2	-6
3	-5
4	-4
5	-3
6	-2
7	-1
8	0
9	1

Moreover, a weight needs to be given to each one of the assessment aspects. This can vary when one individual is using the method recommended in this study, by giving the weight suitable for each decision maker. In this study, the three decision making aspects do not have the same importance for the decision making and thus, weights will be given for the decrease of water level maximum, the cost and the ecological impact. The weights decided are: (0.5) for the decrease of water level maximum, (0.3) for the cost and (0.2) for the ecological impact aspect. The ability of a flood defence strategy or project, to provide with safety against flooding is of a great importance, since usually and this applies for this study, the flood defences protecting the inland (infrastructure, residents' property and lives) against damage. Thus, a weight of 0.5/1.0 will ensure that the aspect of the decrease of water level maximum will have a high influence on the decision screening. By giving the weight of 0.3/1.0 and 0.2/1.0 to cost and ecological impact respectively, implies that the cost is more important in the decision making. However, it is of high significance that the ecology is taken into account in this assessment approach even with a low weight, since this aspect was traditionally not always into the decision-making procedure. Finally, this approach of decrease of water level maximum/cost/ecology – 0.5/0.3/0.2, is not the only one that will be examined in this study. In order to understand better the sensitivity of the approach, more combinations of the three grades will be tested.

For each improvement the grade estimated for each aspect will be multiplied with the related weight. By adding up the three values (grade*weight) for each aspect, an assessment value will be derived. The improvements which will achieve the higher assessment value will be selected for the next stage of assessment. An example with random weight values can be found in the following Table 6.

Table 6 Example with random weight values

	Decrease of water level maximum		Cost		Ecologic Impact		Assessment Value
	Grade	Weight	Grade	Weight	Grade	Weight	
Intervention x	7	0.5	6	0.3	4	0.2	7.1
Intervention y	6	0.5	7	0.3	8	0.2	6.7

Finally, the screening approach, from its nature (fast selection of improvements) introduces uncertainties to the method. The uncertainty will be included in the method for more realistic results. This will be further discussed in the following chapters.

Selection of improvements

After estimating the assessment value for each improvement, the improvements that will score the highest grade will be selected for the second stage of assessment (detailed assessment). The number of improvements that can be selected depends on the budget available for conducting in depth analysis of the improvements. In this study it has been decided to select the 5 most promising improvements, those with the highest assessment score. Since this fast assessment and selection method introduces some uncertainty, it is wise to not only select a very small number of improvements. For that reason, it has been decided to select 25% of the improvements.

Improvements that will not be handled (Wind set-up formula)
After research on the wind set-up formula, it became clear that some parameters have been derived empirically and through comparing prediction with field observations. More specifically, it concerns the friction constant of the wind set-up formula. This constant includes between others the influence of the bottom friction to the wind set-up phenomenon. Although it is clear that the bottom friction has an influence on wind set-up which can be applied through a different friction constant this will not be covered in this study. However, it would possibly have positive results and it could be further researched. The improvements which belong in this category are the improvements which are relevant with changing the bottom friction. More specifically, Improvements 10. Different bottom roughness and 11. Wetland area.

Improvement that will not be handled (Normal flow depth formula)
The improvement of river widening has only temporary results to the water levels at the city of Zwolle. When a parameter of the river is changing as the width of the river, there is an instant decrease of the water level. However, in time, the river is trying to reach a new equilibrium situation which in the case of the widening is associated with aggradation of the bed off the widened part of the river. When the new equilibrium will be finally reached, after 70-100 years, the new relative (measured from NAP) water level of the river will be equal with the one before the implementation of the improvement. Moreover, the higher river discharges and the more intense storms which are expected for the following years, as a consequence of the climate change, imply that in the long term the improvement which proposes a wider river would not be beneficial. Additionally, interventions to a certain reach of a navigable river, would cause problems to navigation even by back water effects or steps which will take place because of the sedimentation in the widened part. Finally, the aggradation of the riverbed can cause problems with irrigation. For that reason, it has been decided to not further investigate the influence of this Improvement (18. River widening).

4.1.2 Decrease of water level maximum

The decrease of water level maximum in this stage of assessment will be handled by calculating the decrease of water level in the water system and by increasing the height of the dikes which have to withstand high water levels. The system under research is a complex one and the decrease in water level can be achieved by a number of interventions, as discussed in Chapter 2 and Chapter 3 (Figure 19).

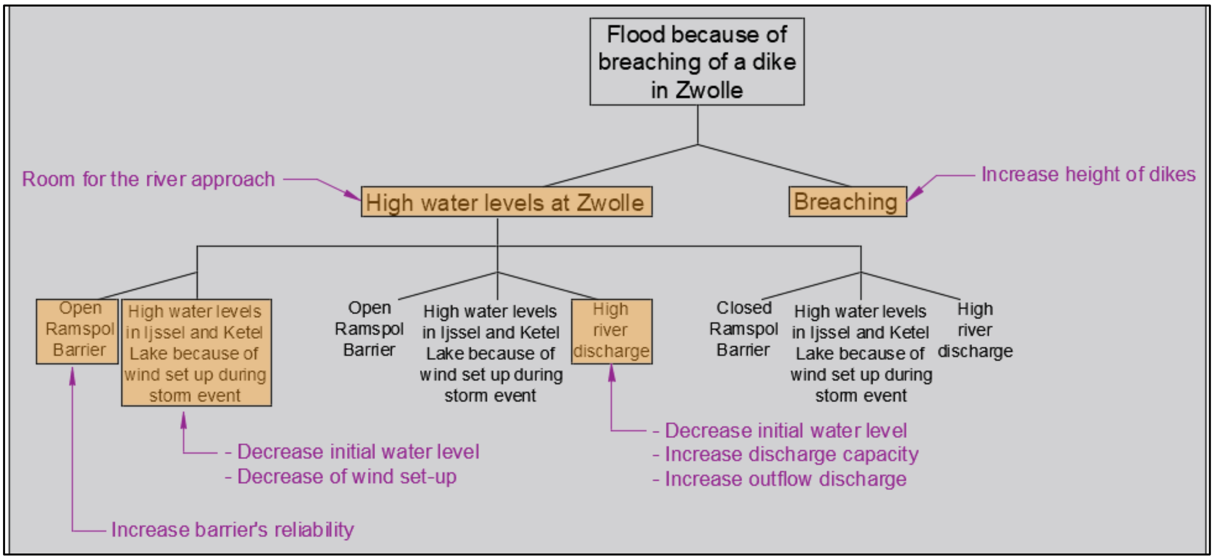


Figure 19 Interventions leading to reduction of water level

In order to maintain a low water level in IJssel Lake, 11 interventions will be assessed and compared. Those interventions aiming to:

- Decrease the initial water level in IJssel Lake
- Decrease of wind set-up phenomenon.

To maintain a low water level in Zwarte Lake and in Zwarte Water River 5 interventions will be assessed and compared which are aiming to:

- Decrease the initial water level in Zwarte Lake
- Increase the discharge capacity of the lake
- Increase the outflow discharge from the lake

To maintain a low water level near Zwolle, 2 interventions will be assessed and compared which are aiming to:

- Increase the discharge capacity of the river branches

Finally, to achieve low water levels in Zwarte Lake and consequently in the city of Zwolle:

- Increase in the reliability of Ramspol Barrier will be considered.

To quantify the influence of the interventions to the water system, 3 formulas will be used. The “wind set-up” formula will be used for the aiming to decrease the wind set-up phenomenon. A “lake-level” formula will be used for the improvements aiming to reduce the water level in Zwarte Lake. A “normal flow depth” formula will be used for the improvements considering a different cross section of the river. For the increasing of the barriers reliability improvement, the results will be derived directly from Hydra-NL model.

Correlation factor

As discussed, the designed improvements do not concern the same location in the water system. The first category concerns improvements in IJssel Lake, the second category improvements in Zwarte Lake and others have been designed directly for the point of. However, all of them aim to improve the high-water level situation near the city of Zwolle. Respectively, the formulas which will be used for the calculation of the decreased water level maximum, give results, for locations (calculation points) away from the “calculation point of interest” in Zwolle. For that reason, a correlation factor will be used in order to transform the results from different calculation points to the “calculation point of interest”. For deriving this factor, Hydra-NL has been used to calculate and compare the water levels in the different points with the water level at the “calculation point of interest” (Figure 20). Then, the correlation factor can be applied to the calculated water levels downstream from the “calculation point of interest”, in order to derive the water levels that the improvements are causing.

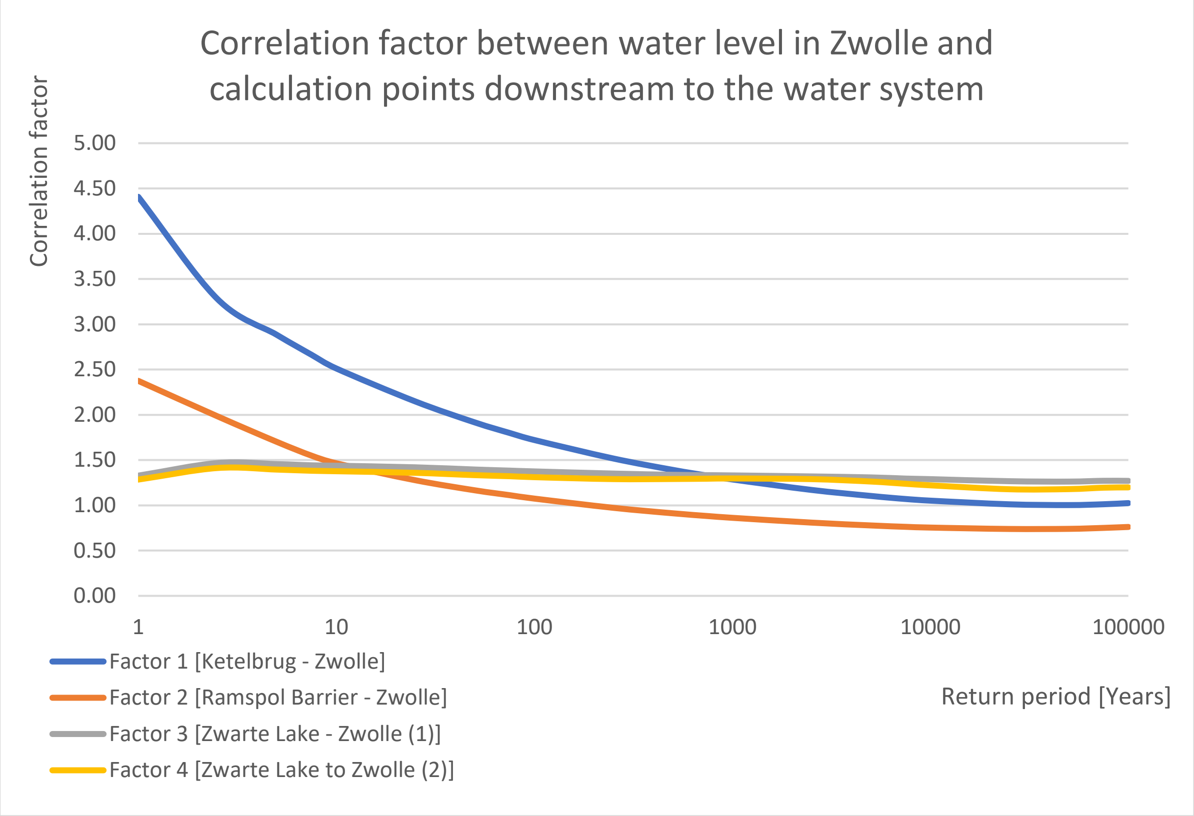


Figure 20 Correlation factor between the calculation point and the "calculation point of interest"

It is expected that by using the correlation factors for the improvements that influence the wind set-up in IJssel Lake (Improvements 1-11), the method will overestimate the decrease in water level maximum in the city of Zwolle. This is expected, since the aforementioned improvements only can influence the wind set-up in Lake IJssel and not in Zwarte Lake. However, the wind set-up in Zwarte Lake is of great importance because the lake has a small depth of around 1,0 m and thus increase in the level of the lake because of the wind set-up can be observed even for low wind speeds. For that reason, a higher uncertainty level has to be applied. For the improvements 12-16, in Zwarte Lake, this uncertainty is not expected.

Handle the uncertainty

In order to take into account the uncertainty, the types of uncertainty that each improvement will be addressed. Following that the improvements will be given an uncertainty level (very low, low medium, high and very high), (Table 7). Each level of uncertainty is connected with an increase of the estimated water level (2.5, 5.0, 7.5, 10 and 15% respectively), (Table 8). In that way the uncertainty will be adjusted in the water levels before the grading of the improvements.

Table 7 Level of uncertainty per improvement and reasoning

	Improvement	Uncertainty level	Reasoning
1.	Breakwaters	High	i. Hydra-NL model uncertainty. ii. Simplicity of wind set-up formula. iii. Wave set-up has been not considered, if existing. iv. Possible wind set-up passing through the edges of the breakwater has not been considered v. Uncertainty because of the correlation factor
2.	Afsluitdijk II	Medium	i. Hydra-NL model uncertainty. ii. Simplicity of wind set-up formula. iii. Wave set-up has not been considered, if existing. iv. Uncertainty because of the correlation factor
3.	Land reclamation	Medium	i. Hydra-NL model uncertainty. ii. Simplicity of wind set-up formula. iii. Wave set-up has not been considered, if existing. iv. Uncertainty because of the correlation factor
4.	Outflow channel (groynes)	High	i. Hydra-NL model uncertainty. ii. Simplicity of wind set-up formula. iii. Wave set-up has not been considered, if existing. iv. Possible new parameters because of the closing of Ketel Lake (IJssel River discharge accumulating into Ketel Lake) v. Uncertainty because of the correlation factor
5.	Ramspol Barrier II	High	i. Hydra-NL model uncertainty. ii. Simplicity of wind set-up formula. iii. Wave set-up has not been considered, if existing. iv. Possible new parameters because of the closing of Ketel Lake (IJssel River discharge accumulating into Ketel Lake) v. Uncertainty because of the correlation factor
6.	Increase Afsluitdijk pump capacity	Medium	i. Hydra-NL model uncertainty. ii. Simplicity of wind set-up formula. iii. Wave set-up has not been considered, if existing. iv. Probability of failure of pump station. v. Uncertainty because of the correlation factor
7.	Pump installation at Marker Lake	Medium	i. Hydra-NL model uncertainty. ii. Simplicity of wind set-up formula. iii. Wave set-up has not been considered, if existing. iv. Probability of failure of pump station. v. Uncertainty because of the correlation factor
8.	Lake deepening	Medium	i. Hydra-NL model uncertainty. ii. Simplicity of wind set-up formula. iii. Wave set-up has not been considered, if existing. iv. Uncertainty because of the correlation factor
9.	Vegetation area	Very High	i. Hydra-NL model uncertainty. ii. Data obtained for the reduction parameter Cm, depends on observation during 1 storm in a different lake. iii. Uncertainty because of the correlation factor
12.	Pump installation at Ramspol Barrier	Low	i. Hydra-NL model uncertainty. ii. The characteristics of the lake (depth, area [km^2]) have been /averaged simplified. iii. Simplicity of lake-level formula
13.	Extension of Vollenhover channel	Low	i. Hydra-NL model uncertainty. ii. The characteristics of the lake (depth, area [km^2]) have been /averaged simplified. iii. Simplicity of lake-level formula
14.	Size up Zwarte Lake	Low	i. Hydra-NL model uncertainty. ii. The characteristics of the lake (depth, area [km^2])

			have been /averaged simplified. iii. Simplicity of lake-level formula
15.	Faster Ramspol's Barrier closure procedure	High	i. Hydra-NL model uncertainty. ii. The characteristics of the lake (depth, area [km^2]) have been /averaged simplified. iii. Simplicity of lake-level formula iv. Probability of failure of the barrier v. The lower water level leads to higher wind set-up
16.	Decrease of the closing limit of NAP + 0.5 m	Medium	i. Hydra-NL model uncertainty. ii. The characteristics of the lake (depth, area [km^2]) have been /averaged simplified. iii. Simplicity of lake-level formula iv. The lower water level leads to higher wind set-up
17.	Raising of the dikes	Very low	Only Hydra-NL model uncertainty.
19.	Flood plains	High	i. Hydra-NL model uncertainty. ii. Initial situation with no floodplains has been considered but in some parts of the river they already exist.
20.	Increase the reliability of Ramspol Barrier	Very low	Only Hydra-NL model uncertainty.

Table 8 Increase of water level per level of uncertainty

Level of uncertainty	Increase of the calculated water level (%)
Very Low	2.5
Low	5
Medium	7.5
High	10
Very High	15

Additionally, the uncertainty could have the opposite results, and some improvements might prove to be more beneficial than expected. However, for being on the safe side of the calculations, only the increase of the calculated water levels will be considered.

Wind set-up formula: The wind set-up formula is well validated in this study by using Hydra-NL the national tool for the assessment of the flood defences in the Netherlands and thus the results it provides are reliable. The validation of the wind set-up formula in Ketel Lake is not as reliable as the validation of the formula in IJssel Lake. This happens because Hydra-NL is also taking into account the discharge from IJssel River which outflows into the lake. Moreover, by considering a closed Ketel lake for improvements 4 and 5, outflow channel and Ramspol Barrier II respectively, the water from IJssel River would accumulate into the lake leading to higher water levels than the calculated. For that reason, the wind set-up formula will not be used for calculating the water levels. Instead, the rise of water level because of the set-up in IJssel Lake (Ketelbrug) will be deducted from the Hydra-NL calculated water levels. Still some uncertainty has to be taken into account. The different types of uncertainties addressed per improvement can be found in Table 8 above.

Lake-level formula calculation of water over time: The Lake-level formula is difficult to validate with Hydra-NL since several variable parameters and formulas are used for the water level calculation from the model. For that reason, it has been decided to use the formula in order to calculate the decrease in water levels (calculated by Hydra-NL) for a certain period of time (12 hours / Hydra-NL storm time calculation), instead of using the formula for calculating the water levels directly. Still, the characteristics of the lake used for calculations have been averaged or simplified (e.g., choosing a cube shape for the lake representation) and thus some uncertainty needs to be considered.

Normal flow depth formula for river branches: The same approach will be applied, as with the lake-level formula. In that case the calculated from Hydra-NL water levels, will be used in order to calculate the respective discharge corresponds to the current cross section of the Zwarte water river in the area of interest (city of Zwolle). Finally, by using the derived discharge and the new cross section of the river (widen reach, flood plain) the new water levels will be calculated. In that case, an initial situation without floodplains has been considered. In reality, over the reach of the Zwarte Water River, floodplains have been constructed, and thus the calculations are lacking reliability.

Ramspol Barrier reliability: For obtaining the water levels for different return periods because of an increased reliability of Ramspol Barrier, Hydra-NL model will be used. Each model contains uncertainties and even though it will be very low it is wise to be considered.

Uncertainty because of the correlation factor: For transferring the calculated water levels from the calculation points to the "calculation point of interest", correlation factors will be used. However, there is uncertainty and most probably by using this approach there will be overestimation of the decrease in the water level maximum at the "calculation point of interest", city of Zwolle, as previously discussed. For that reason, the Improvements 1-11 will have a level of uncertainty higher than initially calculated.

4.1.2.1 Wind set-up formula

The IJssel Lake is a relatively large lake, with a surface area of over 1100 square kilometres. As such, wind set-up in the lake can be quite significant, with wind-driven currents creating waves and changing the water level over large distances. When intense winds blow across the lake, it can push large volumes of water towards the southeast shore, creating a surge that can inundate low-lying areas and cause considerable damage to properties and infrastructure. The phenomenon of the wind set-up in a lake can be seen in the following Figure 21.

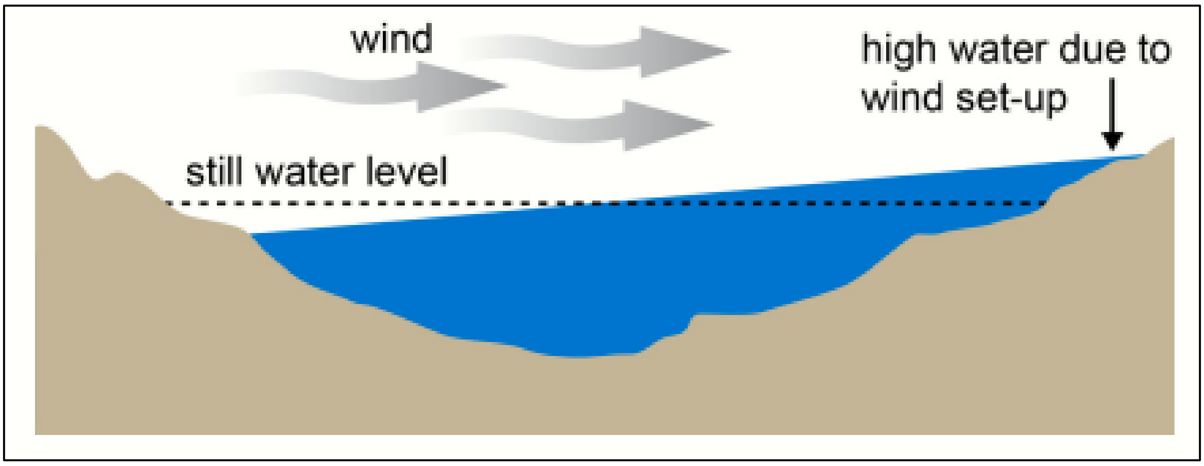


Figure 21 Illustration of wind set-up in a lake [39]

The theoretical development of the wind set-up formula was made by Hellstrom [40], Keulegan [41] and Thijsse [42] between others. While the mechanics of their respective approaches may have differed to some extent, the resulting equations are fundamentally similar giving [38]:

$$\frac{dh}{dx} = \frac{nT_s}{\rho g d} \qquad or \qquad S = \frac{nFT_s}{\rho g d} \tag{1}$$

Where:

h = Surface elevation
x = Horizontal coordinate
dh/dx = Slope of water surface
T_s = Surface shear stress
g = Acceleration due to gravity
ρ = Density of the water
d = Lake depth
S = Set-up, expressed as the difference in water surface elevations at windward and leeward sides of the lake
F = Fetch length
n = Coefficient defined as $n=T_s/T_o$. The coefficient has a value of 1.50 for laminar flow and depends on the theory which is adopted for the turbulent flow. Hellstrom [40] adopting the Boussinesq theory for turbulent flow (n = 1.30 - 1.15 for moderate to large depth). Keulegan [41] used an average value of n=1.25 for laboratory tests.
T_o = Shear stress along the bottom

To derive the wind set-up equation, certain assumptions are required. Those are the assumptions that are applicable for steady state situations, equilibrium case with the set-up is a result of the action of the winds only and that the magnitude of the set-up is significantly smaller compared to the depth of the water body where it occurs.

The surface shear stress T_s, is expressed as a function of the wind velocity:

$$T_s = K\rho_\alpha U^2 \tag{2}$$

Where:

K = A numerical constant ≈ 0.003
ρ_α = Air density
U = Wind velocity

By substituting equation (2) to set-up equation (1), the following equation is schematized:

$$S = \frac{K * n * \rho_\alpha * U^2 * F}{\rho * g * d} \tag{3}$$

For the case that the fetch direction does not coincide with the average wind speed, the use of a resultant shear force in the direction of the fetch is generally deemed best. The resultant force T_s', will then be given by:

$$T_s' = T_s * \cos\vartheta \tag{4}$$

Where:

θ = Angle between the wind and the fetch

Then, the equation for the wind set-up formula will become:

$$S = \frac{K * n * \rho_\alpha * U^2 * F}{\rho * g * d} * cos\theta \tag{5}$$

Steady-state conditions are rarely present in open bodies of water, such as lakes, because wind direction and velocity vary across the water body and change over time. As the wind changes direction, the fetch and average depth along the fetch also change. Therefore, the primary challenge when applying the wind set-up equation to open bodies of water is selecting appropriate average values for the involved parameters. These selected average values must effectively represent the cumulative effect of the actual values.

Marsh-Vegetation effect [38]

After observations of a certain storm event (Lake Okeechobee, Florida, 1950, [38]), it made clear that the vegetation area in a lake produces a damping effect on the set-up, reducing the magnitude of wind set-up due to the increased friction losses occurring as the water moves through the grasses, and to the reduction in surface shear between the water and the wind for those times when the grasses protrude above the water surface. It can be supposed that a correction factor C_m can be applied to the predicted wind set-up.

$$S_o = S(1 - C_m) \tag{6}$$

The correction factor Cm is influenced by the depth over the marshy area and can be expressed dimensionless as a ratio of the depth or the set-up, and a friction length parameter that represents the roughness of the marsh vegetation. In general, as the depth over the marshy area increases, the correction factor Cm will decrease, reflecting the increased damping effect of the vegetation on the water elevation. The friction length parameter of the marsh vegetation affects the magnitude of the damping effect on the water elevation, which depends on the interaction between the water and the vegetation. However, as it can be seen in Figure 22, the influence of the vegetation to the wave set-up is getting near to zero after a certain set-up value. *"This is probably happening because there is enough depth of water over the vegetation for the set-up to take place essentially independently of the vegetation and full set-up results can be observed. This might occur if the bottom return flow occurs above the tops of the vegetation, and the water included within the vegetation is still not a part of the circulatory system of water flow resulting from the set-up. It is possible however, that this correction factor is also dependent on some term embodying the ratio of that portion of the marsh area included in the fetch to the entire length of the fetch. Then when the fetch lies outside the marsh area, after some appropriate lag in time, full set-up would be reached. This postulation may also be an explanation of the sharp change in the correction factor at the higher set-up stage".* (Lake Okeechobee, Florida, 1950, [38]).

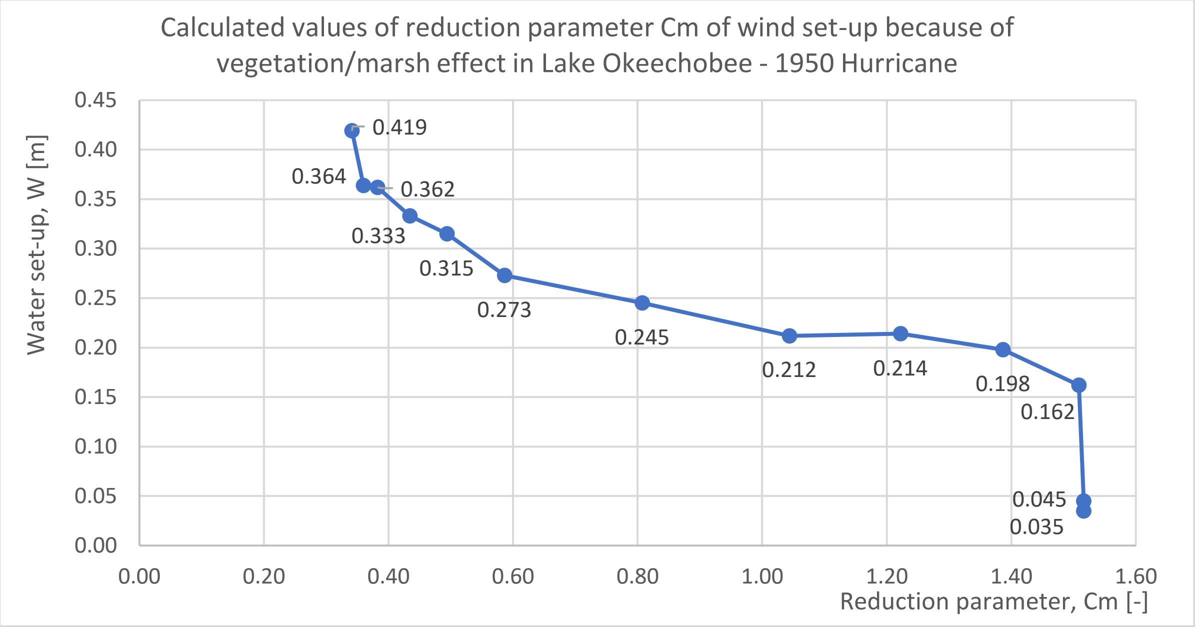


Figure 22 Reduction parameter because of vegetation area (Lake Okeechobee, Florida, 1950, [38])

Finally, since the set-up value (S) is expressed as the difference in water surface elevations at windward and leeward sides of the lake, it can be assumed that for the limiting case of vertical sides, w1=w2=S/2 (Figure 23). Thus, the set-up formula can be then written as follows:

$$w = 0.5\kappa \frac{U^2 * F}{g * d} cos\theta \tag{7}$$

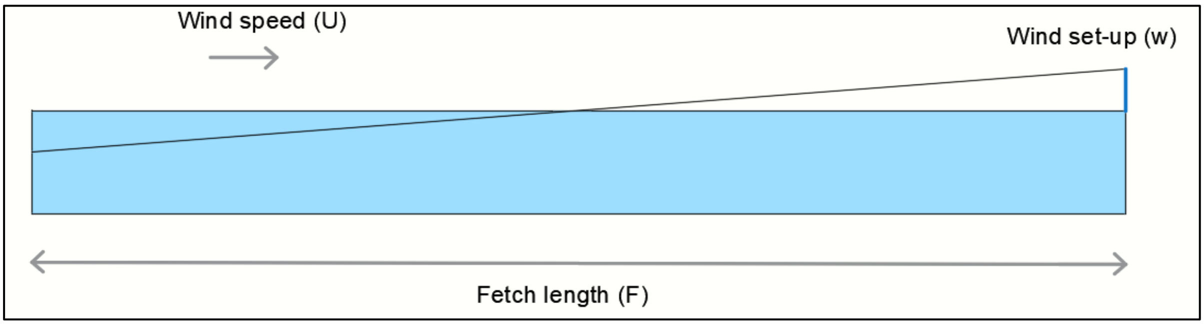


Figure 23 An illustration of a lake experiencing wind set-up, with the wind speed (U), wind set-up (w) and fetch length (F)

Using the wind set-up formula for the different improvements, the water level will be calculated in characteristic places into the IJssel Lake or Ketel Lake, where the increase in water level is mainly caused by the wind set-up phenomenon. The wind set-up at Ketelbrug, will be calculated by using directly the wind set-up formula for all the different improvements which are introducing different initial water level, fetch, depth, or bottom friction. For the calculations, the related wind speeds, initial lake water levels and wind directions will be derived through Hydra-NL model. In that way the calculated water levels will be connected with characteristic return periods. The wind set-up formula will be validated by using the water levels calculated by Hydra-NL model. The validation for the improvements in IJssel Lake gives good results. However, for the case of Ketel Lake, through the validation, it became clear that the wind set-up formula underestimates the rising of water level in the Lake. This is happening because, in the calculation of the rising of the water level in the lake, Hydra-NL takes also into account the discharge outflows into Ketel Lake through IJssel River. For that reason, the water levels at Ramspol Barrier, will be calculated by using the Hydra-NL values, reduced by the wind set-up which would come into Ketel Lake from IJssel Lake if the improvements were not existing. For transferring the calculated water levels at the calculation points to the “calculation point of interest” the correlation factor will be used.

Validation of wind set-up formula at Ketelbrug

For the validation of wind set-up formula at Ketelbrug, the water levels calculated from Hydra-NL has been compared with the water levels calculated with the wind set-up formula, for the 4 important wind directions: west [W], west-northwest [WNW], northwest [NW] and north-northwest [NNW]. First a dike calculation for the water levels has been executed for the dike section “IJsselmeer_8-3a_dk_00582” (Figure 24), for return periods from 1 to 100000.

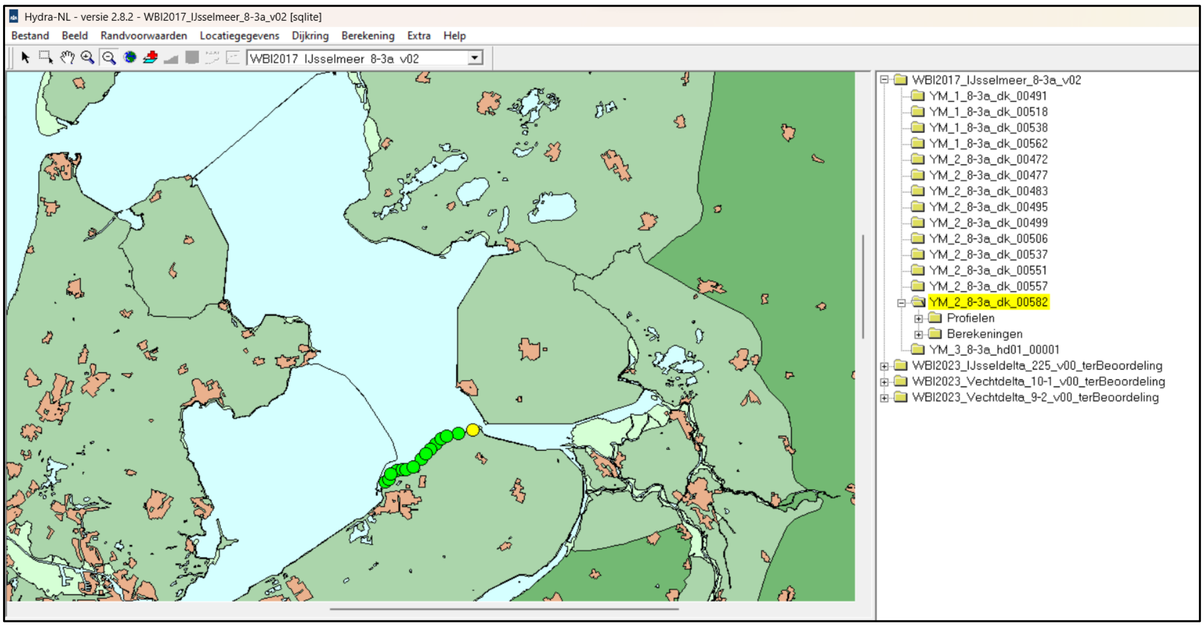
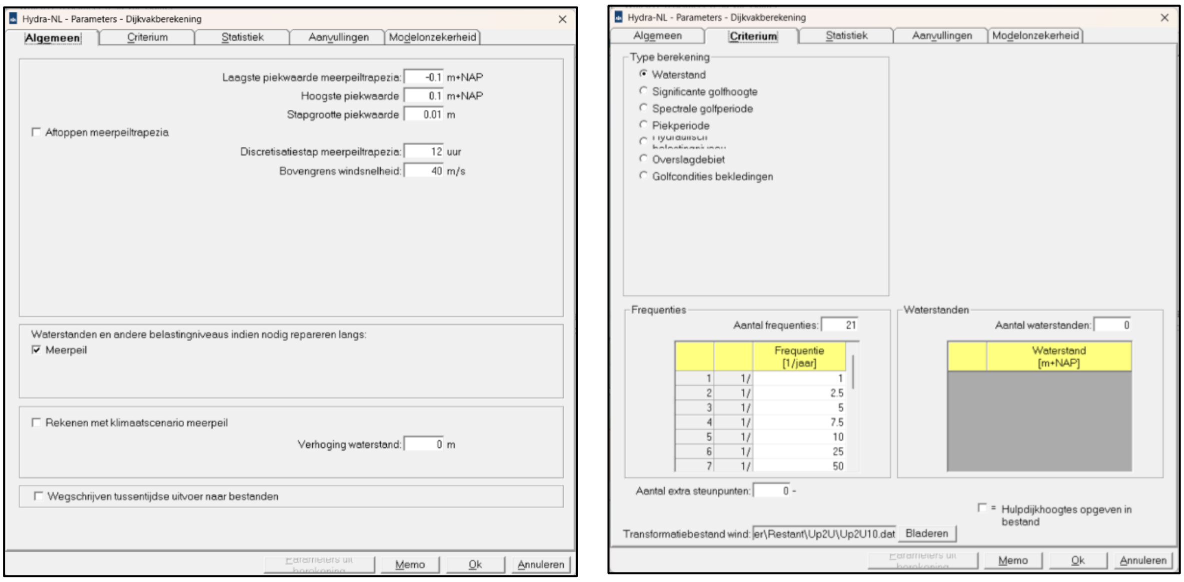


Figure 24 Hydra-NL, calculation point on the map “IJsselmeer_8-3a_dk_00582”, near Ketelbrug

The parameters which have been used for the calculation can be seen in the following Figure 25.



Laagste piekwaarde meerpeiltrapezia: -0.1 m+NAP
Hoogste piekwaarde 0.1 m+NAP
Stapgrootte piekwaarde 0.01 m
☐ Aftoppen meerpeiltrapezia
Discretisatiestap meerpeiltrapezia: 12 uur
Bovengrens windsnelheid: 40 m/s
Waterstanden en andere belastingniveaus indien nodig repareren langs:
☑ Meerpeil
☐ Rekenen met klimaatscenario meerpeil
Verhoging waterstand: 0 m
☐ Wegschrijven tussentijdse uitvoer naar bestanden

Type berekening
● Waterstand
○ Significante golfhoogte
○ Spectrale golfperiode
○ Piekperiode
○ Hydraulisch belastingniveau
○ Overslagdebiet
○ Golfcondities bekledingen

Frequenties
Aantal frequenties: 21

		Frequentie [1/jaar]
1	1/	1
2	1/	2.5
3	1/	5
4	1/	7.5
5	1/	10
6	1/	25
7	1/	50

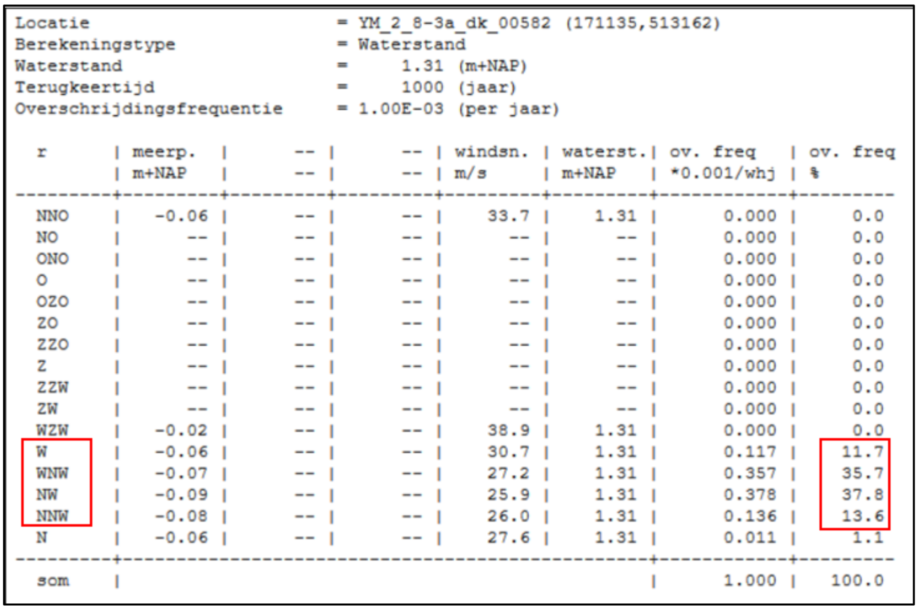
Waterstanden
Aantal waterstanden: 0

	Waterstand [m+NAP]

Aantal extra steunpunten: 0 -
☐ = Hulpdijkhoogtes opgeven in bestand
Transformatiebestand wind: er\Restant\Up2U\Up2U10.dat

Figure 25 Hydra-NL setting the calculation parameters

It was previously understood that the most important wind directions, those that can cause high water levels in the south part of IJssel Lake, would range from N to W. This has been confirmed from the model's results, as can be seen in the following Figure 26. More results for lower and higher return periods can be found in Appendix F). The W, WNW, NW and NNW wind directions have the biggest contribution (percentage), to the development of high-water levels at the calculation point, and thus those 4 wind directions will be used for the calculations.



```
Locatie                         = YM_2_8-3a_dk_00582 (171135,513162)
Berekeningstype                 = Waterstand
Waterstand                      =      1.31 (m+NAP)
Terugkeertijd                   =      1000 (jaar)
Overschrijdingsfrequentie       = 1.00E-03 (per jaar)

  r       | meerp.  |      -- |      -- | windsn.  | waterst.| ov. freq    | ov. freq
          | m+NAP   |      -- |      -- | m/s      | m+NAP   | *0.001/whj  | %
----------+---------+---------+---------+----------+---------+-------------+---------
  NNO     |   -0.06 |      -- |      -- |     33.7 |    1.31 |       0.000 |     0.0
  NO      |      -- |      -- |      -- |       -- |      -- |       0.000 |     0.0
  ONO     |      -- |      -- |      -- |       -- |      -- |       0.000 |     0.0
  O       |      -- |      -- |      -- |       -- |      -- |       0.000 |     0.0
  OZO     |      -- |      -- |      -- |       -- |      -- |       0.000 |     0.0
  ZO      |      -- |      -- |      -- |       -- |      -- |       0.000 |     0.0
  ZZO     |      -- |      -- |      -- |       -- |      -- |       0.000 |     0.0
  Z       |      -- |      -- |      -- |       -- |      -- |       0.000 |     0.0
  ZZW     |      -- |      -- |      -- |       -- |      -- |       0.000 |     0.0
  ZW      |      -- |      -- |      -- |       -- |      -- |       0.000 |     0.0
  WZW     |   -0.02 |      -- |      -- |     38.9 |    1.31 |       0.000 |     0.0
  W       |   -0.06 |      -- |      -- |     30.7 |    1.31 |       0.117 |    11.7
  WNW     |   -0.07 |      -- |      -- |     27.2 |    1.31 |       0.357 |    35.7
  NW      |   -0.09 |      -- |      -- |     25.9 |    1.31 |       0.378 |    37.8
  NNW     |   -0.08 |      -- |      -- |     26.0 |    1.31 |       0.136 |    13.6
  N       |   -0.06 |      -- |      -- |     27.6 |    1.31 |       0.011 |     1.1
----------+--------------------------------------------------+-------------+---------
  som     |                                                  |       1.000 |   100.0
```

Figure 26 Hydra-NL calculation results and important wind directions, return period 1000

After the collection of the results from Hydra-NL, the wind speed "windsn." [m/s] and the initial water level of IJssel Lake "meerp. m+NAP" [m], have been used for the calculation of the wind set-up and water levels to the calculation point with the wind set-up formula for the 4 mentioned dominant wind directions. Following can be seen the parameters used and the calculations for the W wind direction (Tables 9 and 10 respectively). The calculations for the wind directions WNW, NW, NNW can be found in Appendix F.

Table 9 Parameters used for the calculation of wind set-up with the wind set-up formula for W wind direction

Parameter	Value	Unit
g=	9.81	[ms-2]
κ=	0.0000034	[-]
F_W=	14500	[m]
d_{mW}=	1.8	[m]

Table 10 Calculations and results of wind set-up and water level in Ketelbrug with wind set-up formula for W wind direction

W							
Return period	Frequency	Water level Hydra-NL	Initial lake water level Hydra-NL	Wind set-up Hydra-NL	Wind Speed Hydra-NL	Wind Set-up by formula	
						Wind Set-up	Water level
[Years]	[1/years]	[m]	[m]	[m]	[m/s]	[m]	[m]
1	1/ 1	0.13	-0.06	0.19	11.0	0.17	0.11
5	1/ 5	0.37	-0.05	0.42	18.0	0.47	0.42
10	1/ 10	0.47	-0.06	0.53	19.9	0.57	0.51
50	1/ 50	0.72	-0.06	0.78	23.8	0.82	0.76
100	1/ 100	0.84	-0.08	0.92	25.6	0.96	0.88
500	1/ 500	1.15	-0.08	1.23	29.3	1.25	1.17
1000	1/ 1000	1.31	-0.06	1.37	30.7	1.36	1.30
5000	1/ 5000	1.68	-0.08	1.76	34.4	1.73	1.65
10000	1/ 10000	1.84	-0.07	1.91	35.8	1.86	1.79
50000	1/ 50000	2.19	-0.06	2.25	38.9	2.19	2.13
100000	1/ 100000	2.33	-0.06	2.39	40.1	2.32	2.26

Finally, the results of the validation can be seen in the following graphs (Figure 27 to 30), for the 4 different wind directions.

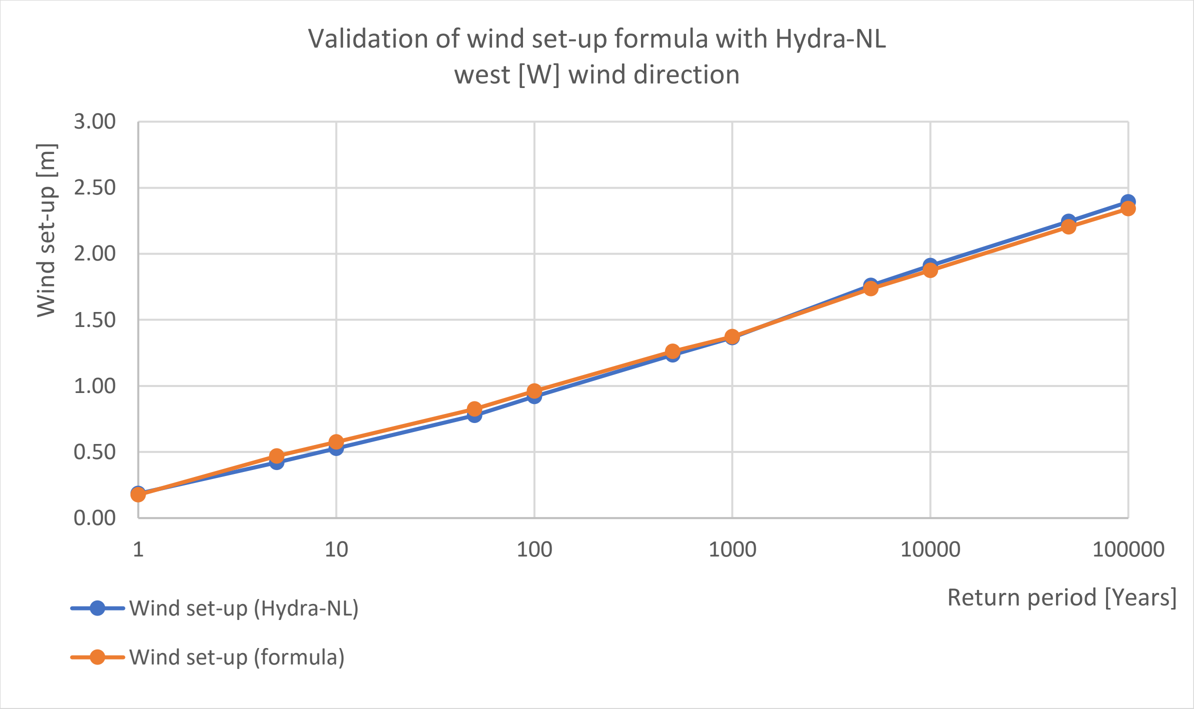


Figure 27 Validation of wind set-up formula for W wind direction

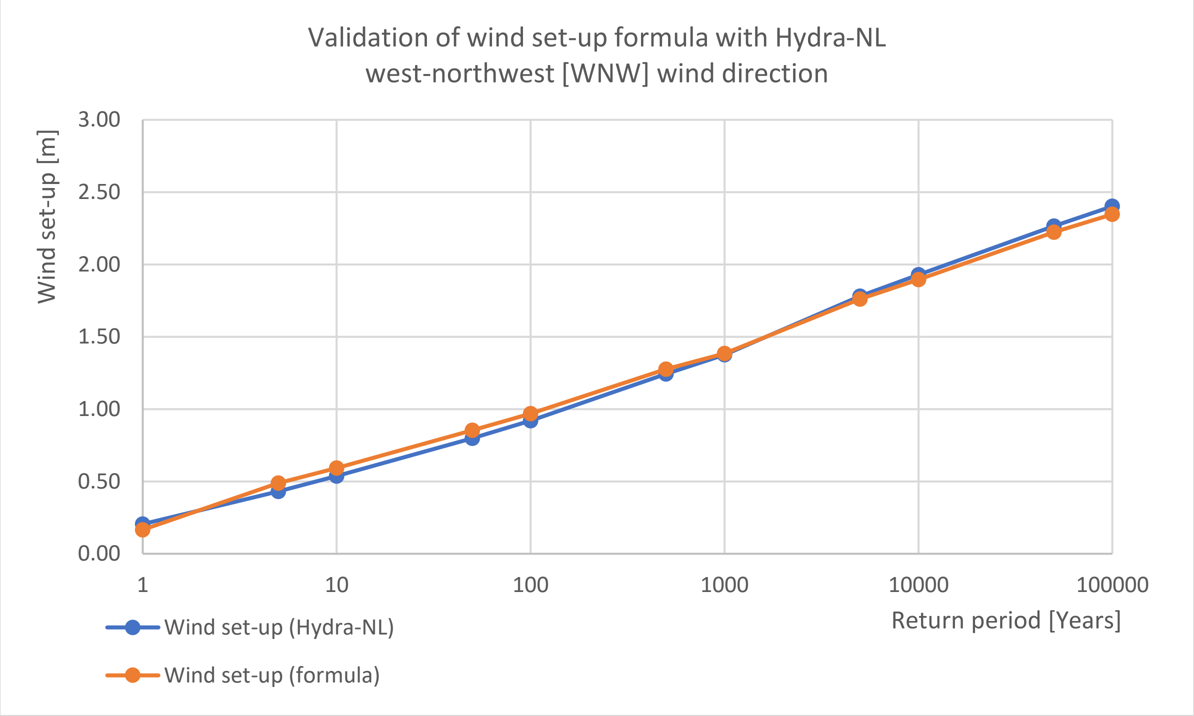


Figure 28 Validation of wind set-up formula for WNW wind direction

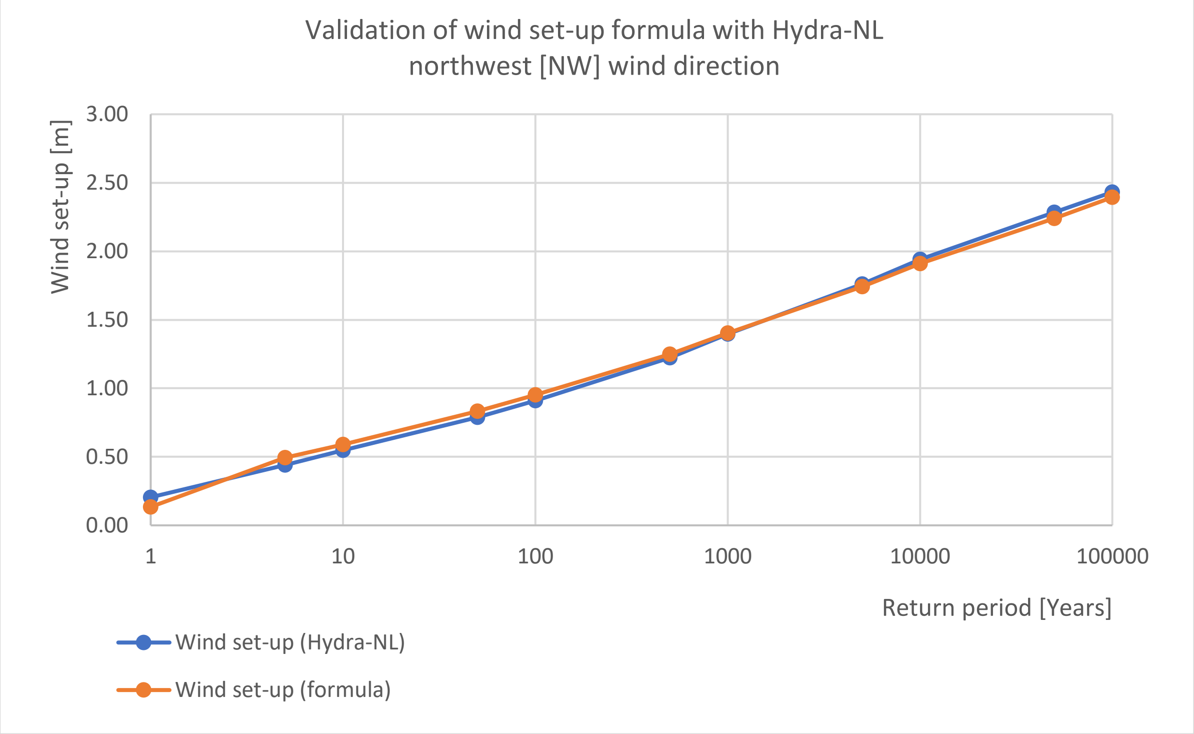


Figure 29 Validation of wind set-up formula for NW wind direction

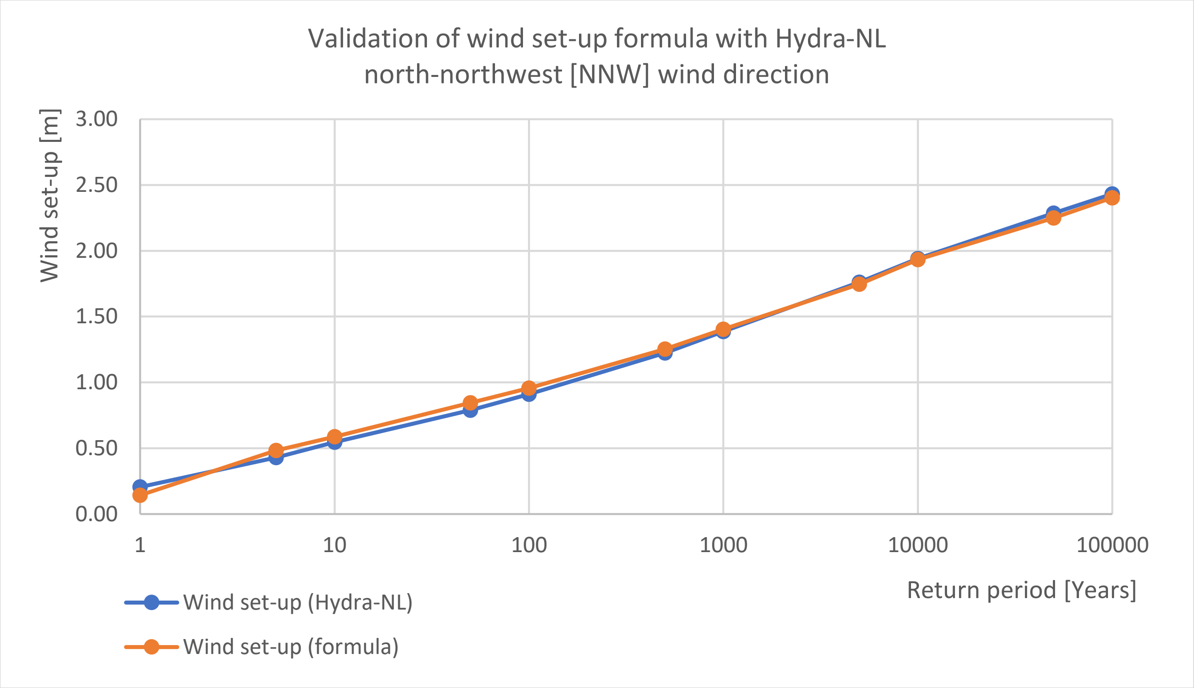


Figure 30 Validation of wind set-up formula for NNW wind direction

To sum up, the validation of the formula seems to give reliable results for all the 4 different wind directions.

Validation of wind set-up formula at Ramspol

For the validation of wind set-up formula at Ramspol (necessary for Improvements 4 and 5), the water levels calculated from Hydra-NL has been compared with the water levels calculated with the wind set-up formula, for the most important wind directions: west [W]. First a dike calculation for the water levels has been executed for the dike section “IJsseldelta_225_094_KM_km0003” (Figure 31), for return periods from 1 to 100000.

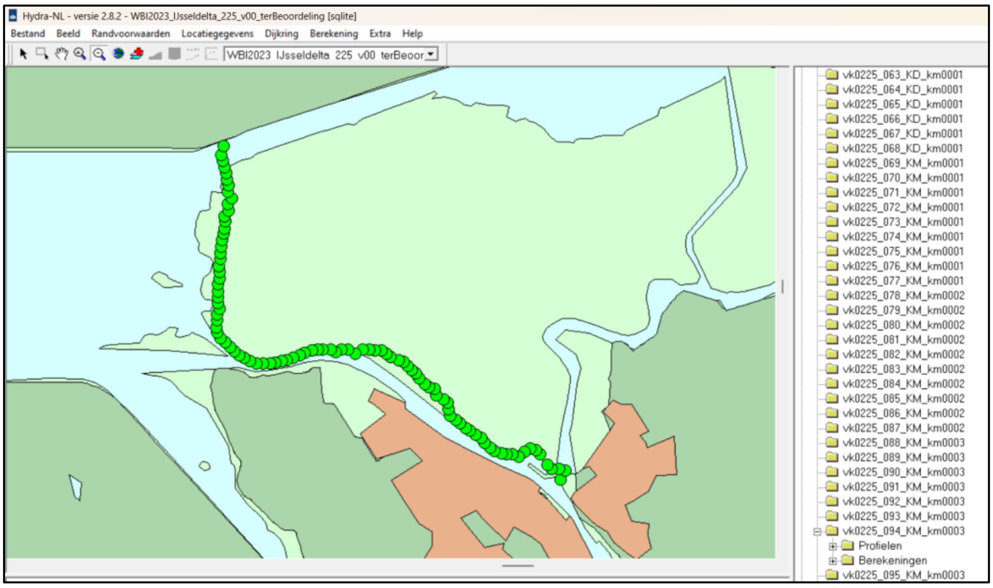
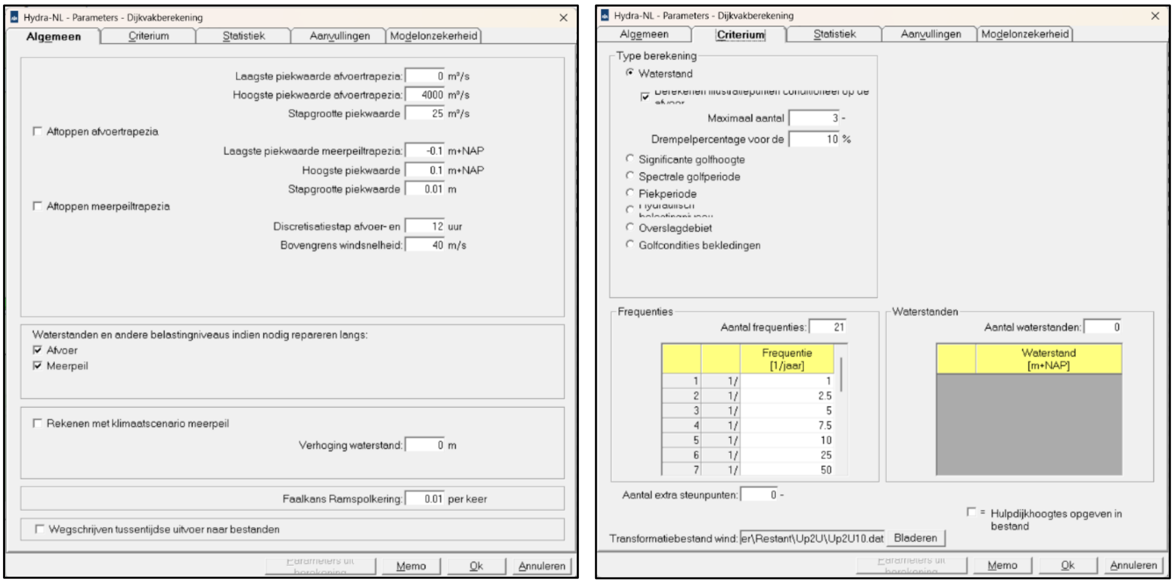


Figure 31 Hydra-NL, calculation point on the map “IJsseldelta_225_094_KM_km0003”, near Ramspol Barrier

The model parameters used for the calculation can be seen in the following Figure 32.



Laagste piekwaarde afvoertrapezia: 0 m³/s
Hoogste piekwaarde afvoertrapezia: 4000 m³/s
Stapgrootte piekwaarde 25 m³/s
☐ Aftoppen afvoertrapezia
Laagste piekwaarde meerpeiltrapezia: -0.1 m+NAP
Hoogste piekwaarde 0.1 m+NAP
Stapgrootte piekwaarde 0.01 m
☐ Aftoppen meerpeiltrapezia
Discretisatiestap afvoer- en 12 uur
Bovengrens windsnelheid: 40 m/s

Waterstanden en andere belastingniveaus indien nodig repareren langs:
☑ Afvoer
☑ Meerpeil

☐ Rekenen met klimaatscenario meerpeil
Verhoging waterstand: 0 m

Faalkans Ramspolkering: 0.01 per keer

☐ Wegschrijven tussentijdse uitvoer naar bestanden

Type berekening
● Waterstand
☑
Maximaal aantal 3 -
Drempelpercentage voor de 10 %
○ Significante golfhoogte
○ Spectrale golfperiode
○ Piekperiode
○
○ Overslagdebiet
○ Golfcondities bekledingen

Frequenties
Aantal frequenties: 21

		Frequentie [1/jaar]
1	1/	1
2	1/	2.5
3	1/	5
4	1/	7.5
5	1/	10
6	1/	25
7	1/	50

Waterstanden
Aantal waterstanden: 0

	Waterstand [m+NAP]

Aantal extra steunpunten: 0 -
☐ = Hulpdijkhoogtes opgeven in bestand
Transformatiebestand wind: er\Restant\Up2U\Up2U10.dat

Figure 32 Hydra-NL setting the calculation model parameters

The Improvements 4 and 5 considers a closed basin since they introduce closing of Ketel Lake at Ketelbrug. Thus, the most important wind direction in Ketelbrug is the west wind direction.

Following can be seen the parameters used and the calculations for the W wind direction (Tables 11 and 12 respectively).

Table 11 Parameters used for the calculation of wind set-up, with the wind set-up formula for W wind direction

Parameter	Value	Unit
g=	9.81	[ms-2]
κ=	0.0000034	[-]
F_W=	11000	[m]
d_{mW}=	4.5	[m]

Table 12 Calculations and results of wind set-up at Ramspol Barrier with wind set-up formula for W wind direction

W								
						Wind Set-up by formula		
Return period	Frequency	Water level at Ramspol Hydra-NL	Initial lake water level Hydra-NL	Wind set-up at Ramspol Hydra-NL	Wind Speed Hydra-NL	Wind set-up in Ketel Lake	Wind set-up at Ketelbrug	Wind set-up at Ramspol
[Years]	[1/Years]	[m]	[m]	[m]	[m/s]	[m]	[m]	[m]
1	1/ 1	0.232	-0.08	0.312	11.8	0.0601	0.176	0.2362
5	1/ 5	0.627	-0.10	0.727	18.7	0.1515	0.470	0.6213
10	1/ 10	0.801	-0.06	0.861	20.6	0.1822	0.577	0.7588
50	1/ 50	1.180	-0.06	1.240	25.2	0.2726	0.825	1.0973
100	1/ 100	1.346	-0.08	1.426	27.3	0.3214	0.962	1.2835
500	1/ 500	1.761	-0.08	1.841	31.7	0.4334	1.260	1.6936
1000	1/ 1000	1.948	-0.07	2.018	33.7	0.4887	1.372	1.8609
5000	1/ 5000	2.384	-0.08	2.464	38.5	0.6393	1.737	2.3764
10000	1/ 10000	2.566	-0.08	2.646	40.6	0.7109	1.874	2.5846
50000	1/ 50000	2.960	-0.10	3.060	45.3	0.8890	2.203	3.0922
100000	1/ 100000	3.139	-0.10	3.239	47.1	0.9611	2.341	3.3023

Finally, the results of the validation can be seen in the following graph (Figure 33), for the west wind directions.

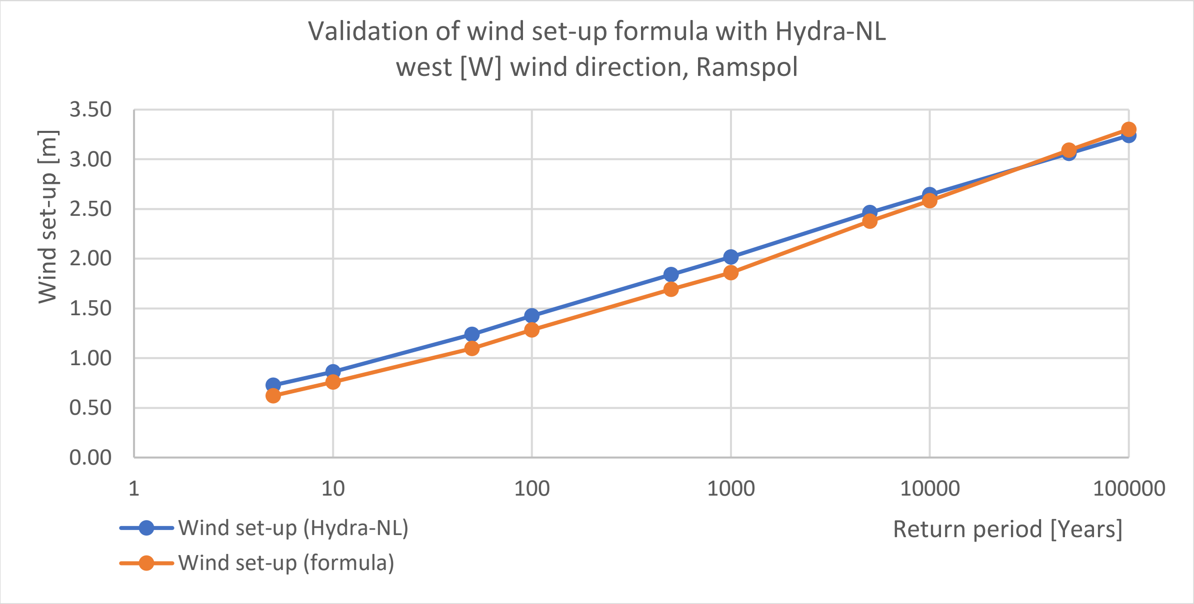


Figure 33 Validation of wind set-up formula for W wind direction

As can be seen in Figure 33 the validation is not working at Ramspol Barrier, as well as it worked for the Ketelbrug. This is happening because the elevation of water in Ketel Lake, except from the wind set-up, also depends on the IJssel River discharge. More specifically, Hydra-NL connects return periods with water levels and then provides values of the parameters (wind speed, wind direction, river discharge, initial water level of IJssel Lake) that can lead to that water level. It has been noticed that the wind set-up formula underestimates the rising in the water level, for the return periods where the Hydra-NL model considers high values of the river discharge parameter. Ketel Lake is a considerable small lake with only a small opening to IJssel Lake and thus it can be understood that a part of the water coming from IJssel River accumulates in the area, leading to rising of water level in Ketel Lake. This phenomenon will be higher, when considering Improvements 4 and 5 because they introduce a closing at Ketelbrug and thus higher Ketel Lake water elevation can be assumed. Since it is not reliable to calculate this increase with the wind set-up formula and setting a formula with many variable parameters would be out of the scope of a rapid estimation method, it has been decided to calculate the decrease in water levels at Ramspol Barrier, by deduct the wind set-up caused in IJssel Lake by the water levels which have been calculated by Hydra-NL model for Ramspol Barrier.

4.1.2.2 Lake-level formula Calculation of water over time

Zwarte Lake is a relatively small lake. When the Ramspol Barrier is closed, the water discharge from Zwarte Water River is accumulating behind Ramspol Barrier leading to in time rising of the water level. Following that, for a high river discharge or a large time period of a storm, the water which is piling up can lead to threatening situations for the stability of the dikes. Thus, time is an important factor for the hydraulic behaviour of the lake. The flood plains already existing in the lake are providing with space for the water to inundate and the response time to flooding is getting shortly extended. Therefore, the dikes in Kampereiland are getting inundated in order to prevent flooding of residential areas. In total 5 interventions have been designed to either influence the initial water level in the lake, create an outflow discharge from the catchment or increase the discharge capacity of the catchment. All the interventions influence the increasing ratio of the lake water level in time.

To evaluate the impact of multiple interventions on the water level of Zwarte Lake, a lake-level model has been considered. An illustration of the model can be seen in the following Figure 34.

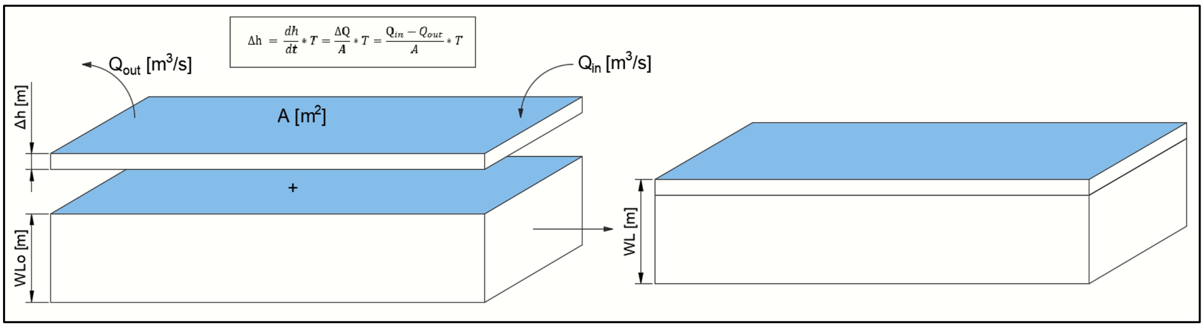


Figure 34 Illustration of the model which calculate the water level in Zwarte Lake

The water level in the lake for a certain time period can be given from:

$$\mathrm{WL} = \mathrm{WL_o} + \Delta\mathrm{h} \tag{8}$$

Where:

$\mathrm{WL_o}$ = Initial water level in the lake (m)
Δh = Increase in water level after a certain time (m)

The increase in water level for a certain water level can be calculated as follows:

$$\Delta\mathrm{h} = \frac{dh}{dt} * T \tag{9}$$

Where:

$\frac{dh}{dt}$ = Increase in water level in time (m/s)

T = Time period (s)

The time rate of change of water level can be calculated from:

$$\frac{dh}{dt} = \frac{\Delta\mathrm{Q}}{A} = \frac{\mathrm{Q}_{in} - Q_{out}}{A} \tag{10}$$

Where:

Q_{in} = Input of water (m^3/s)
$\mathrm{Q_{out}}$ = Output of water (m^3/s)
A = Area of the lake (m^2)

Finally, the equation can be written as follows:

$$\mathrm{WL} = \mathrm{WLo} + \frac{\mathrm{Q}_{in} - Q_{out}}{A} * T \tag{11}$$

This formula will be used in order to calculate the decrease in water level in Zwarte Lake. Following, that value will be decreased from the calculated from Hydra-NL model water levels. The case of a closed barrier will be considered. For obtaining the water levels at the "calculation point of interest" at Zwolle, the correlation factor will be used.

4.1.2.3 Normal flow depth formula

The dike section which has been selected as the "calculation point of interest" in this study is located near the city of Zwolle. The width and the average depth of Zwarte Water River in the area is 80 m and 4m respectively (Navionics, [43]).

This category includes the Improvement 18 and 19, river widening and flood plains respectively. An illustration of those measures can be seen in the Figure 35 following.

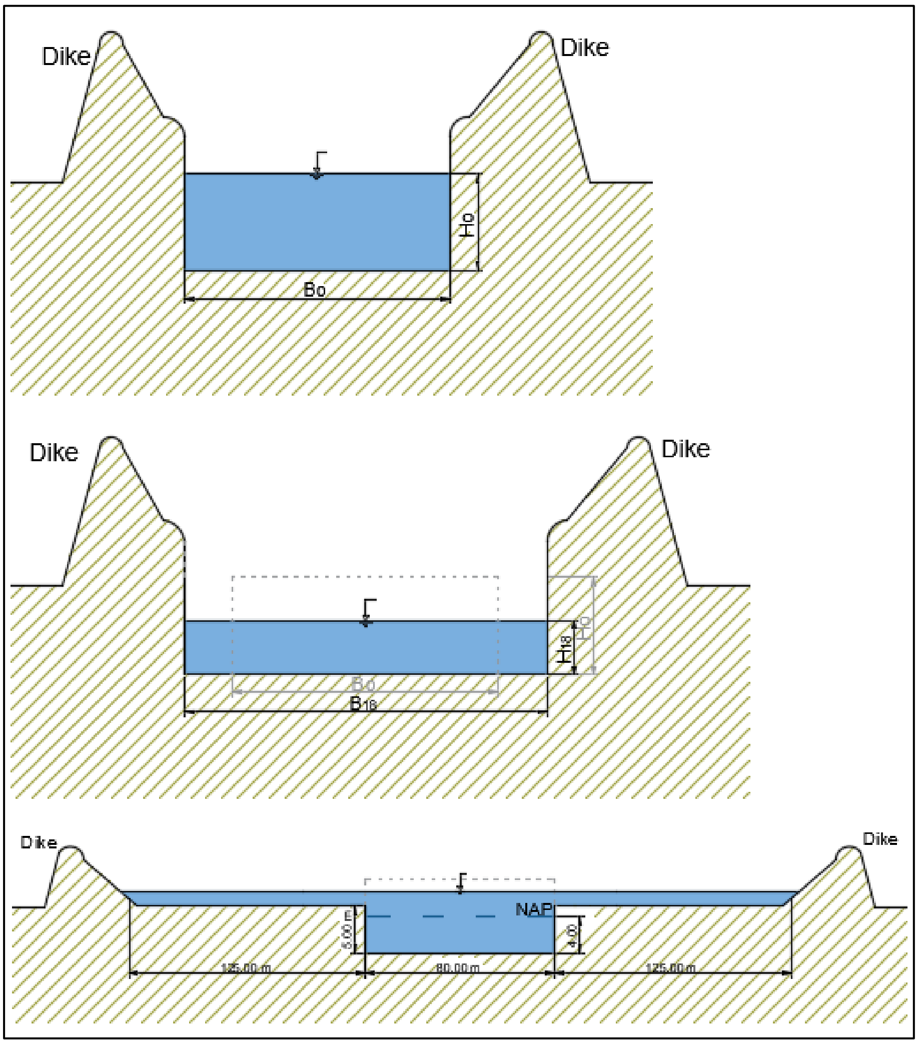


Figure 35 Improvement 18 River widening (middle) and Improvement 19 Flood plains (bottom)

For the calculation of the water level for Improvement 19 Flood plains, the following formula giving the normal flow depth [44] will be used:

$$Q = B * d * U = \sqrt{\frac{g}{C_f} d^3 i_b} * B \tag{12}$$

Using this formula, the discharge related with the current situation which leads to current water levels can be obtained. Following the discharge can be separated into the discharge passing from the main channel cross section and the discharge passing from the floodplain section.

$$Q = Q_f + Q_m = \sqrt{\frac{g}{C_f}(d_f)^3 i_b} * B_f + \sqrt{\frac{g}{C_f}(d_m)^3 i_b} * B_m = \sqrt{\frac{g}{C_f}(d_f)^3 i_b} * B_f + \sqrt{\frac{g}{C_f}(d_f + 5[m])^3 i_b} * B_m \qquad (13)$$

By resolving this equation with only unknown parameter the d_f, the depth on the flood plains and the new NAP + water level [m] can be derived. Finally, since the resulting water levels considers directly the area of interest, dike section to the city of Zwolle, these values will be directly used, with no correlation factor needed to be applied.

4.1.2.4 Increase Ramspol Barrier's reliability

For assessing the influence of a higher reliability of Ramspol Barrier, Hydra-NL model will be used. To achieve this, the failure probability of the barrier will be manually changed through the model and new water levels will be obtained for the characteristic return periods.

4.1.3 Cost Estimation

The second assessment factor for the decision making is the cost that each improvement requires for its implementation. The cost of each intervention has to be calculated. For this early stage of design, the exact dimensions, shape and parameters it is not wise to be calculated. However, representative values for each type of intervention multiplied by a logical expected dimensioning, will give a first approach of the cost. This uncertainty will be introduced by using an upper and lower bound of the estimated cost.

4.1.4 Ecological Impact

Nowadays, ecology plays an important role in the decision making, since the engineering community understands the importance of respecting the environment and making the most out of it without disturbing or destroying it. An example of it is the "Building with Nature" approach, where the "Room for the River" techniques also belongs. The approach develops nature-based solutions for water related infrastructure such as flood defences, sustainable port development and for the development and restoration of ecosystems [45]. It uses the forces of nature to benefit the economy, society and the environment. Some of the recommended improvements have those characteristics while others, more traditional approaches can in short or long term significantly disturb the water system under research.

For the purposes of this study, the improvements are going to be assessed regarding their impact on the ecosystems of the water system (IJssel Lake, Ketel Lake, Zwarte Lake and Zwarte Water River). For the first stage of assessment, attention will be given to the disturbance of the ecosystem as a system and the disturbance to specific flora or fauna species will not be investigated.

To obtain a representation of the ecological impact (qualitatively estimation) of each intervention, the idea of the "ecological sign" has developed. The principle of the method is to give a sign from very negative (--), negative (-), zero (0), positive (+) to very positive (++), for each intervention, for 4 main ecosystem parameters. The ecosystem parameters which decided to be included in this stage of assessment are: (1) the water quality, (2) the habitat disturbance, (3) the disturbance because of noise and vibration and (4) the biodiversity. Following, the signs of the 4 ecosystem parameters will be added, and a net value of the "ecological sign" per parameter will be derived.

First, it is essential to identify and explain the important ecosystems and protected species and then look at the disturbance or benefit that the construction, maintenance and function of each improvement can create to the 4 important ecosystem parameters.

4.1.4.1 Important ecosystems

The most important ecosystems in the water system are:

Sandbanks and islands: Sandbanks and islands provide important nesting and roosting habitat for waterfowl and other bird species. They are also important for maintaining a healthy shoreline ecosystem by stabilising sediments and providing habitat for shoreline vegetation.

Wetlands: Wetlands are areas where the water table is at or near the surface of the land for most of the year. These areas are important for water purification, nutrient cycling, and habitat for a wide variety of plant and animal species. In IJssel Lake, wetlands provide important breeding and feeding habitats for waterfowl, wading birds, and fish.

Marshes: Marshes are a type of wetland that are characterised by the presence of grasses, sedges, and other herbaceous plants that can tolerate waterlogged soils. The marshes around the lakes provide habitat for many species of birds, amphibians, and reptiles. They are also important for preventing erosion and maintaining the water quality in the lake.

Meadows: The meadows around the IJssel Lake are not typically in the water, but they may be located in areas that are seasonally flooded or have high water tables. These meadows are often referred to as "polder meadows" because they were reclaimed from the sea by building dikes and draining the land. They provide habitat for many species of grassland birds and other wildlife. They are also important for agriculture and provide grazing land for livestock.

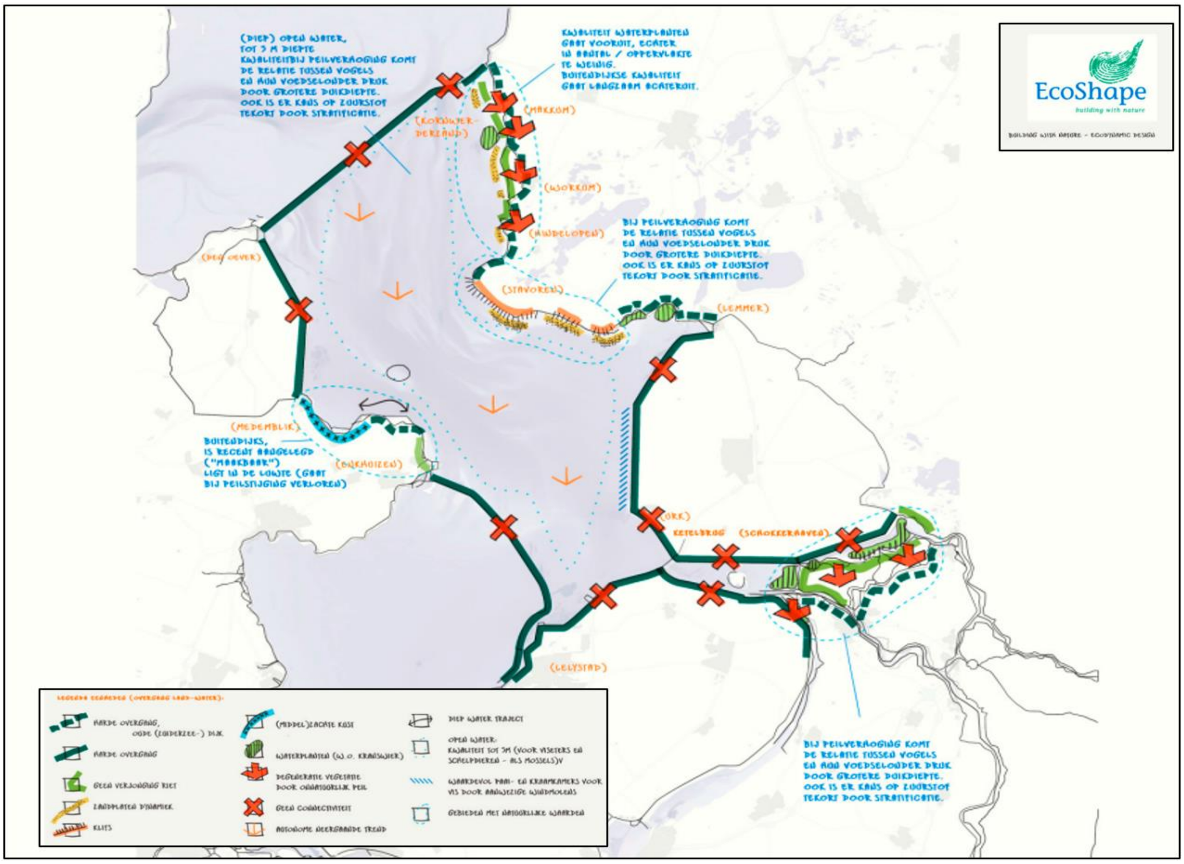
Peat bogs: Peat bogs are a type of wetland ecosystem that is characterised by the accumulation of partially decayed plant material, called peat. Peat is formed when dead plant material, such as mosses, sedges, and heather, accumulates in a waterlogged environment, where it is slow to decompose due to the lack of oxygen. The peat bogs around Zwarte Lake are important ecosystems that store large amounts of carbon and support a unique set of plant and animal species. They are also important for regulating water flow and preventing flooding.

Shallow waters and submerged vegetation: Shallow waters and submerged vegetation provide important habitat for a variety of aquatic species, including fish, invertebrates, and waterfowl. These areas are also important for water quality, as they help to absorb nutrients and filter out pollutants.

Open water: The open water areas of IJssel Lake are also an important ecosystem, providing habitat for a variety of fish species and supporting a range of aquatic plant and animal life. These areas are also important for recreational activities such as boating and fishing.

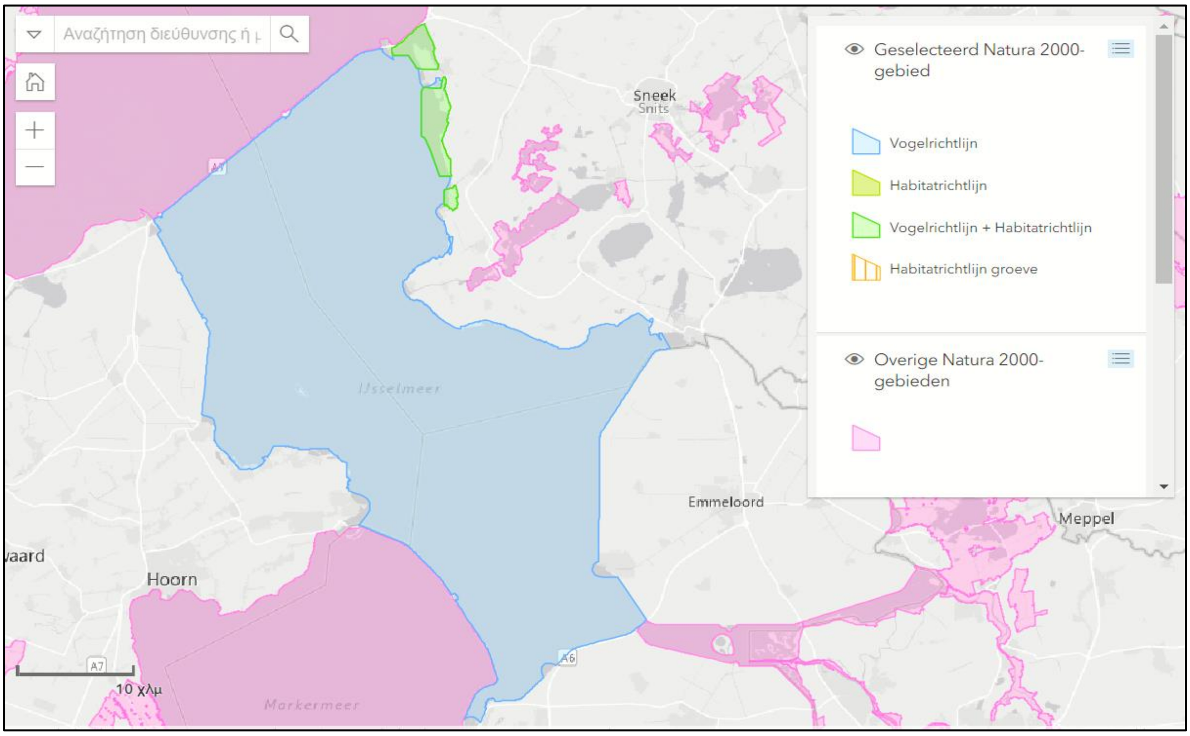
Estuaries: The estuaries of the rivers Zwarte Water and IJssel, are important ecosystems in IJssel Lake, providing habitat for many species of fish and birds. They also act as a nursery area for young fish, and as a migration route for fish travelling between freshwater and saltwater environments.

The characteristics and the vulnerabilities of the studied area regarding the ecosystems belonging to that, can be seen in the following Map 8.



Map 8 Characteristics and vulnerabilities of the area from a natural perspective [45]

Moreover, the Natura2000 map for the water system can be found in the following Map 9.



Map 9 Natura2000 map of the water system [46]

4.1.4.2 Important parameters of the ecosystems

It is important to identify the possible pressure to the ecosystems during the construction, maintenance and function stage of a project. Some of the key parameters that should be considered include:

Water quality: The construction project should avoid any activities that could lead to sedimentation or nutrient inputs into the lake, which can negatively impact water quality.

Habitat disturbance: The construction project should avoid disturbing sensitive habitats within or near the lake, such as wetlands or shorelines. If disturbance is unavoidable, measures such as temporary barriers, re-vegetation, or mitigation strategies should be implemented to minimise the impact on habitat.

Noise and vibration: Construction activities can produce noise and vibration that can be harmful to aquatic species. Measures such as scheduling construction activities during non-sensitive times, using sound barriers, or reducing the use of heavy equipment can help to minimise noise and vibration impacts.

Biodiversity: The construction project should consider the potential impact on biodiversity, including threatened or endangered species that inhabit the lake or surrounding area. Measures such as conducting surveys and studies to identify vulnerable species, avoiding sensitive habitats, and implementing mitigation measures can help to protect biodiversity.

4.2 Second stage of assessment

The second stage considers a more detailed assessment of the improvements and concerns only the selected improvements, validated from the first stage of assessment. For a detailed approach, data, research, resources, and more time are needed. The main aspects of the assessment are the same with the first stage naming, the decrease of water level maximum (reduction in flood risk), the cost (total cost) and the ecological impact (holistic impact). The method will be explained in the following chapters. However, the second stage of assessment is a recommendation of how the assessment could be made, but it will not be handled in this study, since it is out of the scope of the thesis.

4.2.1 Detailed Method

The detailed method, which is proposed in this study, consists of three important decision-making aspects: (1) the decrease of water level maximum, (2) the cost and (3) the ecological impact that one intervention/improvement is associated with.

For assessing the decrease of water level maximum of a measure, the probability of failure of essential dike sections can be estimated with Hydra-NL probabilistic model. For the assessment of the cost, the total cost needs to be calculated. Respectively, for the qualitative estimation of the ecological impact, the influence of the interventions on the ecosystems and on specific species will be identified. By calculating the influence for the three aspects explained above, a number of interventions will be more beneficial for the decrease of water level maximum, the cost or the ecological impact. In order to approach the interventions which are more beneficial for the combination of the three aspects, a “grade and weight” method can be used, as discussed in the first stage of assessment.

Since, a detailed investigation of the influence of the interventions will be conducted there is no need for lower-upper bound, for taking into account the uncertainty.

4.2.2 Decrease of water level maximum

For assessing the decrease of water level maximum of the different improvements to the water system, the probability of failure of the essential dike section can be obtained through the Hydra-NL model. Hydra-NL is a probabilistic assessment model for the safety of the primary flood defences along the main water systems in the Netherlands, specifically for the rivers Rhine and Meuse and their branches as well as the river Vecht, for the lakes (IJssel Lake and Marker Lake) and for the coasts. More information regarding the model can be found in Appendix D.

Hydra-NL can be used as an assessment tool to evaluate the current situation. For the rivers, lakes and the sea, the model uses all kinds of statistical information, and many calculated water levels and wave variables, provided through physical models such as WAQUA and SWAN. Using the Hydra-model for the current safety levels, i.e., the norm frequencies, the normative water levels and required (or desired) dike heights can be determined. A required dike height can then be compared to the existing dike height. It is important to note that the database which is by default used from Hydra-NL concerns the existing water system (Figure 36).

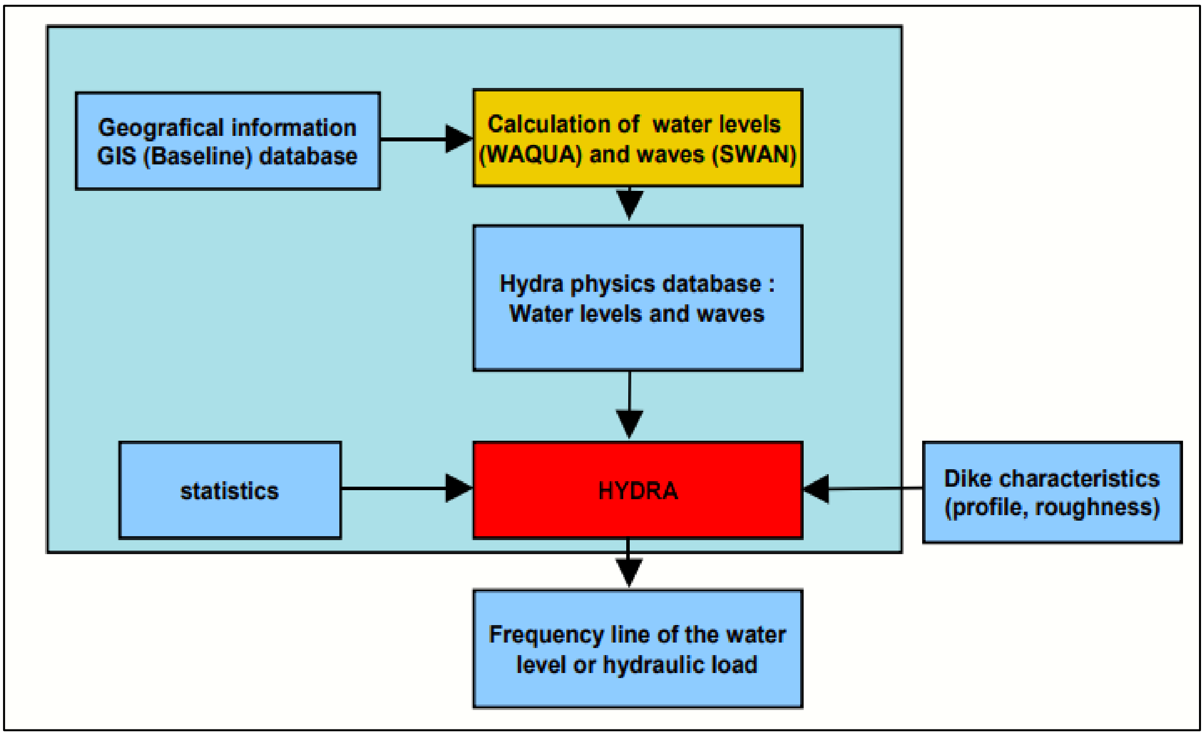


Figure 36 Hydra-Zoet, providing for the current situation frequency lines for water levels and hydraulic load levels [19]

In order to consider new structures/interventions such as new enclosure dams or changes in the riverbed, changes of the input of Hydra-NL are necessary, leading to different “physical databases” of water levels and waves; also, different dike characteristics might have to be used. When considering alternative climate scenarios, changes to the statistical input become necessary. For all kinds of policy studies, such changes to Hydra-NL will be necessary, leading to the scheme of Figure 37, where also extra random variables are indicated that could be necessary.

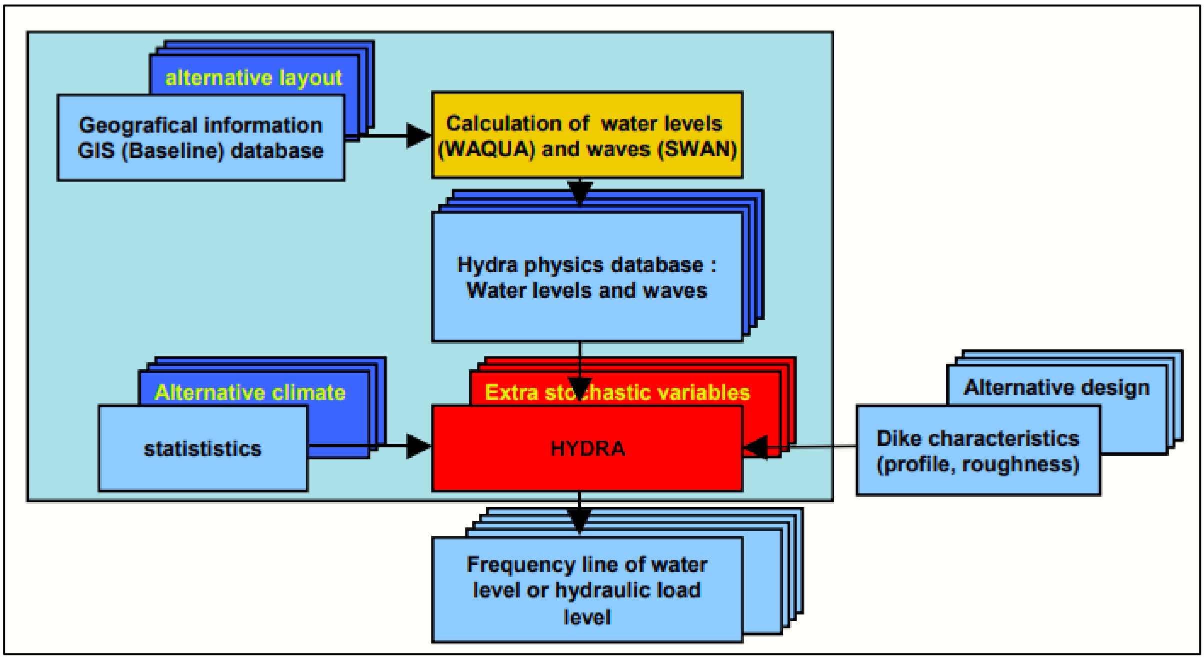


Figure 37 Hydra-Zoet, providing frequency lines for water levels and hydraulic load levels for policy design studies [19]

4.2.3 Cost Estimation

For the detailed assessment (2nd stage) of the cost of the interventions to the water system, the total analytical cost that each improvement introduces, needs to be taken into account. Leidraad Kunstwerken [47] gave the follow definition of the total cost:

$$C_{total,discounted} = \sum_{j=0}^{jl} \left(\frac{C_{acquisition}}{(1+r)^t} + \frac{C_{inspection}}{(1+r)^t} + \frac{C_{maintenance}}{(1+r)^t} + \frac{C_{management}}{(1+r)^t} + \frac{C_{function\ loss}}{(1+r)^t} \right) \quad (13)$$

The different types of costs which are necessary to include in the total cost estimation are:

- The implementation/construction cost

The construction cost refers to the total expenses associated with the physical construction of a project, including materials, labour, equipment, and related construction activities. It encompasses all the direct costs incurred during the building or installation process.

- The maintenance cost

The maintenance cost concerns the costs during the life of a project, in order for this to continuously be functional and meet the designing requirements. Usually, construction assets lose their strength during their lifetime because of deterioration processes. Maintenance costs can include, regular inspections, repairs and renovations, cleaning and maintenance, structural reinforcements, safety and security measures etc.

- The management cost

Operation or management costs refer to the expenses incurred in the day-to-day operation and management of a structure/asset. These costs are necessary for keeping the asset running smoothly and effectively. They can include various expenses such as personnel costs, utilities, consumables and supplies, insurance, training and development, regulatory compliance etc. This type of cost is only relevant with the improvements such as the construction of a new storm surge barrier or the implementation of pumping stations, where physical inspection or management is needed for the operation.

- End-of-life cost

“Net cost or fee for disposing of an asset at the end of its service life or interest period, including costs resulting from decommissioning, deconstruction and demolition of a building, recycling, making environmentally safe and recovery and disposal of components and materials and transport and regulatory costs.” [48]

- Function loss cost / Cost because of failure

Each flood defence structure as a dike, is associated with a failure probability. Moreover, each dike-ring in the Netherlands is associated with a failure probability. In the case of failure of a flood protection structure, the areas behind it are facing an instant damage threat. Not all the areas would lead to the same level of damage. This depends on the special characteristics of each area. For example, the damage of a flood in a rural area would be way less than in an urban area. The Netherlands, holding data about the failure probability of all flood defences, and a failure probability requirement plan is being followed. Also, damage calculations for different failure scenarios of its flood defences are available.

The cost because of failure is the risk cost and can be calculated by multiplying the probability of failure of a structure (in that case, dike) by the cost of the consequences in case of failure in a year.

$$\text{Risk} = P_f * \text{Damage} \tag{14}$$

This type of cost is connected with the aspect of the decrease of water level maximum of the improvements, since a more effective intervention would lead to lower probability of failure of a dike section and since the associated risk would decrease.

4.2.4 Ecological Impact

For the detailed assessment (2nd stage) of the ecological impact of the interventions to the water system, except from the influence on the ecosystems as in 1st stage of assessment, also the influence on the different species needs to be investigated in order to approach a more realistic and holistic estimation of the interventions’ impact to the water system. The same scheme as in the first stage of assessment will be followed by determining the ecological sign for each intervention. There are several flora and fauna species that are protected under Dutch and European laws in the water system. An overview of the most important fish, bird, other animal and plant species can be found in the Appendix E.

5. Assessment results and selection

By applying the grading and weighing technique on the calculated values for each assessment aspect, the final assessment values can be obtained. Three weight distributions have been considered (Table 13).

Table 13 Weights distribution scenarios

	Assessment aspect		
	Decrease of water level maximum	Cost	Ecological impact
Weight distribution	Weight 1	Weight 2	Weight 3
1. (0.5/0.3/0.2)	0.5	0.3	0.2
2. (0.4/0.3/0.3)	0.4	0.3	0.3
3. (0.5/0.2/0.3)	0.5	0.2	0.3

The final assessment value per considered scenario of weighing can be found in the following tables (Table 14, 15 and 16). The improvements indicated in the table by green colour are the prevailing ones since they are achieving a higher assessment value.

Table 14 Final assessment value for weight distribution (0.4/0.3/0.3)

		Assessment aspect				Final assessment value (range)	
		Decrease of water level maximum	Cost		Ecological impact		
		Weight 1	Weight 2		Weight 3		
		0.4	0.3	0.3	0.3		
Improvement		Grade 1	Grade 2 (range)		Grade 3		
1	Breakwater	8.5	5.6	5.3	6.0	6.9	6.7
2	Afsluitdijk II	2.6	2.3	1.4	5.0	3.2	3.0
3	Reclamation land	2.6	7.2	7.2	1.0	3.5	3.5
4	Outflow channel	9.0	4.8	4.3	5.0	6.5	6.4
5	Ramspol Barrier II	7.5	5.9	5.9	5.0	6.3	6.3
6	Increase Afsluitdijk pump capacity	2.7	5.8	4.4	8.0	5.2	4.8
7	Pump installation at Marker Lake	2.4	6.1	5.3	8.0	5.2	4.9
8	IJssel Lake deepening	4.5	3.2	2.9	4.0	4.0	3.9
9	Vegetation area	1.0	8.5	8.2	8.0	5.3	5.3
12	Pump installation at Ramspol Barrier	4.0	7.3	5.8	9.0	6.5	6.0
13	Extension of Vollenhover channel	3.9	4.7	4.3	6.0	4.8	4.6
14	Size-up Zwarte Lake	6.2	5.9	4.9	9.0	6.9	6.6
15	Ramspol Barrier faster closure procedure	2.0	8.5	7.9	8.0	5.7	5.6
16	Closing of Ramspol Barrier in a lower water level	2.8	9.0	9.0	8.0	6.2	6.2
17	Rising the height of the dikes	9.0	5.5	5.5	4.0	6.4	6.4
19	Flood plains	5.3	8.8	8.4	7.0	6.9	6.7
20	Increase Ramspol Barrier reliability	3.7	8.4	8.0	8.0	6.4	6.3

Table 15 Final assessment value for weight distribution (0.5/0.2/0.3)

		Assessment aspect				Final assessment value (range)	
		Decrease of water level maximum	Cost		Ecological impact		
		Weight 1	Weight 2		Weight 3		
		0.5	0.2	0.2	0.3		
Improvement		Grade 1	Grade 2		Grade 3		
1	Breakwater	8.5	5.6	5.3	6.0	7.2	7.1
2	Afsluitdijk II	2.6	2.3	1.4	5.0	3.3	3.1
3	Reclamation land	2.6	7.2	7.2	1.0	3.0	3.0
4	Outflow channel	9.0	4.8	4.3	5.0	7.0	6.9
5	Ramspol Barrier II	7.5	5.9	5.9	5.0	6.4	6.4
6	Increase Afsluitdijk pump capacity	2.7	5.8	4.4	8.0	4.9	4.6
7	Pump installation at Marker Lake	2.4	6.1	5.3	8.0	4.8	4.7
8	IJssel Lake deepening	4.5	3.2	2.9	4.0	4.1	4.0
9	Vegetation area	1.0	8.5	8.2	8.0	4.6	4.5
12	Pump installation at Ramspol Barrier	4.0	7.3	5.8	9.0	6.2	5.9
13	Extension of Vollenhover channel	3.9	4.7	4.3	6.0	4.7	4.6
14	Size-up Zwarte Lake	6.2	5.9	4.9	9.0	7.0	6.8
15	Ramspol Barrier faster closure procedure	2.0	8.5	7.9	8.0	5.1	5.0
16	Closing of Ramspol Barrier in a lower water level	2.8	9.0	9.0	8.0	5.6	5.6
17	Rising the height of the dikes	9.0	5.5	5.5	4.0	6.8	6.8
19	Flood plains	5.3	8.8	8.4	7.0	6.5	6.4
20	Increase Ramspol Barrier reliability	3.7	8.4	8.0	8.0	5.9	5.8

A cumulative table with the selected improvements can be found below (Table 16).

Table 16 Cumulative table with the selected improvements per weighing scenario

Weight distribution	Selected improvements
1. (0.5/0.3/0.2)	1. Breakwater 4. Outflow channel blocking the water flow between Ijssel Lake and Ketel Lake 14. Size up Zwarte Lake 17. Rising the height of the dikes 19. Flood plains
2. (0.4/0.3/0.3)	1. Breakwater 4. Outflow channel blocking the water flow between Ijssel Lake and Ketel Lake 14. Size up Zwarte Lake 17. Rising the height of the dikes 19. Flood plains
3. (0.5/0.2/0.3)	1. Breakwater 4. Outflow channel blocking the water flow between Ijssel Lake and Ketel Lake 14. Size up Zwarte Lake 17. Rising the height of the dikes 19. Flood plains

In all three weighing scenarios, the same improvements are scoring the best assessment values and getting selected.

5.1 Assessment aspect: Decrease of water level maximum

In order to compare the influence of the twenty different interventions to the water levels, a “calculation point of interest” needs to be selected. The point selected, belongs in the Zwarte Water

River near the city of Zwolle (dike section "Vechtdelta_10-01_35_ZW_km0002"), (Figure 38). The model parameters used for Hydra-NL calculations can be seen in Figure 39 below.

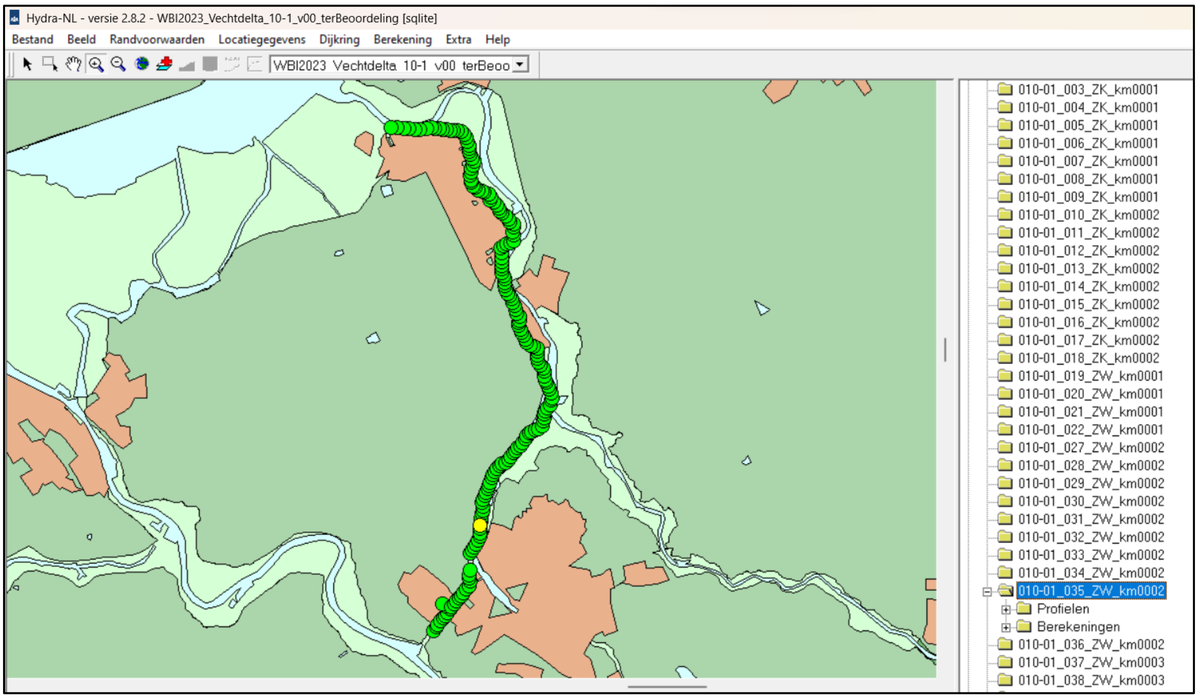
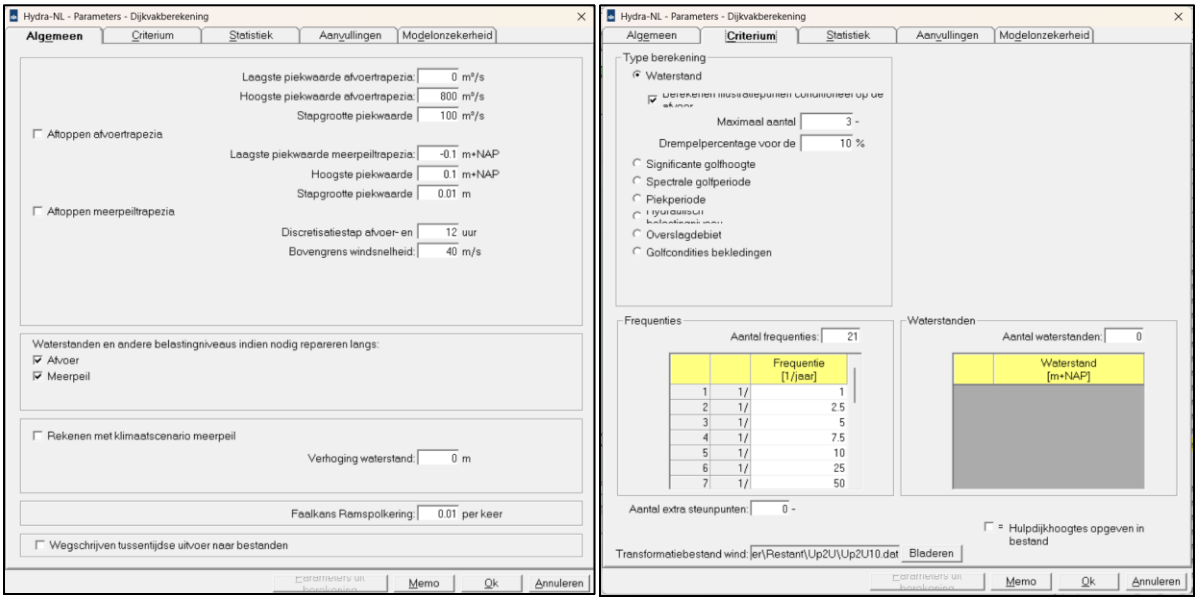


Figure 38 Hydra-NL, calculation point on the map "Vechtdelta_10-01_35_ZW_km0002", near Zwolle



Laagste piekwaarde afvoertrapezia: 0 m³/s
Hoogste piekwaarde afvoertrapezia: 800 m³/s
Stapgrootte piekwaarde 100 m³/s
☐ Aftoppen afvoertrapezia
Laagste piekwaarde meerpeiltrapezia: -0.1 m+NAP
Hoogste piekwaarde 0.1 m+NAP
Stapgrootte piekwaarde 0.01 m
☐ Aftoppen meerpeiltrapezia
Discretisatiestap afvoer- en 12 uur
Bovengrens windsnelheid: 40 m/s

Waterstanden en andere belastingniveaus indien nodig repareren langs:
☑ Afvoer
☑ Meerpeil

☐ Rekenen met klimaatscenario meerpeil
Verhoging waterstand: 0 m

Faalkans Ramspolkering: 0.01 per keer

☐ Wegschrijven tussentijdse uitvoer naar bestanden

Type berekening
● Waterstand
☑ Berekenen illustratiepunten conditioneel op de afvoer
Maximaal aantal 3 -
Drempelpercentage voor de 10 %
○ Significante golfhoogte
○ Spectrale golfperiode
○ Piekperiode
○ Hydraulisch belastingniveau
○ Overslagdebiet
○ Golfcondities bekledingen

Frequenties
Aantal frequenties: 21

		Frequentie [1/jaar]
1	1/	1
2	1/	2.5
3	1/	5
4	1/	7.5
5	1/	10
6	1/	25
7	1/	50

Waterstanden
Aantal waterstanden: 0

	Waterstand [m+NAP]

Aantal extra steunpunten: 0 -
☐ = Hulpdijkhoogtes opgeven in bestand
Transformatiebestand wind: er\Restant\Up2U\Up2U10.dat

Figure 39 Hydra-NL setting the calculation model parameters

First, by using the formulas discussed in Chapter 5 the water level for all twenty improvements have been calculated in selected calculation points (Table 17).

Table 17 Calculation points per type of improvements

Method used	Improvements	Dike section, calculation point
Wind set-up formula (7)	Improvements 1-3 and 6-9	“IJsselmeer_8-3a_dk_00582”
	Improvements 4-5	“IJsseldelta_225_094_KM_km0003”
Lake-Level formula (11)	Improvements 12-16	“Vechtdelta_9-2_037_ZM_km0001”
Local depth formula (13)	Improvement 19	“Vechtdelta_10-01_35_ZW_km0002”
Increase barrier reliability	Improvement 20	“Vechtdelta_10-01_35_ZW_km0002”

The cumulative results for the assessment aspect of the decrease of water level maximum in the “calculation point of interest” can be found in the following Table 18 and 19 and Figure 40, 41 and 42. Improvement 17 represents the current situation of water levels for different return periods.

Table 18 Water level at Zwolle (Improvements 1-9)

Water Level at Zwolle (Improvements 1-9)									
	1	2	3	4	5	6	7	8	9
	Breakwater	Afsluitdijk II	Land reclamation	Outflow channel	Ramspol Barrier II	Increase pump capacity at Afsluitdijk	Pump Installation at Marker Lake	Deepening of IJssel Lake	Vegetation Land
Wind direction	NNW	W	W	W	W	NW	NW	NW	NW
Return period	Water Level								
[Years]	[m]								
1		0.51	0.51	0.15	1.02				
2.5		1.01	1.01	0.29	1.06	0.51	0.79	0.86	0.63
5	0.35	1.12	1.12	0.40	1.09	0.91	1.06	1.04	0.95
7.5	0.36	1.19	1.19	0.47	1.11	0.99	1.11	1.09	1.01
10	0.39	1.23	1.23	0.55	1.13	1.05	1.15	1.12	1.06
25	0.49	1.34	1.34	0.67	1.17	1.18	1.27	1.22	1.16
50	0.65	1.40	1.40	0.78	1.21	1.31	1.36	1.31	1.28
75	0.73	1.44	1.44	0.84	1.24	1.37	1.41	1.36	1.33
100	0.67	1.47	1.47	0.82	1.23	1.38	1.42	1.36	1.34
250	0.82	1.56	1.56	0.93	1.28	1.49	1.52	1.45	1.43
500	0.86	1.62	1.62	0.97	1.30	1.55	1.58	1.50	1.49
750	0.93	1.65	1.65	1.02	1.32	1.60	1.64	1.54	1.53
1000	0.96	1.68	1.68	1.04	1.34	1.63	1.67	1.57	1.57
2500	1.03	1.77	1.77	1.07	1.36	1.74	1.77	1.65	1.79
5000	1.06	1.84	1.84	1.09	1.37	1.79	1.82	1.69	1.84
7500	1.10	1.88	1.88	1.10	1.38	1.84	1.87	1.74	1.89
10000	1.13	1.91	1.91	1.12	1.39	1.88	1.91	1.76	1.94
25000	1.14	2.05	2.05	1.11	1.38	1.97	2.00	1.82	2.03
50000	1.22	2.14	2.14	1.16	1.42	2.11	2.15	1.89	2.19
75000	1.24	2.22	2.22	1.16	1.42	2.19	2.24	1.93	2.29
100000	1.26	2.29	2.29	1.18	1.43	2.27	2.33	1.96	2.39

Table 19 Water levels at Zwolle (Improvements 12-19 and 19-20)

Water Level at Zwolle (Improvements 12-17 and 19-20)								
12	13	14	15	16	17 (0)	19	20	
Pump installation at Ramspol Barrier	Extension of Vollenhover channel	Size up Zwarte Lake	Faster closure procedure of Ramspol Barrier	Closing of Ramspol at a lower water level	Increase the height of the dikes	Flood plains	Increase Ramspol Barrier reliability	Always failing barrier
-	-	-	-	-	-	-	-	-
Water Level								
[m]								
					0.55	0.55	0.55	0.56
0.60	0.60	0.57	0.85	0.77	0.94	0.94	0.94	0.98
0.77	0.77	0.68	1.00	0.94	1.07	1.06	1.07	1.11
0.85	0.85	0.73	1.07	1.01	1.13	1.01	1.13	1.19
0.91	0.91	0.77	1.11	1.05	1.17	1.01	1.17	1.25
1.06	1.06	0.89	1.24	1.18	1.30	1.21	1.30	1.42
1.15	1.15	0.97	1.33	1.27	1.38	1.26	1.38	1.55
1.20	1.20	1.00	1.37	1.32	1.42	1.28	1.42	1.64
1.23	1.23	1.03	1.40	1.35	1.45	1.30	1.44	1.70
1.33	1.33	1.10	1.49	1.43	1.54	1.35	1.53	1.90
1.39	1.39	1.14	1.54	1.49	1.61	1.39	1.60	2.05
1.42	1.42	1.17	1.58	1.52	1.65	1.41	1.64	2.15
1.44	1.44	1.19	1.61	1.54	1.68	1.43	1.67	2.21
1.52	1.52	1.25	1.72	1.66	1.78	1.48	1.76	2.42
1.64	1.64	1.32	1.81	1.76	1.85	1.52	1.83	2.57
1.72	1.72	1.37	1.87	1.83	1.90	1.55	1.87	2.66
1.78	1.78	1.40	1.90	1.87	1.94	1.57	1.90	2.72
1.91	1.91	1.51	2.03	1.99	2.06	1.63	1.99	2.91
1.99	1.99	1.60	2.13	2.07	2.19	1.70	2.08	3.07
2.04	2.04	1.66	2.22	2.15	2.30	1.75	2.14	3.17
2.11	2.11	1.72	2.33	2.25	2.39	1.79	2.20	3.27

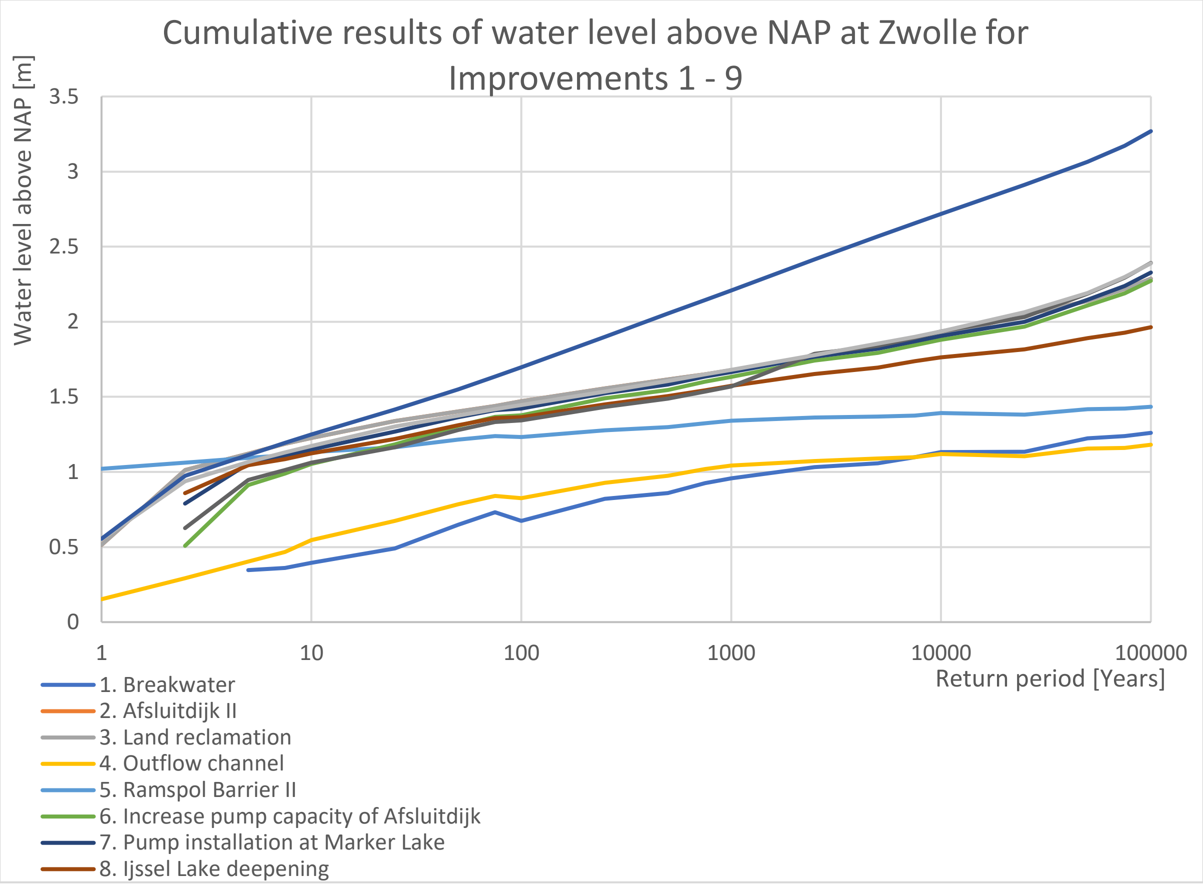


Figure 40 Curve of water level – return period (Improvements 1 - 9)

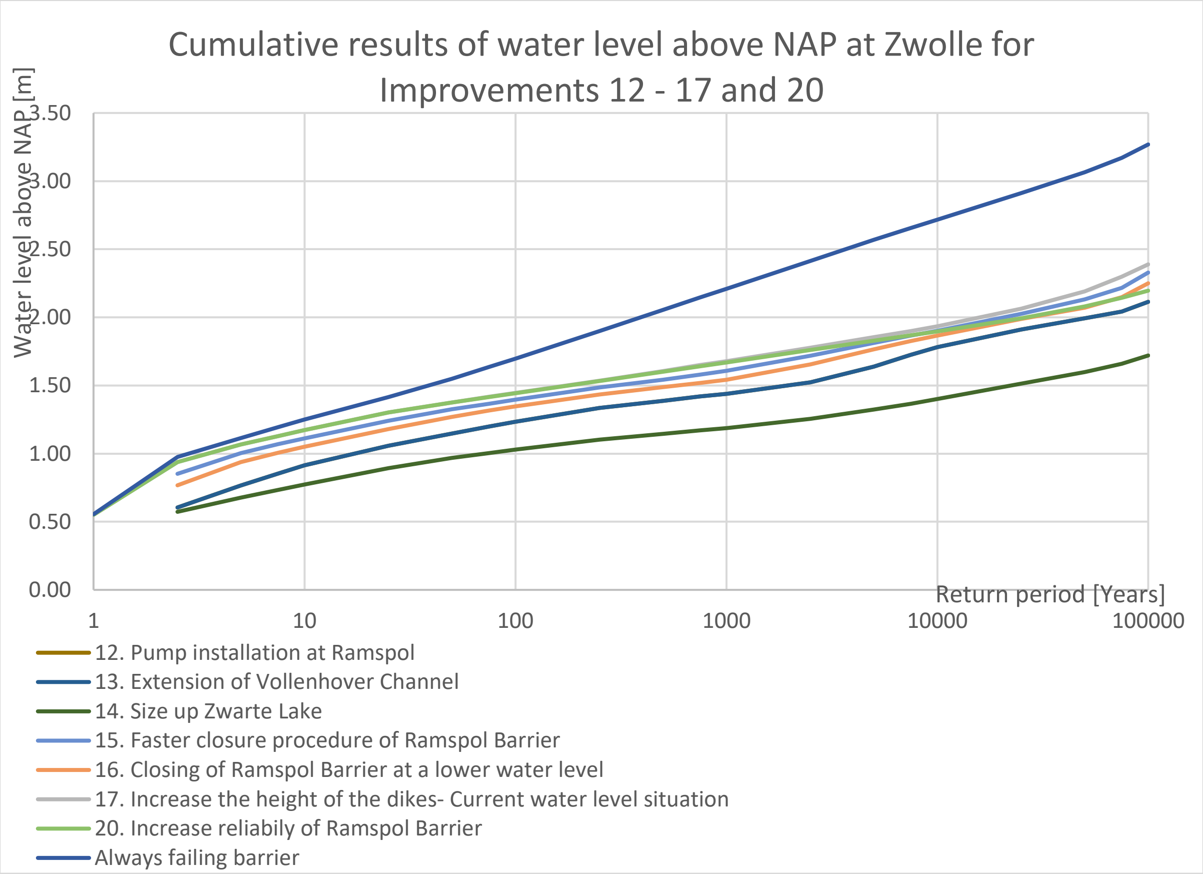


Figure 41 Curve of water level – return period (Improvements 12-17 and 20)

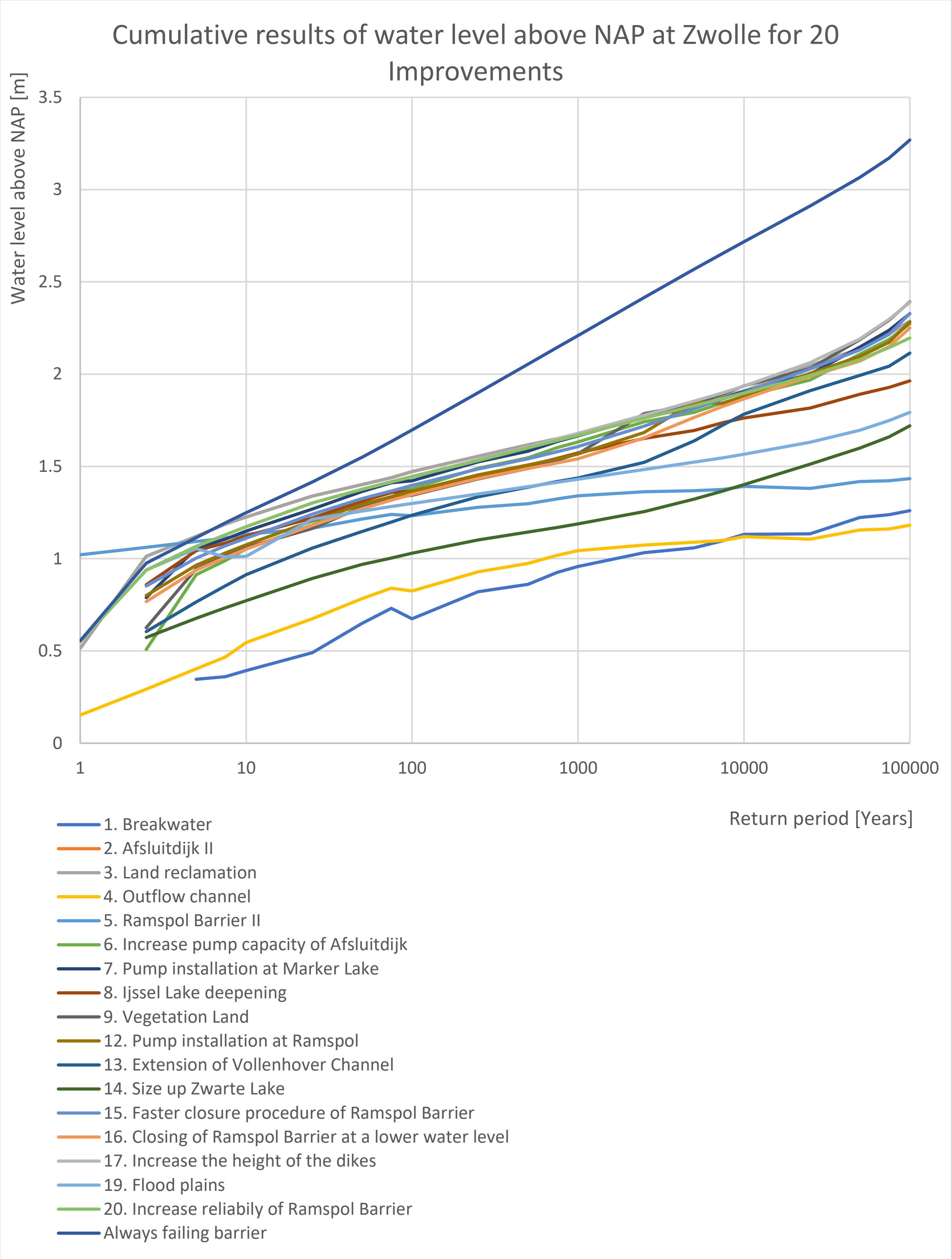


Figure 42 Curve of water level per return period (Improvements 1-9, 12-17 and 18-19)

5.1.1 Calculation of water level maximum per improvement

5.1.1.1 Improvements limiting wind set-up

Using the wind set-up formula, the wind set-up has been calculated for those improvements which have been designed to limit its effect. Aiming to more reliable results, a distinction has been made. The formula has been used for two different areas. The first batch of calculations considers the wind set-up formation in IJssel Lake. As a point of calculation has been decided the Ketelbrug. 4 dominant wind direction has been selected the W, the NW, the WNW and the NNW. The second batch of calculations concerns only the improvements which block the water flow from IJssel Lake in Ketel Lake and thus it calculates the resulting water levels in the area of Ramspol Barrier because of the blocking of the wind set-up coming from IJssel Lake. The prevailing wind direction in this case is the W.

Comparative results of water level at Ketelbrug

Following the validation of wind set-up formula, the wind set-up has been calculated for different wind speeds (10-30 m/s) for the different Improvements, for the 4 dominant wind directions (W, WNW, NW and NNW). Those calculations give a first impression of the influence of the improvements in the water level but most importantly showing the wind direction, which after the intervention can lead to the highest water levels, per improvement. This output is of high importance since the final curve (water level-return period) will only contain the worst wind scenario for each improvement. Again 2 different calculations have been conducted. The first batch of calculations concerns the Improvements 1-3 and 6-9 (Ketelbrug area), and the Improvements 4-5 (Ramspol area).

After the implementation of the proposed improvements, the fetch length, the depth and the initial water level responsible for the wind set-up to some cases, has been changed. Moreover, a reduction parameter is going to be taken into account for the “Vegetation area” improvement. The aforementioned parameters for each improvement and wind direction can be found in the following Table 20.

Table 20 Calculation parameters for Improvements 1-3 and 6-9

g=	9.81	[ms-2]			
κ=	3.4E-06	[-]			
Current situation					
F_{NNW}=	51500	[m]	d_{mNWN}=	4.4	[m]
F_{NW}=	52000	[m]	d_{mNW}=	4.4	[m]
F_{WNW}=	42200	[m]	d_{mWNW}=	4.0	[m]
F_{W}=	14500	[m]	d_{mW}=	1.8	[m]
1. Breakwater					
$F_{NWN(1)}$=	11000	[m]	$d_{mNWN(1)}$=	3.7	[m]
$F_{NW(1)}$=	8000	[m]	$d_{mNW(1)}$=	4.2	[m]
$F_{WNW(1)}$=	7000	[m]	$d_{mWNW(1)}$=	4.1	[m]
$F_{W(1)}$=	7400	[m]	$d_{mW(1)}$=	2.8	[m]
2. Afsluitdijk II					
$F_{NWN(2)}$=	23150	[m]	$d_{mNWN2)}$=	4.2	[m]
$F_{NW(2)}$=	21800	[m]	$d_{mNW(2)}$=	4.5	[m]
$F_{WNW(2)}$=	18500	[m]	$d_{mWNW(2)}$=	2.7	[m]
$F_{W(2)}$=	14500	[m]	$d_{mW(2)}$=	1.8	[m]
3. Reclamation Land					
$F_{NWN(3)}$=	1250	[m]	$d_{mNWN(3)}$=	3.6	[m]
$F_{NW(3)}$=	1750	[m]	$d_{mNW(3)}$=	3.8	[m]
$F_{WNW(3)}$=	3500	[m]	$d_{mWNW(3)}$=	3.9	[m]
$F_{W(3)}$=	14500	[m]	$d_{mW(3)}$=	1.8	[m]
6. Increase pump capacity at Afsluitdijk					
$F_{NNW(6)}$=	51500	[m]	$d_{mNWN(6)}$=	4.2	[m]
$F_{NW(6)}$=	52000	[m]	$d_{mNW(6)}$=	4.2	[m]
$F_{WNW(6)}$=	42200	[m]	$d_{mWNW(6)}$=	3.8	[m]
$F_{W(6)}$=	14500	[m]	$d_{mW(6)}$=	1.6	[m]
7. Pump installation at Marker Lake					
$F_{NNW(7)}$=	51500	[m]	$d_{mNWN(7)}$=	4.3	[m]
$F_{NW(7)}$=	52000	[m]	$d_{mNW(7)}$=	4.3	[m]
$F_{WNW(7)}$=	42200	[m]	$d_{mWNW(7)}$=	3.9	[m]
$F_{W(7)}$=	14500	[m]	$d_{mW(7)}$=	1.7	[m]
8. Lake deepening					
$F_{NWN(8)}$=	51500	[m]	$d_{mNWN(8)}$=	5.4	[m]
$F_{NW(8)}$=	52000	[m]	$d_{mNW(8)}$=	5.4	[m]
$F_{WNW(8)}$=	42200	[m]	$d_{mWNW(8)}$=	5.0	[m]
$F_{W(8)}$=	14500	[m]	$d_{mW(8)}$=	2.8	[m]
9. Vegetation land					
$F_{NWN(9)}$=	51500	[m]	$d_{mNWN(9)}$=	4.4	[m]
$F_{NW(9)}$=	52000	[m]	$d_{mNW(9)}$=	4.4	[m]
$F_{WNW(9)}$=	42200	[m]	$d_{mWNW(9)}$=	4.0	[m]
$F_{W(9)}$=	14500	[m]	$d_{mW(9)}$=	1.8	[m]

After observations of a certain storm event (Lake Okeechobee, Florida, 1950, [38]), it became clear that the vegetation area in a lake produces a damping effect on the set-up. It can be supposed that a correction factor C_m, can be applied to the predicted wind set-up as discussed in Chapter 4. For calculating the wind set-up above the vegetation area, the reduction factor, applied to the wind set-up of the original scenario. In order to obtain the reduction parameter for the relevant wind set-up values, the method of linear interpolation has been used (Appendix F).

A number of the improvements considers change in the initial water level and thus, by comparing the development of wind set-up would not be possible to have a good impression on the influence of the improvements to the resulting water levels. For that reason, water level/wind speed graphs have been created (Figure 43 to 46).

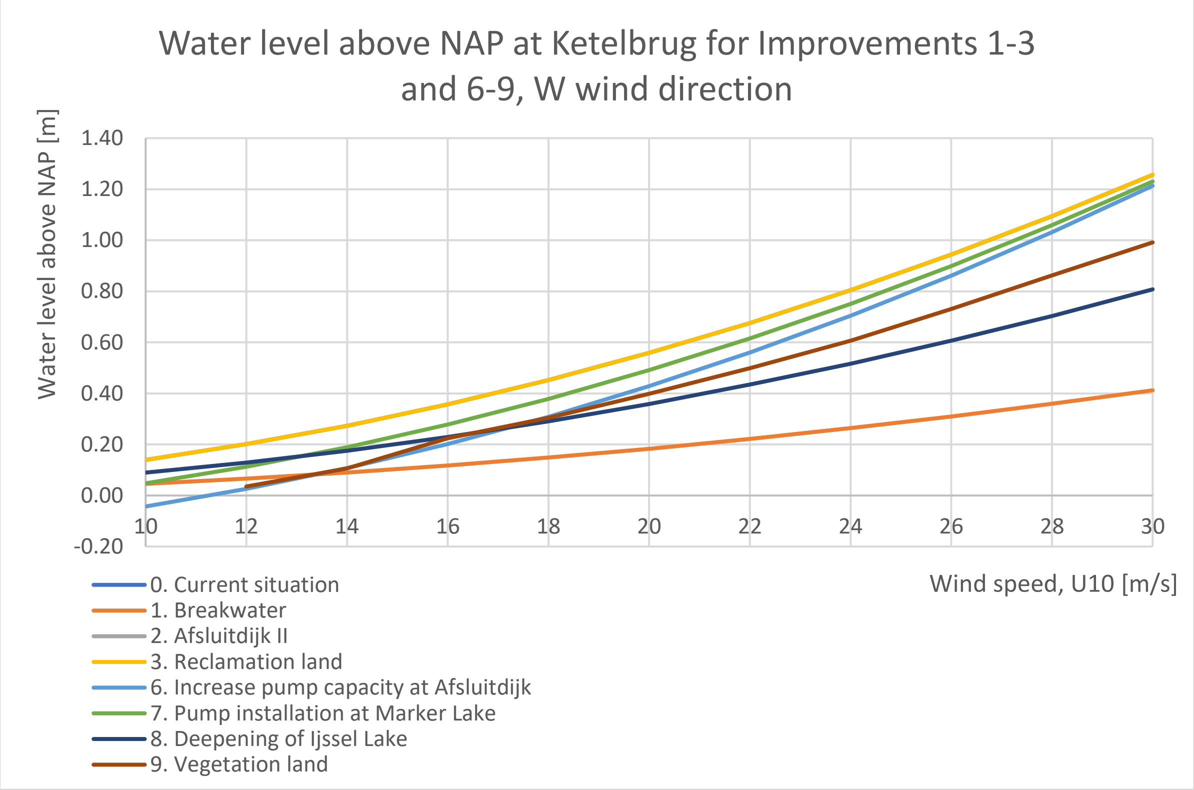


Figure 43 Water level above NAP at Ketelbrug for Improvements 1-3 and 6-9, W wind direction

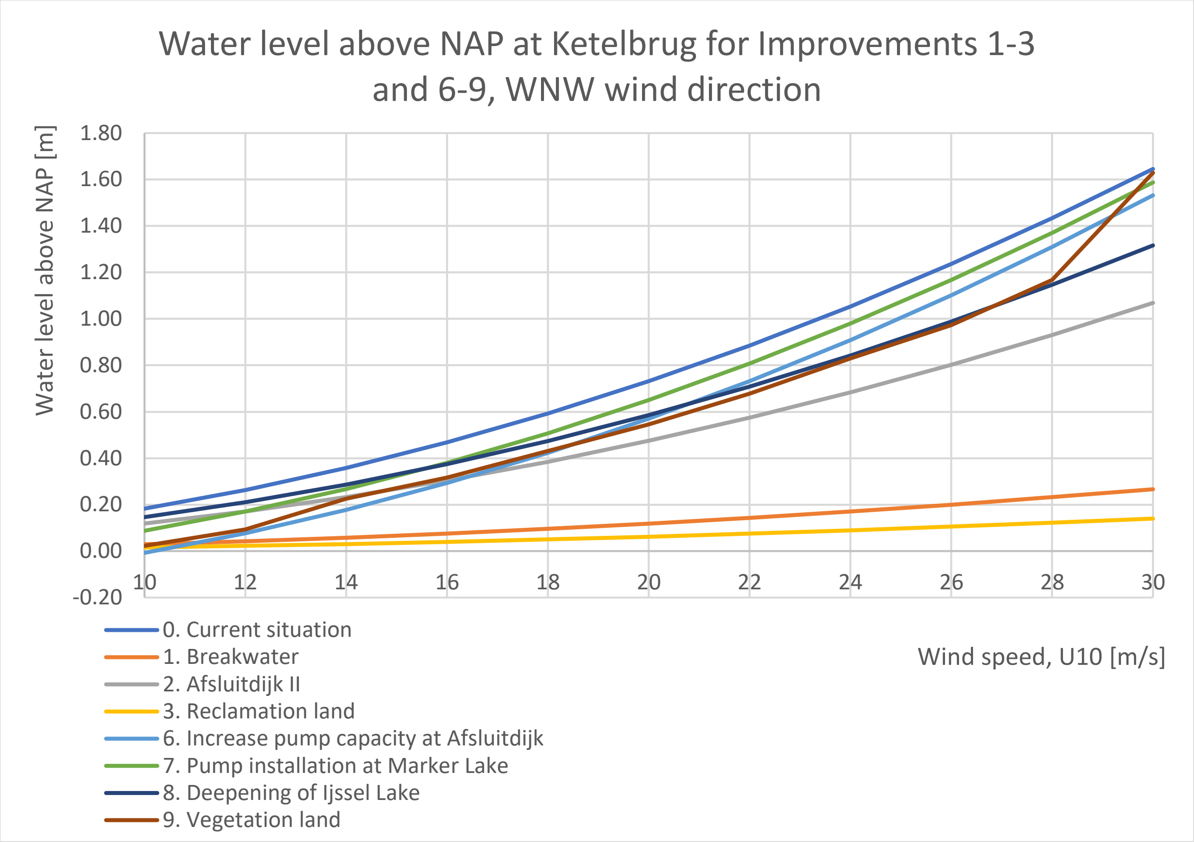


Figure 44 Water level above NAP at Ketelbrug for Improvements 1-3 and 6-9, WNW wind direction

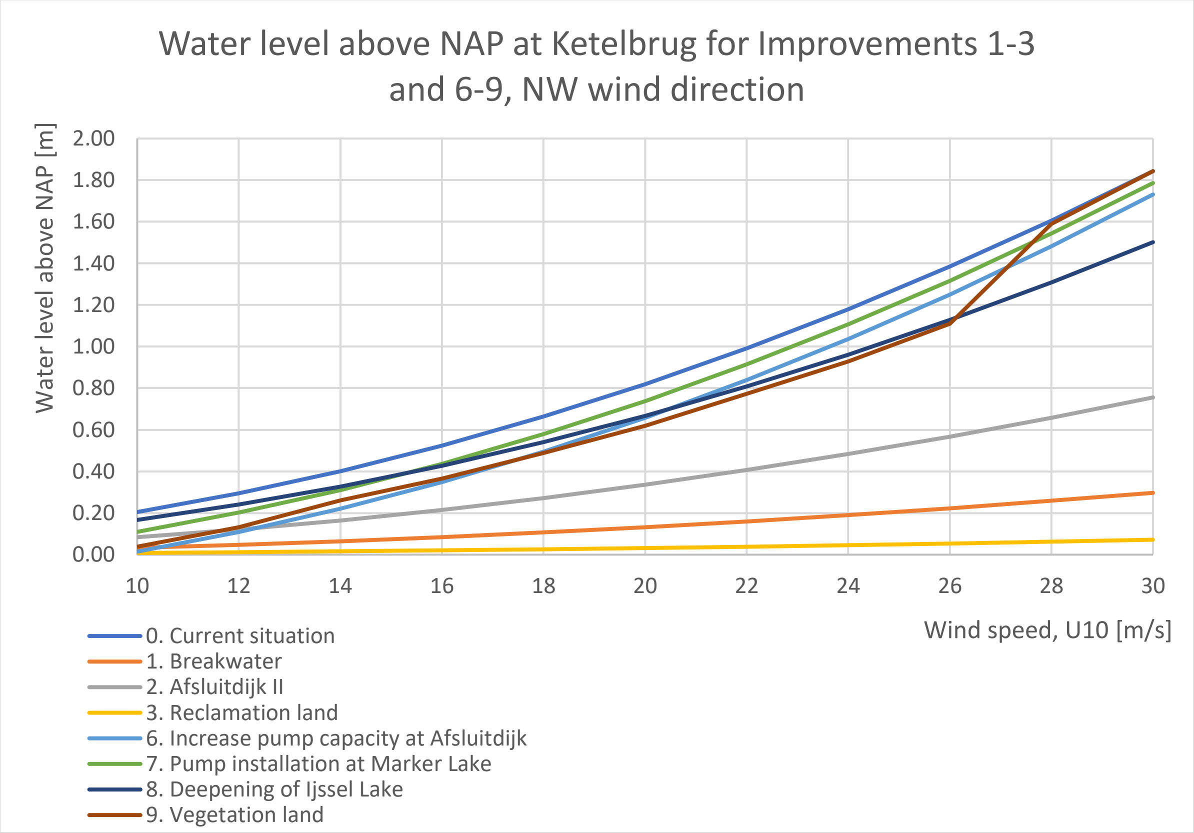


Figure 45 Water level above NAP at Ketelbrug for Improvements 1-3 and 6-9, NW wind direction

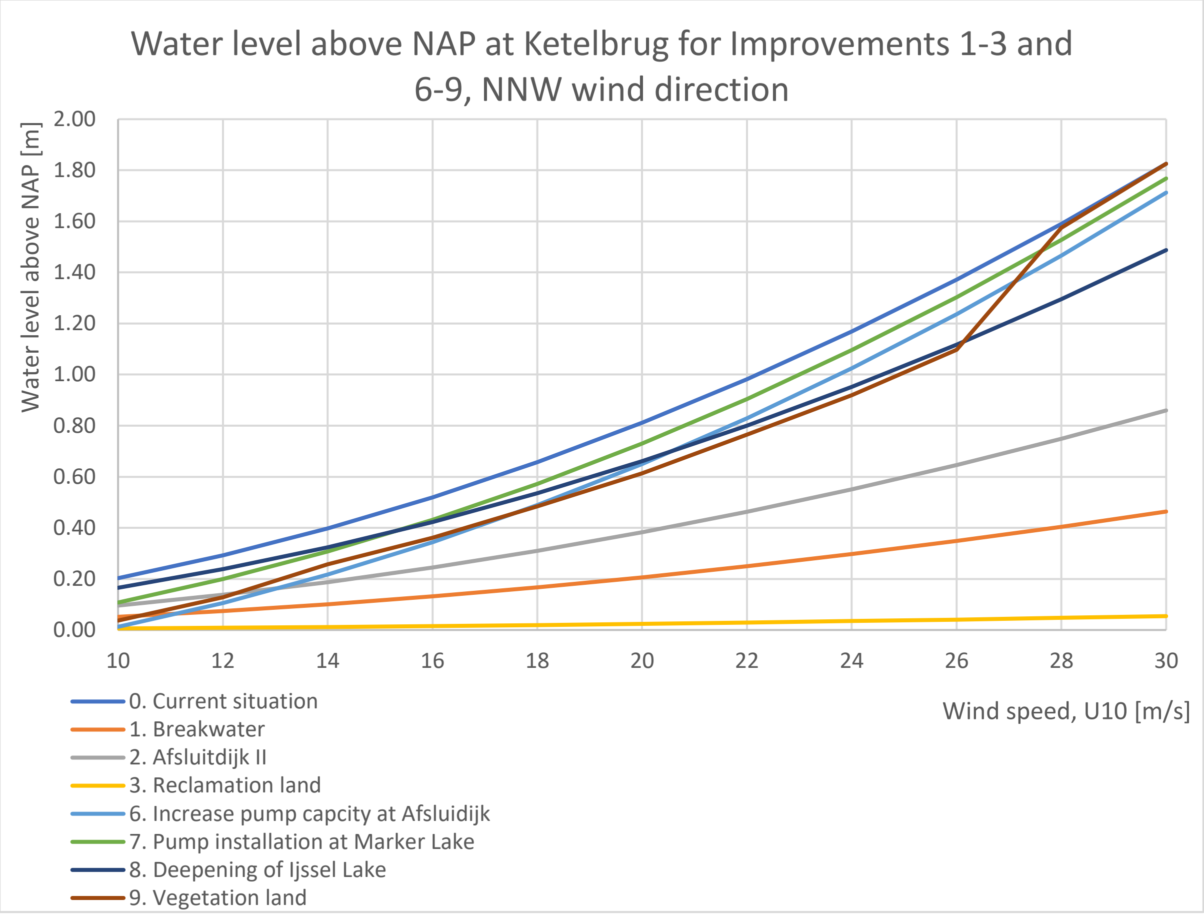


Figure 46 Water level above NAP at Ketelbrug for Improvements 1-3 and 6-9, NNW wind direction

Comparative results of water level at Ramspol Barrier

The calculation parameters for the Improvements 4-5 can be seen in the following Table 21.

Table 21 Calculation parameters for Improvements 4-5

Parameter	Value	Unit
g=	9.81	[ms-2]
κ=	0.0000034	[-]
F_W=	11000	[m]
d_{mW}=	4.5	[m]

The water level/wind speed graph for Improvements 4-5 can be found in the following Figure 47.

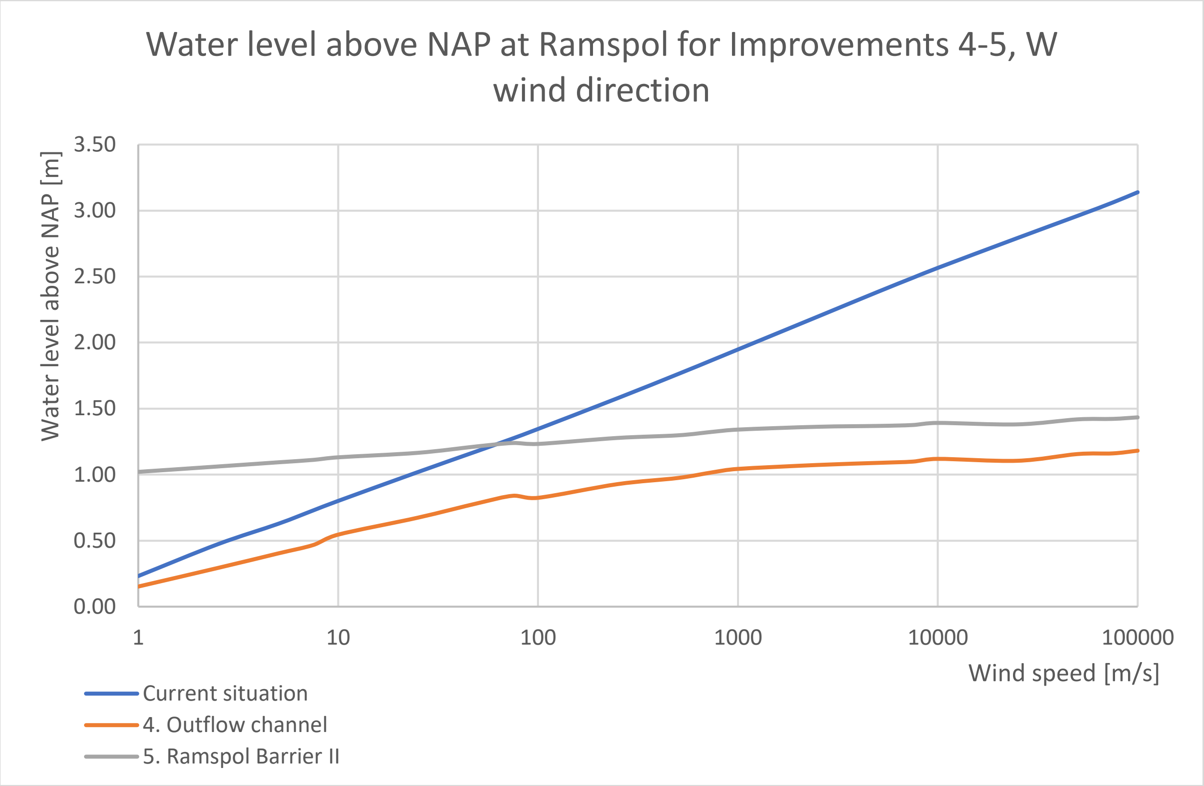


Figure 47 Water level above NAP at Ramspol for Improvements 4-5, W wind direction

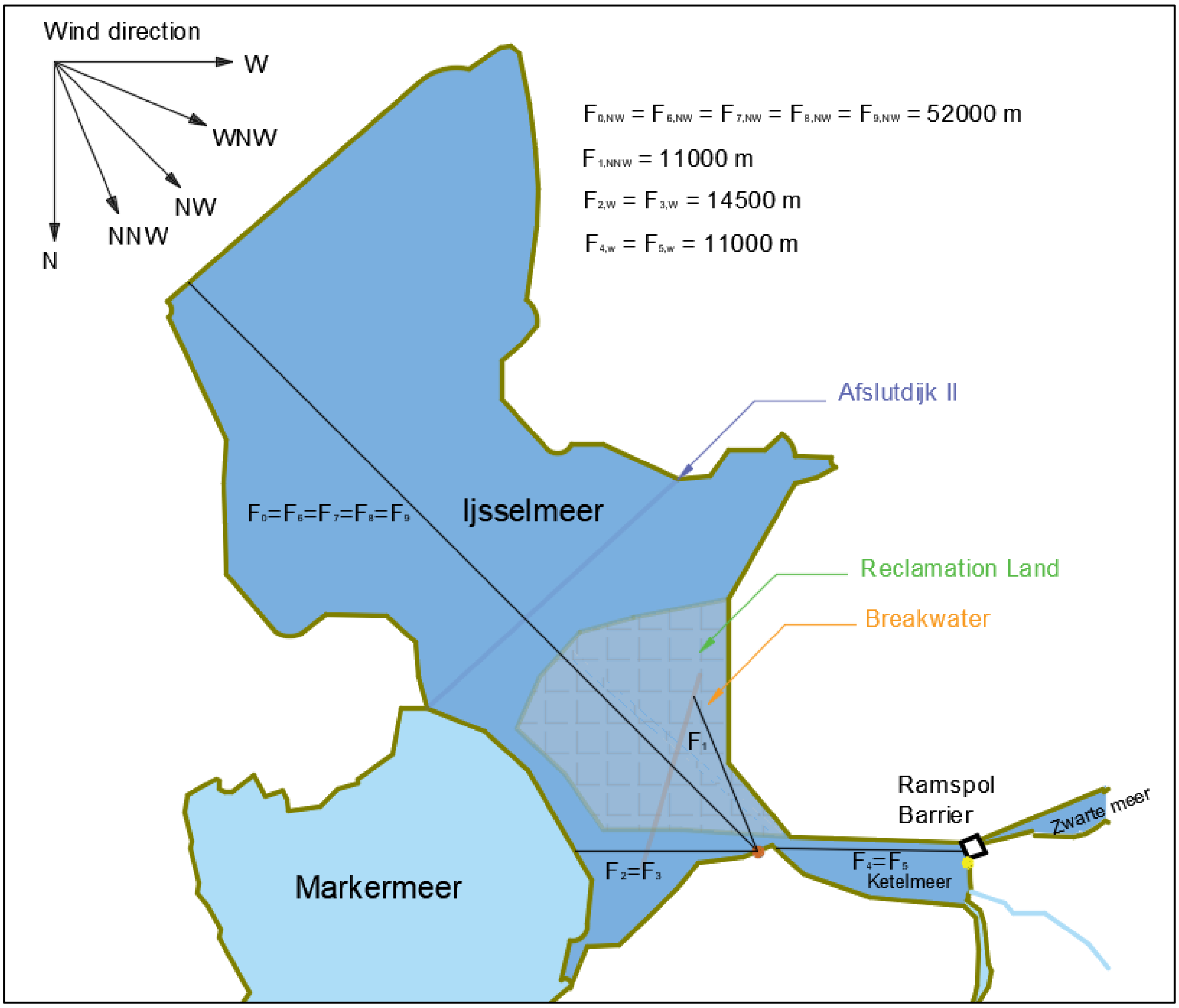
Important wind direction per improvement

As has been previously discussed, it is important to obtain the wind direction per Improvement which can lead to the highest water levels in the characteristic calculation point. This can be found in the following Table 22. The analytical tables with the calculation of wind set-up and water level results for each improvement, for different wind directions and wind velocities, can be found in the Appendix F. Also, a table with the highest water level per improvement and wind direction can be found in the Appendix F.

Table 22 Wind direction per improvement which leading to the highest water level

Wind direction causing the maximum wind set-up per improvement		
Wind direction	Improvement	
NW	0	Current situation
NNW	1	Breakwater
W	2	Afsluitdijk II
W	3	Reclamation land
NW	6	Increase pump capacity at Afsluitdijk
NW	7	Pump installation at Marker Lake
NW	8	Deepening of IJssel Lake
NW	9	Vegetation land
W	4	Outflow channel
W	5	Ramspol Barrier II

A map representing the related fetch lengths for the wind direction causing the maximum wind set-up per improvement is following (Map 10).



Map 10 Fetch length per wind direction which leading to the highest water level per improvement

Finally, in order to calculate the water level per improvement for different return periods, the wind speeds (associated with return periods and wind directions) provided from Hydra-NL, the identified important per improvement wind directions and fetches have been used. The results of the calculation for the improvements 1-9 can be found in the cumulative Tables 18 and 19 and Figures 40, 41 and 42.

5.1.1.2 Improvements decreasing water level in Zwarte Lake

For the calculation of the influence of the Improvements 12-16 in Zwarte Lake, the lake-level formula discussed in Chapter 4 has been used, in order to calculate the decrease that each intervention causes to the water level, which has initially been calculated by Hydra-NL. Hydra-NL provides results for a running time of 12 hours. It is known that by the time that the wind starts blowing with sufficient wind speed, one hour later, the water level at the Ramspol Barrier reaches the closing level of NAP + 0.5 m and a reverted flow direction is observed. Thus, a time period of 11 hours would be wise to use in order to be on the safe side for the calculation.

The calculation for water levels with Hydra-NL, has been executed for the dike section “Vechtdelta_9-2_037_ZM_km0001” (Figure 48), for return periods from 1 to 100000.

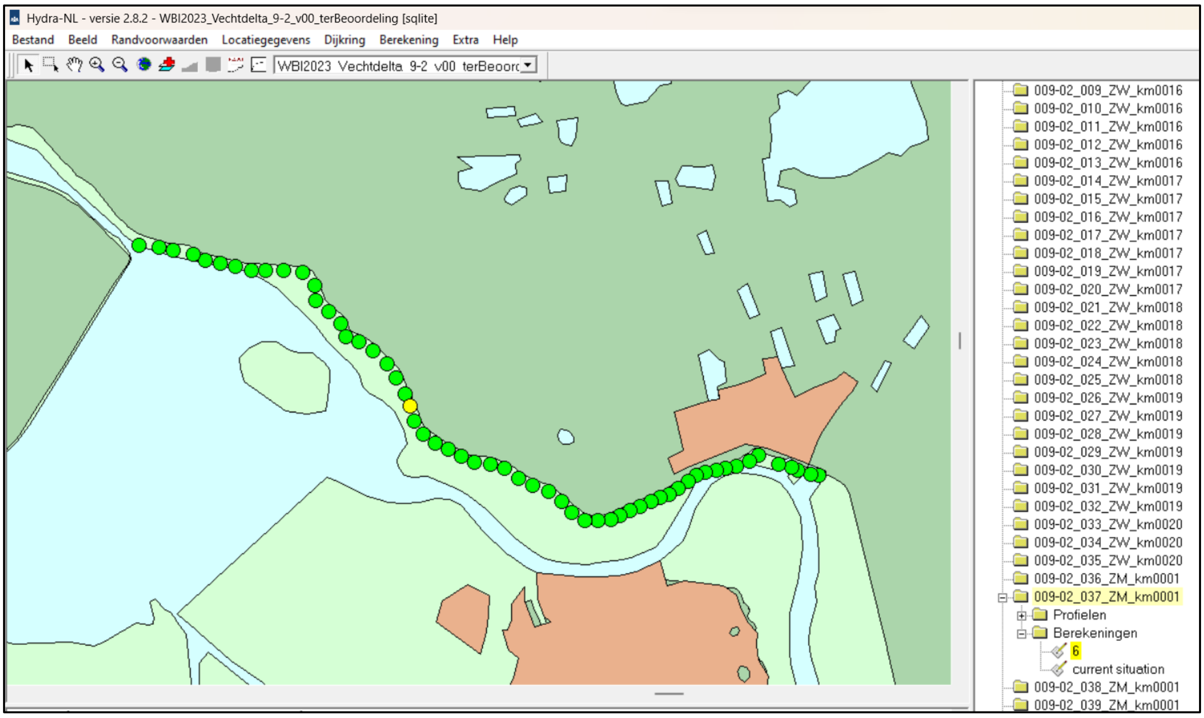
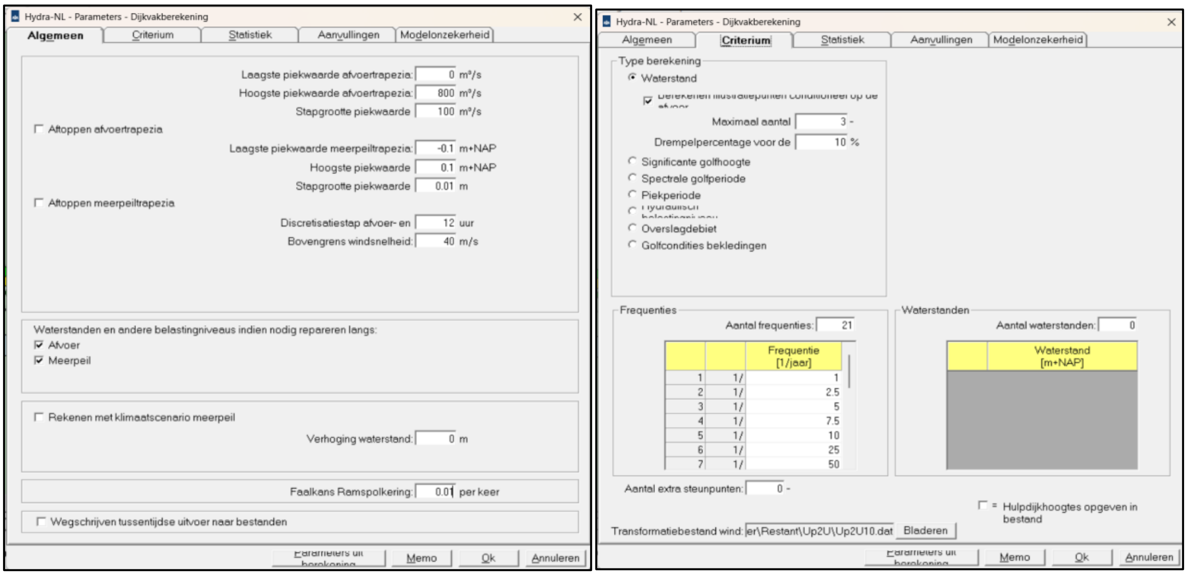


Figure 48 Hydra-NL, calculation point on the map "Vechtdelta_9-2_037_ZM_km0001", in Zwarte Lake

The model parameters used for the calculation of the water levels by Hydra-NL, can be seen in the following Figure 49.



Laagste piekwaarde afvoertrapezia: 0 m³/s
Hoogste piekwaarde afvoertrapezia: 800 m³/s
Stapgrootte piekwaarde 100 m³/s
☐ Aftoppen afvoertrapezia
Laagste piekwaarde meerpeiltrapezia: -0.1 m+NAP
Hoogste piekwaarde 0.1 m+NAP
Stapgrootte piekwaarde 0.01 m
☐ Aftoppen meerpeiltrapezia
Discretisatiestap afvoer- en 12 uur
Bovengrens windsnelheid: 40 m/s

Waterstanden en andere belastingniveaus indien nodig repareren langs:
☑ Afvoer
☑ Meerpeil

☐ Rekenen met klimaatscenario meerpeil
Verhoging waterstand: 0 m

Faalkans Ramspolkering: 0.01 per keer

☐ Wegschrijven tussentijdse uitvoer naar bestanden

Type berekening
● Waterstand
☑ Berekenen illustratiepunten conditioneel op de afvoer
Maximaal aantal 3 -
Drempelpercentage voor de 10 %
○ Significante golfhoogte
○ Spectrale golfperiode
○ Piekperiode
○ Hydraulisch belastingniveau
○ Overslagdebiet
○ Golfcondities bekledingen

Frequenties
Aantal frequenties: 21

		Frequentie [1/jaar]
1	1/	1
2	1/	2.5
3	1/	5
4	1/	7.5
5	1/	10
6	1/	25
7	1/	50

Waterstanden
Aantal waterstanden: 0

	Waterstand [m+NAP]

Aantal extra steunpunten: 0 -
☐ = Hulpdijkhoogtes opgeven in bestand
Transformatiebestand wind: er\Restant\Up2U\Up2U10.dat

Figure 49 Hydra-NL setting the calculation model parameters

The calculation parameters used for the calculation of the reduction of water level for each improvement can be seen in the following Table 23.

Table 23 Lake-level formula parameters for Improvements 12-16

Parameter	Unit	0. Current situation	12. Pump Installation at Ramspol	13 Extension of Vollenhover channel	14. Size up Zwarte Lake	15. Faster closure procedure	16. Closure procedure at a lower level
A	[m^2]	21500000	21500000	21500000	32250000	21500000	21500000
Q_{out}	[m^3/s]	no	100	100	no	no	no
T	[sec]	43200	43200	43200	43200	43200	43200
h_o	[m]	0.00	0.00	0.00	0.00	-0.05	-0.10

The results of the calculation for Improvements 12-16, can be found in the cumulative Tables 18 and 19 and Figures 40, 41 and 42.

Moreover, the influence of different pump capacity values to the water level has been investigated (Figure 50). The associated calculations can be found in Appendix F. However, using high values of pump capacity (150-200 [m^3/s]) at the suggested pump station at Ramspol, could introduce uncertainty. This is happening because Zwarte Lake is a considerable shallow lake with a depth around 1 m and thus wind set-up plays an important role to the high-water levels in the lake. For the calculation of the water level in Zwarte Lake, the water levels calculated by Hydra-NL are getting used. Since the model does not use high values of the discharge of Zwarte Water River, by introducing an improvement with high pump capacity at Zwolle, would mean decrease in the initial water level and thus even higher wind set-up in the lake. For avoiding this uncertainty, a pump capacity of 100 m^3/s will be used.

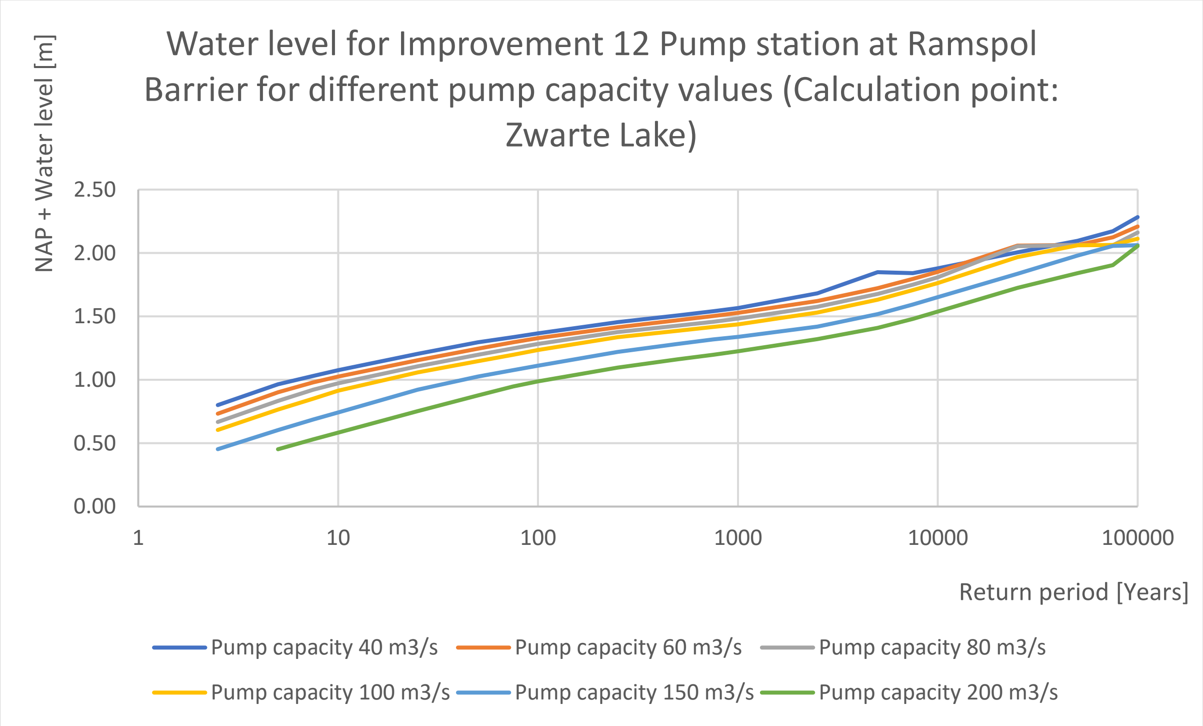


Figure 50 Improvement 12: Pump installation at Ramspol Barrier. Water levels for pump capacity 40, 60, 80, 100, 150 and 200

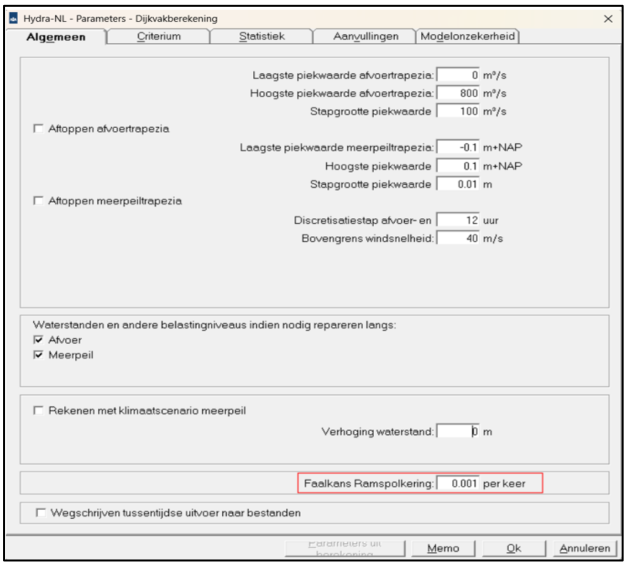
5.1.1.3 Improvements increasing the water capacity in river branches

This category considers 2 improvements (18. River widening and 19. Flood plains). As discussed in Chapter 5 Improvement 18. River widening will not be handled. The calculation point which has been selected for that case, is directly the “calculation point of interest” (dike section “Vechtdelta_10-

01_35_ZW_km0002”), near the city of Zwolle and thus no extra calculations are necessary. For the influence of the Improvement 19 in the water levels at Zwolle, the normal flow depth formula has been used. The width of the main channel of the river has been measured equal to B_m = 80 m. The proposed intervention considers a total width of flood plains of B_f = 250 m. The results of the calculation can be found in the cumulative Tables 18 and 19 and Figures 40, 41 and 42.

5.1.1.4 Improvement 20. Increasing the reliability of Ramspol Barrier

For the calculation of the water level per return period for a higher reliability of Ramspol Barrier (Improvement 20), the Hydra-NL model has been used. The calculation point which has been selected for that case, is directly the “calculation point of interest” (dike section “Vechtdelta_10-01_35_ZW_km0002”), (Figure 38) near the city of Zwolle and thus no extra calculations are necessary. The initial failure probability for the Ramspol Barrier, that Hydra-NL is considering by default, is 0.01. Through Hydra-NL (Test mode), the capability of changing the Ramspol Barrier’s failure probability is provided. The probability that will be used for the increase of the reliability of the barrier Improvement, is 0.001 (Figure 51). The results of the calculation can be found in the cumulative Tables 18 and 19 and Figures 40, 41 and 42.



Laagste piekwaarde afvoertrapezia: 0 m^3/s
Hoogste piekwaarde afvoertrapezia: 800 m^3/s
Stapgrootte piekwaarde 100 m^3/s
☐ Aftoppen afvoertrapezia
Laagste piekwaarde meerpeiltrapezia: -0.1 m+NAP
Hoogste piekwaarde 0.1 m+NAP
Stapgrootte piekwaarde 0.01 m
☐ Aftoppen meerpeiltrapezia
Discretisatiestap afvoer- en 12 uur
Bovengrens windsnelheid: 40 m/s

Waterstanden en andere belastingniveaus indien nodig repareren langs:
☑ Afvoer
☑ Meerpeil

☐ Rekenen met klimaatscenario meerpeil
Verhoging waterstand: 0 m

Faalkans Ramspolkering: 0.001 per keer

☐ Wegschrijven tussentijdse uitvoer naar bestanden

Figure 51 Parameters setting to Hydra-NL, Ramspol Barrier failure probability=0.001

5.1.2 Uncertainty to the estimated water levels

Finally, the uncertainty has been applied as previously discussed (Chapter 4) in the water levels for the return period of 100,000 years (Table 24).

Table 24 Uncertainty adjusted in water levels

	Improvement	Water level at Zwolle [m]		Water level reduction [m]	Level of uncertainty	Increase of calculated water level (%)	Water level with uncertainty adjusted at Zwolle [m]
1	Breakwaters	1.26		1.13	High	10.0	1.39
2	Afsluitdijk II	2.29		0.10	Medium	7.5	2.46
3	Land reclamation	2.29		0.10	Medium	7.5	2.46
4	Outflow channel (groynes)	1.18		1.21	High	10.0	1.30
5	Ramspol Barrier II	1.43		0.96	High	10.0	1.57
6	Increase Afsluitdijk pump capacity (0.2 m decrease in 5.4 days)	2.27		0.12	Medium	7.5	2.44
7	Pump installation at Marker Lake (0.1 m decrease in 5.4 days)	2.33		0.06	Medium	7.5	2.50
8	Lake deepening	1.96		0.43	Medium	7.5	2.11
9	Vegetation area	2.39		0 (for return periods ≥5000 years)	Very high	15.0	2.75
12	Pump installation at Ramspol (pump capacity 40-200 m^3/s)	$[m^3/s]$	[m]		Low	5.0	
		40	2.28	0.11			2.39
		60	2.21	0.18			2.32
		80	2.16	0.23			2.27
		100	**2.11**	**0.28**			**2.21**
		150	2.06	0.33			2.16
		200	2.06	0.33			2.16
13	Extension of Vollenhover channel	2.11		0.28	Low	5.0	2.22
14	Size up Zwarte Lake	1.72		0.67	low	5.0	1.81
15	Faster closure of Ramspol	2.33		0.06	high	10.0	2.56
16	Decrease of the closing water level of Ramspol Barrier	2.25		0.14	medium	7.5	2.42
17 (0)	Raising of the dikes	2.39		-	very low	2.5	2.45
19	Flood plains (1 km river reach)	1.79		0.60	high	10.0	1.97
20	Increase the reliability of Ramspol Barrier	2.20		0.19	very low	2.5	2.25

5.1.3 Grading of the decrease of water level maximum aspect

To apply the grades on the decrease of water level maximum aspect, first the range of the expected water levels caused by the different improvements, has been identified. The lowest water level has been graded with a 9 and the highest with a grade = 1 (Table 25). For the intermediate calculated water levels, the technique of the linear interpolation has been used.

Table 25 Grading of the decrease of water level maximum aspect

	Water level [m]	Grade
Lowest	1.30	9
Highest	2.75	1

The calculated grades per improvement for the aspect of the decrease of water level maximum can be seen in the following Table 26.

Table 26 Grade per improvement (Assessment aspect: decrease of water level maximum)

	Improvement	Water level [m]	Grade
1	Breakwater	1.39	8.5
2	Afsluitdijk II	2.46	2.6
3	Reclamation land	2.46	2.6
4	Outflow channel	1.30	9.0
5	Ramspol Barrier II	1.57	7.5
6	Increase Afsluitdijk pump capacity	2.44	2.7
7	Pump installation at Marker Lake	2.50	2.4
8	IJssel Lake deepening	2.11	4.5
9	Vegetation area	2.75	1.0
12	Pump installation at Ramspol Barrier	2.21	4.0
13	Extension of Vollenhover channel	2.22	3.9
14	Size-up Zwarte Lake	1.81	6.2
15	Ramspol Barrier faster closure procedure	2.56	2.0
16	Closing of Ramspol Barrier in a lower water level	2.42	2.8
17	Rising the height of the dikes	2.45	9.0
19	Flood plains	1.97	5.3
20	Increase Ramspol Barrier reliability	2.25	3.7

5.2 Assessment aspect: Cost (construction cost)

5.2.1 Cost estimation and uncertainty

For the calculation of the cost for each designed Improvement, first a table with the costs per unit of structure has been derived. The characteristic costs can be found in the following Table 27. For the assessment aspect of cost the uncertainty will be applied through a cost range per type of structure.

Table 27 Cost per unit of structure

	Type of structure	Unit cost 2016/CPI (€)	Country	Ref.
1.	Breakwaters	20-30 million per km	Developed countries	[49]
2.	Afsluitdijk II	0.42 – 3.35 billion per km	United States	[50]
3.	Land reclamation	250 per m^2	The Netherlands	[51]
4.	Outflow channel (groynes)	20-30 million per km	Developed countries	[49]
5.	Ramspol Barrier II	0.11 million per m (1997 price level)	The Netherlands (Ramspol Barrier)	[53]
6.	Increase Afsluitdijk pump capacity	0.37-1.58 million per m^3/s	Global	[52]
7.	Pump installation at Marker Lake	0.37-1.58 million per m^3/s	Global	[52]
8.	Lake deepening 1. Dredging 2. Transport	13.8 - 17.7 per m^3	The Netherlands	[54]
9.	Vegetation area	4.5 - 8 million per km^2	Developed countries	[55]
10.	Wetland	77729 per ha	Development countries	[55]
11.	Changed roughness area (reef)	25000-80000 per ha	United Kingdom	[55]
12.	Pump installation at Ramspol	0.37-1.58 million per m^3/s	Global	[52]
13.	Extension of Vollenhover channel 1. Mechanical dredging 2. Storage	33.45 – 44.60 per m^3	United Kingdom	[56]
14.	Size up Zwarte Lake 1. Dredging and transport 2. Dike relocation	4.2 – 16.7 per m^3	United Kingdom	[57]
15.	Faster Ramspol's closure procedure	5 - 15 million (1997 price level)	The Netherlands (Ramspol Barrier)	[53]
16.	Decrease of the closing limit of NAP + 0.5 m	-	-	-
17.	Raising of the dikes	5.3 million per km per m raised	Canada	[58]
18.	Widening of river branches 1. Dredging and transport 2. Dike relocation	4.2 – 16.7 per m^3	United Kingdom	[57]
19.	Flood plains	4.2 – 16.7 per m^3	United Kingdom	[57]
20.	Increase the reliability of Ramspol Barrier	8.5 million	The Netherlands (Ramspol Barrier)	[53]

Following this, the dimensions of each intervention and the cost per improvement in millions of euros has been estimated (Table 28). A lower and upper bound is applied through the characteristic cost per unit of structure.

Table 28 Cost per Unit, Dimensions and final construction cost to ***million (€)***

	Type of structure	Unit cost 2016/CPI (€)	Dimensions	Cost million (€)
1.	Breakwaters	20-30 million per km	13 km	260 – 390
2.	Afsluitdijk II	0.42 – 3.35 billion per km	20 km	8,400 – 67,000
3.	Land reclamation	250 per m^2	172,000 m^2	43
4.	Outflow channel (groynes)	20-30 million per km	29 km	580 – 870
5.	Ramspol Barrier II	0.11 million per m (1997 price level)	1,200 m	120 – 140
6.	Increase Afsluitdijk pump capacity (0.2 m decrease in 5.4 days)	0.37-1.58 million per m^3/s	500 m^3/s	185 – 790
7.	Pump installation at Marker Lake (0.1 m decrease in 5.4 days)	0.37-1.58 million per m^3/s	250 m^3/s	93 - 395
8.	Lake deepening 1. Dredging 2. Transport	13.8 - 17.7 per m^3	310,415,820 m^3	4,283 -5,494
9.	Vegetation area	4.5 - 8 million per km^2	172,000 m^2	0.8 – 1.4
12.	Pump installation at Ramspol	0.37-1.58 million per m^3/s	100 m^3/s	37 – 158
13.	Extension of Vollenhover channel 1. Mechanical dredging 2. Storage	33.45 – 44.60 per m^3	18,600,000 m^3	622.2 – 829.6
14.	Size up Zwarte Lake 1. Dredging and transport	4.2 – 16.7 per m^3	32,250,000 m^3	135 – 539
15.	Faster closure of Ramspol	5 - 15 million (1997 price level)	-	5 - 15
16.	Decrease of the closing water level of Ramspol Barrier	-	-	-
17.	Raising of the dikes	5.3 million per km per m raised	60 km	318
19.	Flood plains (1 km river reach) 1. Dredging and transport 2. Dike relocation	4.2 – 16.7 per m^3	375000 m^3	1.6 – 6.3
20.	Increase the reliability of Ramspol	8.5 million	-	6 - 10

All numbers are converted into comparable units, and cost estimations were converted to U.S. dollars at 2016 price levels, unless otherwise specified. This was done using inflation rates for each country based on the consumer price index (CPI).

5.2.2 Grading of the cost aspect

As discussed in the method chapter 5, a cost range has been connected with grades (Table 29). Then, a grade has been calculated, for each estimated cost (Table 30).

Table 29 Range of grade per cost

Grade	Cost
1 - 2	50,000 – 10,000
2 – 3	10,000 – 5,000
3 – 4	5,000 – 1,000
4 – 5	1,000 – 500
5 – 6	500 – 100
6 – 7	100 – 50
7 – 8	50 – 10
8 – 9	10 – 0

Table 30 Grade per improvement (Assessment aspect cost)

	Type of structure	Cost million (€)	Grade
1.	Breakwaters	260 – 390	5.6 - 5.3
2.	Afsluitdijk II	8,400 – 67,000	2.3 – 1.4
3.	Land reclamation	43	7.2
4.	Outflow channel (groynes)	580 – 870	4.8 – 4.3
5.	Ramspol Barrier II	120 – 140	5.9
6.	Increase Afsluitdijk pump capacity (0.2 m decrease in 5.4 days)	185 – 790	5.8 – 4.4
7.	Pump installation at Marker Lake (0.1 m decrease in 5.4 days)	93 - 395	6.1 – 5.3
8.	Lake deepening 1. Dredging 2. Transport	4,283 -5,494	3.2 – 2.9
9.	Vegetation area	4.5 – 8.0	8.5 – 8.2
12.	Pump installation at Ramspol	37 – 158	7.3 – 5.8
13.	Extension of Vollenhover channel 1. Mechanical dredging 2. Storage	622.2 – 829.6	4.7 - 4.3
14.	Size up Zwarte Lake 1. Dredging and transport	135 – 539	5.9 – 4.9
15.	Faster closure of Ramspol	5 - 15	8.5 – 7.9
16.	Decrease of the closing water level of Ramspol Barrier	0	9
17.	Raising of the dikes	318	5.5
19.	Flood plains (1 km river reach) 1. Dredging and transport 2. Dike relocation	1.6 – 6.3	8.8 - 8.4
20.	Increase the reliability of Ramspol Barrier	6 - 10	8.4 - 8

5.3 Assessment aspect: Ecological Impact

5.3.1 Ecological sign of improvements for the four important parameters

The ecological impact that each improvement introduces to the water system needs to be addressed. This happens, through evaluating the improvement over 4 important ecological parameters during construction, maintenance and life of the structures. The habitat disturbance, the water quality, the biodiversity and the noise and vibration.

1. Breakwater
   During the construction stage of a breakwater, the local ecosystems will be disturbed because of the construction activities. Moreover, noise and vibration are expected. The water quality during the construction stage of structures like this will be negatively influenced. Finally, more ecosystems can settle on the structure and thus the biodiversity is positively influenced.
2. Afsluitdijk II
   During the construction stage of the "Afsluitdijk II" project, the local ecosystems will be disturbed because of the construction activities. Moreover, noise and vibration are expected. The water quality during the construction stage of structures like this will be negatively influenced. Moreover, the dike will separate the lake in half and the water quality will be decreased since the water flow will not be so easy. Finally, more ecosystems can settle on the structure and thus the biodiversity is positively influenced.
3. Land reclamation
   The creation of reclamation land in the lake can cause significant negative influence in the local ecosystems which were established in the bottom of the lake. The water quality will also be negatively influenced because the water body of the lake will be limited, and the water circulation will be less. The land reclamation will be offered for residential purposes and thus

it is not expected the establishment of new ecosystems. Finally, during the construction stage noise and vibration are expected.

4. Outflow channel
   The construction of a channel which will lead the water out of Ketel Lake is a hard structure with a significant impact to the local ecosystems. Also, the water quality in Ketel Lake can possibly negatively influence because the water circulation and exchange of water will be limited. The biodiversity can be possibly improved as ecosystems can establish on the structure. Finally, during the construction stage noise and vibration are expected.
5. Ramspol Barrier II
   During the construction stage of a new storm surge barrier, the local ecosystems will be disturbed because of the construction activities. Moreover, noise and vibration are expected. No influence on the biodiversity and the water quality is expected.
6. Increase Pump capacity at Afsluitdijk
   During the construction stage of the pump facilities, habitat disturbance on the dikes will be caused. Noise and vibration through the construction also is expected.
7. Pump installation at Marker Lake
   During the construction stage of the pump facilities, habitat disturbance on the dikes will be caused. Noise and vibration through the construction also is expected.
8. Lake deepening
   To increase the depth of IJssel Lake, dredging works are needed. These works create a significant disturbance to the habitats and to the water quality. Moreover, noise and vibration will also disturb the ecosystems in the lake. Finally, the deepening of the lake will create opportunities for species that live in deeper waters.
9. Vegetation area
   Creating a vegetation area would cause an initial disturbance to the species living in the lake. However, in the long term, wetlands create opportunities for species to establish and grow. The water quality is getting improved because of wetlands, however during the construction stage noise and vibration is expected.
10. Wetland
    Creating wetland would have the same influence as Improvement 9: Vegetation area.
11. Area with a difference roughness
    A way to achieve a rougher bottom in the lake, is to place artificial reefs on the bottom of the lake. This will create an initial disturbance to the ecosystems which live in the bottom of the lakes but in the long term can create opportunities for more species to establish and thrive. Thus, the biodiversity improves. Finally, through the construction stage noise and vibration is expected.
12. Pump installation at Ramspol Barrier
    By pumping water out of Zwarte Lake from Ramspol Barrier, a lower water level in the lake will be achieved. Thus, it creates less disturbance to the local habitats by avoiding the flooding. On the other hand, by avoiding the flooding, the biodiversity of floodplains can decrease. The hydrology of the estuary will be influenced less due to the lower water levels. No influence on water quality and noise, vibration disturbance is expected.
13. Extension of Vollenhover channel
    During the extension of the Vollenhover channel, a significant disturbance in the ecosystems will be caused. However, the water quality will be improved in the lake because of more water

circulation through the channel. Moreover, new opportunities for species to establish in the channel will arise.

14. Size up Zwarte Lake
    By sizing up Zwarte Lake, initially a significant disturbance on the local habitats will be caused. However, in the long term there will be more opportunities for species to establish in the lake. The water quality in the lake will also be improved in the long term since there will be more volume of water in the lake. Finally, during the construction stage, noise and vibration may cause some disturbance.
15. Achieve a faster closure procedure at Ramspol Barrier
    A faster closure procedure of Ramspol Barrier will lead to lower water level at Zwarte Lake. The same signs with Improvement 15 are applied.
16. Closure procedure of Ramspol Barrier at a lower water level
    Closing the Ramspol Barrier at a lower water level will lead to lower water level at Zwarte Lake. The same signs with Improvement 15 are applied.
17. Rising the height of the dikes
    By increasing the height of the dikes along the lake and river branches, a significant disturbance in the species which are living along the dikes will be caused. During the construction stage noise and vibration are expected. No influence in the water quality and biodiversity is expected.
18. Widening of the river branches
    For widening the river branches and creating more room for the river, significant local habitats' disturbance would be caused. During the construction stage noise and vibration are expected. However, this room for the river project introduces several opportunities for ecosystems to be established and thrive.
19. Flood plains
    During the construction of the floodplains, disturbance in the local ecosystems will take place. Noise and vibration are expected because of the excavation works. No influence in the water quality in the long term is expected. Finally, the floodplains give the chance to different flora and fauna species to establish and thrive in the area.
20. Increase the reliability of Ramspol Barrier
    Not significant disturbance in the area will be caused because of this intervention. It concerns work in the station and probably replacement of the barrier's elements. The reliability can also be increased by investing on the optimization of the barrier's operation, maintenance, inspection and function procedures.

Following, a cumulative table with the ecological signs of each improvement, is illustrated in Table 31 below.

Table 31 Ecological assessment (Ecological sign) of the improvements

Improvement		Habitat disturbance	Water quality	Biodiversity	Noise and vibration	Sum
1	Breakwaters	-	-	+	-	3(-), 1(+)
2	Afsluitdijk II	-	--	+	-	1(--), 2(-), 1(+)
3	Land reclamation	--	-	--	--	3(--), 1(-)
4	Outflow channel (groynes)	--	-	+	-	1(--), 2(-), 1(+)
5	Ramspol Barrier II	-	-	0	-	3(-)
6	Increase Afsluitdijk pump capacity (0.2 m decrease in 5.4 days)	+	0	0	-	1(-), 1(+)
7	Pump installation at Marker Lake (0.1 m decrease in 5.4 days)	+	0	0	-	1(-), 1(+)
8	Lake deepening	--	-	+	--	2(--), 1(-), 1(+)
9	Vegetation area	--	+	++	-	1(--), 1(-), 1(+), 1(++)
12	Pump installation at Ramspol	+	0	-	0	1(-), 2(+)
13	Extension of Vollenhover channel	--	+	+	--	2(--), 2(+)
14	Size up Zwarte Lake	-	+	++	-	2(-), 1(+), 1(++)
15	Faster closure of Ramspol	+	0	-	0	1(-), 1(+)
16	Decrease of the closing water level of Ramspol Barrier	+	0	-	0	1(-), 1(+)
17	Raising of the dikes	--	0	0	--	2(--)
19	Flood plains (1 km river reach)	--	0	++	-	1(-),1(--),1(++)
20	Increase the reliability of Ramspol Barrier	0	0	0	0	0

*

--	Very negative
-	Negative
0	O effect or not defined
+	Positive
++	Very positive

In order to apply a grade first the net value of the “ecological sign” needs to be calculated (Table 32). A 1(-) value has the same importance with a 1(+) value. A 1(--) value is equal with 2(-) value and a 1(++) value is equal with 2(+) value. Using these relations, the net “ecological sign” can be then calculated.

Table 32 Net value "ecological sign" per improvement

Improvement		Sum	Net
1	Breakwaters	3(-), 1(+)	2(-)
2	Afsluitdijk II	1(--), 2(-), 1(+)	3(-)
3	Land reclamation	3(--), 1(-)	7(-)
4	Outflow channel (groynes)	1(--), 2(-), 1(+)	3(-)
5	Ramspol Barrier II	3(-)	3(-)
6	Increase Afsluitdijk pump capacity (0.2 m decrease in 5.4 days)	1(-), 1(+)	0
7	Pump installation at Marker Lake (0.1 m decrease in 5.4 days)	1(-), 1(+)	0
8	Lake deepening	2(--), 1(-), 1(+)	4(-)
9	Vegetation area	1(--), 1(-), 1(+), 1(++)	0
12	Pump installation at Ramspol	1(-), 2(+)	1(+)
13	Extension of Vollenhover channel	2(--), 2(+)	2(-)
14	Size up Zwarte Lake	2(-), 1(+), 1(++)	1(+)
15	Faster closure of Ramspol	1(-), 1(+)	0
16	Decrease of the closing water level of Ramspol Barrier	1(-), 1(+)	0
17	Raising of the dikes	2(--)	4(-)
19	Flood plains (1 km river reach)	1(-),1(--),1(++)	1(-)
20	Increase the reliability of Ramspol Barrier	0	0

5.3.2 Grading of ecological sign method

It came out that 9 values from 1(+) to 7(-) have been evaluated for the "ecological sign" of the improvements. Thus, a grade of 9 to 1 will be applied respectively (Table 33).

Table 33 Grade per ecological sign

Grade	Ecological Sign
1	-7
2	-6
3	-5
4	-4
5	-3
6	-2
7	-1
8	0
9	1

The grades applied per improvement can be seen in the following Table 34.

Table 34 Grade per improvement (Assessment aspect ecological impact)

Improvement		Net	Grade
1	Breakwaters	2(-)	6
2	Afsluitdijk II	3(-)	5
3	Land reclamation	7(-)	1
4	Outflow channel (groynes)	3(-)	5
5	Ramspol Barrier II	3(-)	5
6	Increase Afsluitdijk pump capacity (0.2 m decrease in 5.4 days)	0	8
7	Pump installation at Marker Lake (0.1 m decrease in 5.4 days)	0	8
8	Lake deepening	4(-)	4
9	Vegetation area	0	8
12	Pump installation at Ramspol	1(+)	9
13	Extension of Vollenhover channel	2(-)	6
14	Size up Zwarte Lake	1(+)	9
15	Faster closure of Ramspol	0	8
16	Decrease of the closing water level of Ramspol Barrier	0	8
17	Raising of the dikes	4(-)	4
19	Flood plains (1 km river reach)	1(-)	7
20	Increase the reliability of Ramspol Barrier	0	8

6. Discussion

In this chapter, the assumption made for the calculations will be discussed. During the calculation several assumptions have been made which could influence the reliability of the results. The uncertainty has been taken into account in all levels of assessment but it is important to address the weaknesses in order to be taken into account for future studies. The types of assumptions which are introduced because of the fast screening procedure (first stage of assessment), will be discussed.

6.1 Assumptions to the assessment of decrease of water level maximum aspect

Simplicity of wind set-up formula

- Depth
  For the estimation of wind set-up with the wind set-up formula, an average value for the depth of IJssel and Zwarte Lake has been considered. In reality the depth of the lakes is not constant and thus the very depth of the lake at different places would have an influence on the wind set-up phenomenon. For example, an analytical model could take into account the differences in the depth of the lake. However, this study concerns a rapid selection of the improvements and thus this approach is not suitable, since it requires more data, research and computational time.
- Kappa (κ)
  Kappa is an empirical friction constant and its value is different for each water system. It depends on a number of parameters as the bottom friction and surface friction and thus it is not only changing by water system but also by the very characteristics of the lake in each location. For example, previous research [59] has provided lower values for the parameter, than the one that is used from Hydra-NL and for the wind set-up formula calculations. For a reliable value of the parameter the specific situation needs to be studied.

The case of Ketel Lake / Ramspol Barrier II

In this study an attempt for validating the wind set-up formula for the Ketel Lake has been made. However, the formula was failing to approach the results which were obtained through Hydra-NL model. This is happening because Hydra-NL, for the case of Ketel Lake, is taking into account the river discharge coming from the IJssel River. A part of this discharge moves to IJssel Lake, but in reality, because of the storm scenarios which are taken into account the water is obstructed to flow to IJssel Lake and thus getting accumulated into Ketel Lake, leading to raising of the water level. As discussed before, for that reason in order to calculate the water level at Ramspol Barrier, the wind set-up formula has not been used in Ketel Lake. Instead, the water elevation (wind set-up) which was calculated at Ketelbrug and in case of an unprotected Ketelbrug would be further pushed into Ketel Lake, has been deducted from the expected water level values (Hydra-NL) at Ramspol. Even with this adjustment, there is some lack of reliability, because the water discharge of IJssel River, would accumulate (all the discharge) in Ketel Lake and no part of it could outflow in IJssel Lake.

Vegetation area

For calculating the influence of the vegetation area to the water level, a reduction parameter has been considered. The values for this parameter are only dependent on observations of a specific storm even at Lake Okeechobee in Florida in 1950. However, every lake has their very characteristics and research in the specific lake needs to be done.

Breakwater

When calculating the wind set-up for the Breakwater (Improvement 1), it is not taken into account possible influence of the wind set-up passing through the gaps between the edges of the breakwater and the mainland. This might have some small influence on the estimated water levels in Ketelbrug.

Simplicity of lake-level formula

As with the case of wind set-up formula, the parameters used in this formula are also roughly estimated, such as the area of the lake, the slope of the lake banks and the depth. Also, the existing floodplains have not been taken into account. It would be wise, this to be calculated with a higher detail.

The case of Zwarte Lake

Through the different calculations and observations of Hydra-NL, it came out that for a median discharge of Zwarte Water River, and a closed Ramspol Barrier scenario, the biggest part of the rising of water level in Zwarte Lake is caused because of the wind set-up in the lake and not because of the river's discharge. Considering that Improvement 15 and 16, faster closure procedure of Ramspol Barrier and closing of Ramspol Barrier in a lower water level respectively introduce an initial lower water level in the lake and the fact the Zwarte Lake is already very shallow, it came out that, the wind-set-up in the lake will be significantly increased. This increase in the water level because of the set-up cannot be applied through the method that this study recommends.

Point of calculations

The points which have been selected for the calculations, are relatively close to the desired location. However, the exact desired location cannot be applied for all cases. For example, for calculating the water level at Ketelbrug, the closest dike section at "Dike Ring 8" has been selected. This difference might indicate some small difference in the water level estimation.

Correlation factor

In order to obtain the water level at the city of Zwolle, correlation factors have been used between the calculation points (Ketelbrug, Ramspol Barrier and Zwarte Lake) and the "calculation point of interest". For doing that, the calculated water levels through Hydra-NL for the different points have been calculated and by division, the correlation factor for different water levels is obtained. By using the linear interpolation and extrapolation technique, then the factor is getting calculated for intermediate water levels. It has been observed that the factor shows a consistency. However, by using the factor for the improvements related with the reduction of wind set-up, a high level of uncertainty is being introduced. This is happening because the generation source of high water levels in IJssel Lake (wind speed), can not be reduced. The parameters (through the applying the improvements) which are responsible for reducing the wind set-up in IJssel Lake are the depth, the fetch length, the roughness of the bottom and not the wind speed. Thus, those improvements do not influence the wind set-up which is being developed in Zwarte Lake. This incosistency introduces a high uncertainty to the estimated water levels in the "calculation point of interest". In fact, it is expected that the calculated water levels will be overestimated.

The case of flood plains

In that case an assumption of a river cross section with only dikes has been made. In reality, along the reach of the Zwarte Water River there are already floodplains in some locations.

6.2 Assumptions to the assessment of cost aspect

For calculating the cost per improvement, the dimensions of each structure have been roughly approached. In reality the exact dimensions and special characteristics of the structures plays an important role in the estimation of the cost. Moreover, the first stage of assessment is taking into account only the associated with the construction costs and not the maintenance operational, life cycle etc., types of costs which occasionally can be higher than the construction cost of a project.

6.3 Assumptions to the assessment of ecological impact aspect

For calculating the “ecological sign” per improvement, the previous knowledge on environmental impact and structures and research has been used. However, it is possible that the impact has been over or underestimated on some cases, because of lack of relevant expertise or documentation.

7. Conclusions and Recommendations for future research

In this chapter, the answer to the research and design question is provided. Several recommendations are described for interesting future research.

7.1 Conclusions and answers to the research and design questions

The assessment method which has been developed for the purposes of this thesis, is fast, reliable, flexible and can provide with more opportunities than the assessment of a specific water system. It depends on reliable calculations (Hydra-NL) and the application of simple formulas for estimating the water level reduction that each improvement is associated with. Lower water levels are connected with lower flood risk, but for this stage of screening of many interventions the focus can be only in the reduction of water level without using more complex probabilistic calculations for the flood risk. This assist to have a fast first estimate of the influence of the different interventions to the water level and flood safety of the area. Because of the fast assessment some uncertainty is introduced and thus the reliability level is not as high as it would if analytical models would have been used. However, this uncertainty is treated by selecting the five most promising interventions. Moreover, except for the reduction of the water level, the method considers the decision-making aspects of cost and ecological impact which is a crucial consideration for such early stages of the assessment. For the assessment of the ecological impact of the interventions, a simple but holistic approach, the "ecological sign" has been developed. The method can consider at the same time hard and soft measures and provide comparative results. Additionally, this method provides the opportunity to the decision makers and researchers to intervene by adjusting the importance of the decision-making aspects. Finally, the same method can be used for similar water systems as represented. For water systems with different characteristics, other formulas can be used for estimating the reduction of water levels.

The answer to the main research and design questions can be seen below.

7.1.1 Research question

How to assess a large number of improvements, which increase the flood safety of the area protected by a storm surge barrier against the effects of climate change, in terms of (1) decrease of water level maximum, (2) cost and (3) ecological impact, in a fast and yet reliable way?

First it is important to have a good understanding of the very characteristics of the water system under research and identify the procedure which can lead to high water levels and thus threatening situations. From the research on the water system, a list of requirements for the improvements has been conducted, which has been considered through the brainstorming procedure. From the brainstorming, a thorough list of twenty improvements, which can positively impact the flood safety in the area of interest (city of Zwolle), has been conducted. Then an assessment method developed, consists of 2 assessment stages. The first stage of assessment is the main objective of this thesis. It is a screening method and with its application, is possible to fast but yet in a reliable manner evaluate the influence of the designed requirements to the three decision making aspects, the decrease of water level maximum (increase of flood safety), the cost and the ecological impact. For selecting the most favourable solutions for the combination of the three decision making aspects, a grading and weighing technique has been used. The uncertainty for the calculation of the water levels and the cost has also been taken into account.

For calculating the water level for different return periods, the Hydra-NL model, the wind set-up formula, the lake-level formula and the normal flow depth formula have been used. Additionally, using the aforementioned formulas and Hydra-NL, the resulting water levels for the designed improvements, have been calculated in different calculation points in the water system. For transferring all the results to the “calculation point of interest” and comparing their influence, correlation factors which have been calculated by using Hydra-NL calculations, have been used. For the calculation of the implementation cost, values for cost, per unit, per type of structure have been found through research. Using approximate dimensions for the designed improvements, the cost has been calculated. Finally, to get an approach of the ecological impact that each intervention is associated with, the term “ecological sign” has been introduced. The concept of the ecological sign has been developed in order to quantify the impact of the intervention in the ecosystems. It represents the positive, neutral or negative ecological impact.

Moreover, an assessment method for the second assessment stage has been proposed. In general, it follows the same approach with the first assessment stage, but it is more detailed. For assessing the decrease of water level maximum of an improvement, the probability of failure of essential dike sections can be estimated with Hydra-NL which is a probabilistic model. More Hydra-NL databases will be needed, to support the changes in the current situation (Breakwater, deepening of the lake, outflow discharge e.g.). For the assessment of the cost, the total cost needs to be calculated. The total cost consists of the implementation/construction cost, the maintenance cost. The management cost, the end-of-life cost and the function loss cost/cost because of failure. Respectively, for the qualitative estimation of the ecological impact, the influence of the interventions on the ecosystems and on specific species will be identified. The grading and weighing technique will also be used.

In this study the second stage of assessment will not be handled since the main research objective is the development of the fast selection method (first assessment stage).

7.1.2 Design question

What is the best strategy to adapt the flood protection system of the area behind the Ramspol barrier to climate change.

Three different distribution scenarios have been considered. For all of the three scenarios, the same improvements lead to the highest assessment value and thus have been selected for the second stage of assessment. Those improvements are:

- 1. Breakwater
- 4. Outflow channel connecting Ketel Lake to centre Ijssel Lake
- 14 Size up Zwarte Lake
- 17. Rising the height of the dikes
- 19. Flood plains

7.2 Recommendations for future research

Bottom roughness and wind set-up

As discussed, the improvements which concern a different lake bottom friction have not been handled. This is happening because the friction constant kappa, κ, which contains the bottom friction, is derived through observation and calibration and not sufficient documentation has been found in order to back up the assessment of the related improvements. That would be interesting to research how the variation of bottom friction can possibly influence this parameter.

Vegetation area / wind set-up in a lake

For the improvement of the vegetation area, a reduction parameter Cm has been used in order to consider the influence of the vegetation to the set-up. The data for the parameter has been obtained through observation in Okeechobee in Florida. That would be an interesting research topic to obtain data for the parameter from research in IJssel Lake. This can be done with a physical model.

Usage of the method for the case of another storm surge barrier

The water system under research in this study is a complex one, as are most of the water systems, which are governed from a storm surge barrier. It would be interesting to apply the same assessment method for deriving the most beneficial improvements for other water systems governed by a storm surge barrier and compare the results.

Usage of the second stage of assessment for a limited number of improvements

In this study, the second stage of improvement is proposed but it is not handled. It would be interesting to conduct the assessment based on that and compare the results.

Validation with numerical models

In order to validate the assessment method which was recommended from this study, it would be interesting to conduct a detailed assessment of the improvements with the usage of numerical models.

Application of uncertainty to the ecological impact decision making aspect

The ecological impact for the purposes of this study has been qualitatively estimated, with the concept of the “ecological sign”, which has been developed by the researcher. The uncertainty in this case was difficult to be introduced because of lack of relevant knowledge and expertise. Even though the researcher’s background is in civil, hydraulic and environmental engineering, it would be optimal for this topic, to be further investigated by a student with deep knowledge on ecology.

Correlation factor

For the purposes of this study, correlation factors have been used in order to transfer the estimated water levels from different calculation points, to the calculation point of interest in the city of Zwolle. It is expected that by using this factor for transfering the water levels from the calculation point in Zwarte Lake to the “calculation point of interest”, the resulting water levels will be reliable. However, there is high uncertainty, as previously addressed in the discussion chapter, when using the correlation factors for the case of Ketelbrug and Ramspol Barrier calculation points. For that reason, it would be important to check the reliability of the correlation factor. This can be done, by using a new database for Hydra-NL, containing one of the designed improvements for limiting the wind set-up in IJssel and Ketel Lake.

Navigation

The navigation is an important aspect for the function of Ramspol Barrier. If an improvement implies more frequent closure of the barrier, the vessels will have difficulties to pass the barrier in accepted time and thus more costs can arise from this situation. In case this factor is important for the decision maker, would be essential to contain it to the decision making aspects. Of couse the extra costs because of delays in navigation need to be taken into account to the cost estimation to the second assessment stage where all the relevant with the function of the barrier costs are recommended to be considered.

References

[1] *https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/stormvloedkeringen/stormvloedkering-ramspol*

[2] http://www.wgs.nl/

[3] Van der Schrier, D. (2000). De balgstuw Ramspol en zijn overlaten. *De Vriendenkring Cultuurhistorisch tijdschrift voor Flevoland*, 25-40.

[4] Kolkman, M. J., van der Veen, A., & Geurts, P. A. T. M. (2007). Controversies in water management: Frames and mental models. *Environmental Impact Assessment Review*, *27*(7), 685-706.

[5] de Graaf, M. (2017). Effect of overtopping discharges on accessibility, maintenance and costs of dikes.

[6] *https://land-id.nl/project/pagw-IJssel-vechtdelta/*

[7] Achtergrondrapportage hydraulische belasting voor de Vechtdelta Juli 2012 Achtergrondrapport WTI-2011 voor de Vechtdelta
https://publications.deltares.nl/1204143_003d.pdf

[8] Eijgenraam, S.J. (2000) De balgstuwkering bij Ramspol. *Cement 7*

[9] *https://www.dmc.nl/projects/inflatable-barrier-ramspol-the-netherlands*

[10] Mooyaart, L. F., & Jonkman, S. N. (2017). Overview and design considerations of storm surge barriers. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *143*(4), 06017001.

[11] Grin, S. (2016). The optimal capacity for temporal control measures for dikes in the IJssel-Vecht delta.

[12] https://emmeloord.info/kadoelerkeersluis/

[13] Chbab, H. (2012). Achtergrondraportage WTI-2011 voor de Vechtdelta. *Deltares, Rijkswaterstaat*.

[14] *https://nl.wikipedia.org/wiki/Meppelerdiep_(kanaal)#Meppelerdiepsluis*

[15] Wet op de Waterkeringen. 1996 Wet, houdende algemene regels ter verzekering van de beveiliging door waterkeringen tegen overstromingen door het buitenwater en regeling van enkele daarmee verband houdende aangelegenheden. Staatsblad 304.

[16] *https://www.wdodelta.nl/*

[17] Vergouwe, R. (2014). De veiligheid van Nederland in kaart: Eindrapportage VNK. *Eindverslag, Document HB2540621*.

[18] De veiligheid van de primaire waterkeringen in Nederland. Voorschrift Toetsen op Veiligheid voor de derde toetsronde 2006-2011 (VTV). Ministerie van Verkeer en Waterstaat, September 2007.

[19] Geerse, C. P. M. (2011). Hydra-zoet for the freshwater systems in the netherlands-probabilistic model for the assessment of dike heights. *PR2168 HKV rapport voor Rijkswaterstaat, Waterdienst;*.

[20] *https://www.nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/fa4cc54e-26b3-4f25-b643-59458622901c?tab=general*

[21] Hydraulische Randvoorwaarden 2006 voor het toetsen van primaire waterkeringen. Ministerie van Verkeer en Waterstaat. Netherlands, Delft, september 2007.

[22] Kok, M., Jongejan, R., Nieuwjaar, M., & Tanczos, I. (2017). Fundamentals of flood protection. *Ministry of Infrastructure and the Environment and the Expertise Network for Flood Protection: The Hague, The Netherlands*.

[23] VNK. (2014). The National Flood Risk Analysis for The Netherlands, Final Report.

[24] Kolen, B., & Geerts, R. (2006). Als het toch misgaat: Overstromingsscenario's voor rampenplannen. *Betooglijn. HKV lijn in water (in Dutch)*.

[25] Schumann, A. (2017). Flood safety versus remaining risks-options and limitations of probabilistic concepts in flood management. *Water Resources Management, 31(10),* 3131-3145.

[26] Ludy, J., & Kondolf, G. M. (2012). Flood risk perception in lands "protected" by 100-year levees. *Natural hazards*, *61*, 829-842.

[27] Jonkman, S. N., Kok, M., Van Ledden, M. K., & Vrijling, J. K. (2009). Risk-based design of flood defence systems: a preliminary analysis of the optimal protection level for the New Orleans metropolitan area. *Journal of Flood Risk Management*, *2*(3), 170-181.

[28] National Research Council. (2013). *Levees and the national flood insurance program: improving policies and practices*. *The National Academies Press*.

[29] National Research Council. (2014). Reducing coastal risk on the east and gulf coasts. *The National Academies Press.*

[30] Lendering, K. T., Sebastian, A., Jonkman, S. N., & Kok, M. (2019). Framework for assessing the performance of flood adaptation innovations using a risk-based approach. *Journal of Flood Risk Management*, *12*(S2), e12485.

[31] KNMI. (2021). KNMI Klimaatsignaal'21: Hoe het Klimaat in Nederland snel Verandert.

[32] Te Linde, A. H., Bubeck, P., Dekkers, J. E. C., De Moel, H., & Aerts, J. C. J. H. (2011). Future flood risk estimates along the river Rhine. *Natural Hazards and Earth System Sciences*, *11*(2), 459-473.

[33] Görgen, K., Beersma, J., Brahmer, G., Buiteveld, H., Carambia, M., De Keizer, O., ... & Volken, D. (2010). *Assessment of climate change impacts on discharge in the Rhine River Basin: results of the RheinBlick2050 project* (p. 211). Lelystad: CHR.

[34] Ter Maat, G.J. & van Meurs, G.A.M. (2010). IJsselmeerpeil bij zeespiegelstijging. Deltares.

[35] KNMI. (2015). KNMI'14 climate scenarios for the Netherlands; A guide for professionals in climate adaptation, KNMI, De Bilt, The Netherlands, 34 pp

[36] Lenderink, G., & Van Meijgaard, E. (2008). Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geoscience*, *1*(8), 511-514.

[37] Schwierz, C., Köllner-Heck, P., Zenklusen Mutter, E., Bresch, D. N., Vidale, P. L., Wild, M., & Schär, C. (2010). Modelling European winter windstorm losses in current and future climate. Climatic change, 101, 485-514.

[38] Saville, T. (1952). Wind set-up and waves in shallow water.

[39] *https://www.nps.gov/articles/coastal-geohazards-seiches.htm*

[40] Hellstrom, B. (1941). Wind effects on lakes and rivers, Ingen. *Vetensk. Akad. Handl*, (158).

[41] Keulegan, G. H. (1951). *Wind tides in small, closed channels*. National Bureau of Standards.

[42] Thijsse, J. T., & Schijf, J. B. (1949). Report on Waves. In *17th International Navigation Congress, Section II, Communication* (Vol. 4).

[43] *https://webapp.navionics.com/#boating@6&key=shy%7BHsieZ*

[44] River Dynamics I, TU Delft, course material

[45] Groot, A. M. E., Lenselink, G., van Slobbe, E. J. J., Meurs, G. A., Noordhuis, R., Wiersma, A., ... & Wilms, T. (2012). *Natuurlijk IJsselmeer: ecodynamisch visie IJsselmeer 2100*. Ecoshape.

[46] https://natura2000.eea.europa.eu/

[47] Leidraad Kunstwerken. (2003, May). TAW. Retrieved from *http://repository.tudelft.nl/assets/uuid:3a3aead8-08a8-4c99-afe9-ada2811d15c1/L15-Leidraadkunstwerken.pdf*

[48] *https://www.cewoordenboek.nl/zoeken?limiet=10&q=maintenance+cost&sortering%5B0%5D=-relevantie&sortering%5B1%5D=-datum&pagina=5*

[49] Aerts, J. C., et al (2018). Sea Level Rise, Flood Risk, and Adaptation Options in Los Angeles.

[50] Aerts, J. C., et al (2013). Cost estimates for flood resilience and protection strategies in New York City., 1294, 1–104.

[51] *https://www.cedaconferences.org/documents/dredgingconference/downloads/2/qatar2008_2008-18-05_41_schaart.pdf*

[52] Aerts, J. C. (2018). A review of cost estimates for flood adaptation. *Water*, *10*(11), 1646.

[53] Van der Valk, K. (2014). Life Cycle Costs: a comparison between inflatable and traditional barriers.

[54] Timmermans, M. Beheerplan Baggerwerken Waterschap Hollandse Delta. 2014, p. 32. *https://www.wshd.nl/binaries/content/assets/wshd---website/common/agendapunt_12_beheerplan_ baggerwerken_2014-2018.pdf*

[55] Bayraktarov, E., Saunders, M. I., Abdullah, S., Mills, M., Beher, J., Possingham, H. P., ... & Lovelock, C. E. (2016). The cost and feasibility of marine coastal restoration. *Ecological Applications*, *26*(4), 1055-1074.

[56] Jones, P., Keating, K., & Pettit, A. (2015). Cost estimation for channel management–summary of evidence. *Bristol, England: Environment Agency*.

[57] City of Bath. Bath and North East Somerset Flood Risk Management Strategy Report. Appendix J. *http://www.bathnes.gov.uk/sites/default/files/sitedocuments/Planning-and-Building-Control/Planning-Policy/Evidence-Base/Flood-Risk/FRMSAppendixJ.pdf*

[58] Lenk, S., Rybski, D., Heidrich, O., Dawson, R. J., & Kropp, J. P. (2017). Costs of sea dikes–regressions and uncertainty estimates. *Natural Hazards and Earth System Sciences*, *17*(5), 765-779.

[59] Feij, C. C. L. (2015). Nauwkeurigheid van formules voor windopzet aan de hand van meetgegevens van het IJsselmeer.

[60] voor de Leefomgeving, P. B. (2010). Correctieformulering over overstromingsrisico. *http://www.pbl.nl/dossiers/klimaatverandering/content/correctie-formulering-over-overstromomgsrisico*

[61] *https://www.government.nl/topics/delta-programme/delta-programme-flood-safety-freshwater-and-spatial-adaptation*

[62] Nillesen, A. L. (2019). Integrated Design for Flood Risk and Spatial Quality Enhancement: Examples from the Dutch Delta Programme. *A+ BE| Architecture and the Built Environment*, (1), 147-175.

[63] de Bake, D., Wolters, A. (2006) Safety assessment of primary flood defences in the Netherlands. An ongoing concern. *Rijkswaterstaat.*

[64] Slomp, R. (2016). Implementing risk-based flood defence standards. *Rijkswaterstaat: Rotterdam, The Netherlands*.

[65] PIANC Working Group 26. (2006). Design of movable weirs and storm surge barriers (Tech. Rep. No. ISBN 2-87223-154-4). PIANC. Retrieved from *http://pianc.us/workinggroups/docs_wg/incom-wg26 .pdf*

[66] Dircke, P. T. M., Jongeling, T. H. G., & Jansen, P. L. M. (2012). An overview and comparison of navigable storm surge barriers. In *Proceedings, Innovative Dam and Levee Design and Construction, USSD conference, New Orleans, LA, April*.

[67] Jongeling, T. H. G. (2005). Hydraulische aspecten van balgstuwen en balgkeringen, Rijkswaterstaat.

[68] Geerse, C. P. M. (2009). Overzichtsdocument probabilistische modellen zoete wateren – Hydra-VIJ, Hydra-B en Hydra-NL. *PR1391 HKV rapport voor Rijkswaterstaat, Waterdienst;*.

[69] Geerse, C. P. M. (2003a). Probabilistisch model hydraulische randvoorwaarden IJssel- en Vechtdelta. *RIZAwerkdocument 2003.129x voor Rijkswaterstaat, Waterdienst;.*

[70] Geerse, C. P. M. (2003a). Probabilistisch model hydraulische randvoorwaarden Benedenrivierengebied. *RIZAwerkdocument 2003.128x voor Rijkswaterstaat, Waterdienst;.*

[71] Geerse, C. P. M. (2004). Hydraulische randvoorwaarden Benedenrivierengebied, Methodiek dijkbekledingen. *RIZAwerkdocument 2004.140x voor Rijkswaterstaat, Waterdienst;.*

[72] van Manen, S. (2008). Prestatiepeilen Oosterschelde – Vervolg. *Voor Rijkswaterstaat, Waterdienst;*.

[73] Geerse, C. P. M. (2008a). Methode effectbepaling overgangsgebieden – Afschatten effect van een maatregel op de waterstanden met conditionele illustratiepunten. *PR1534.10 HKV rapport voor Rijkswaterstaat, Waterdienst;.*

[74] Geerse, C. P. M. (2008b). Memorandum Managementsamenvatting – Uitwerken methodiek overgangsgebieden. *PR1534.10 HKV rapport voor Rijkswaterstaat, Waterdienst;.*

[75] van Nieuwenhuijzen, L.W., Geerse C.P.M., Bosters M. (2010). Aansluiting Hydra's op VTV-tools voor bekledingen in WTI2011. 9V6063.A0 Royal Haskoning en HKV lijn in water.

[76] Hoogeveen, J., & Hoogeveen, H. (2023). Winds are changing: An explanation for the warming of the Netherlands. *International Journal of Climatology*, *43*(1), 354-371.

[77] USACE. (1996). Risk-based analysis for flood damage reduction studies-Manual No. 1110-2-1619.

[78] Lund, J. R. (2002). Floodplain planning with risk-based optimization. *Journal of water resources planning and management*, *128*(3), 202-207.

[79] Voortman, H. G., Van Gelder, P. H. A. J. M., & Vrijling, J. K. (2003). Risk-based design of large-scale flood defence systems. In *Coastal Engineering 2002: Solving Coastal Conundrums* (pp. 2373-2385).

[80] Dupuits, E. J. C., Schweckendiek, T., & Kok, M. (2017). Economic optimization of coastal flood defense systems. *Reliability Engineering & System Safety*, *159*, 143-152.

[81] Gouldby, B., Sayers, P., Mulet-Marti, J., Hassan, M. A. A. M., & Benwell, D. (2008, June). A methodology for regional-scale flood risk assessment. In *Proceedings of the Institution of Civil Engineers-Water Management* (Vol. 161, No. 3, pp. 169-182). Thomas Telford Ltd.

[82] Aerts, J. C., Botzen, W. W., Emanuel, K., Lin, N., De Moel, H., & Michel-Kerjan, E. O. (2014). Evaluating flood resilience strategies for coastal megacities. *Science*, *344*(6183), 473-475.

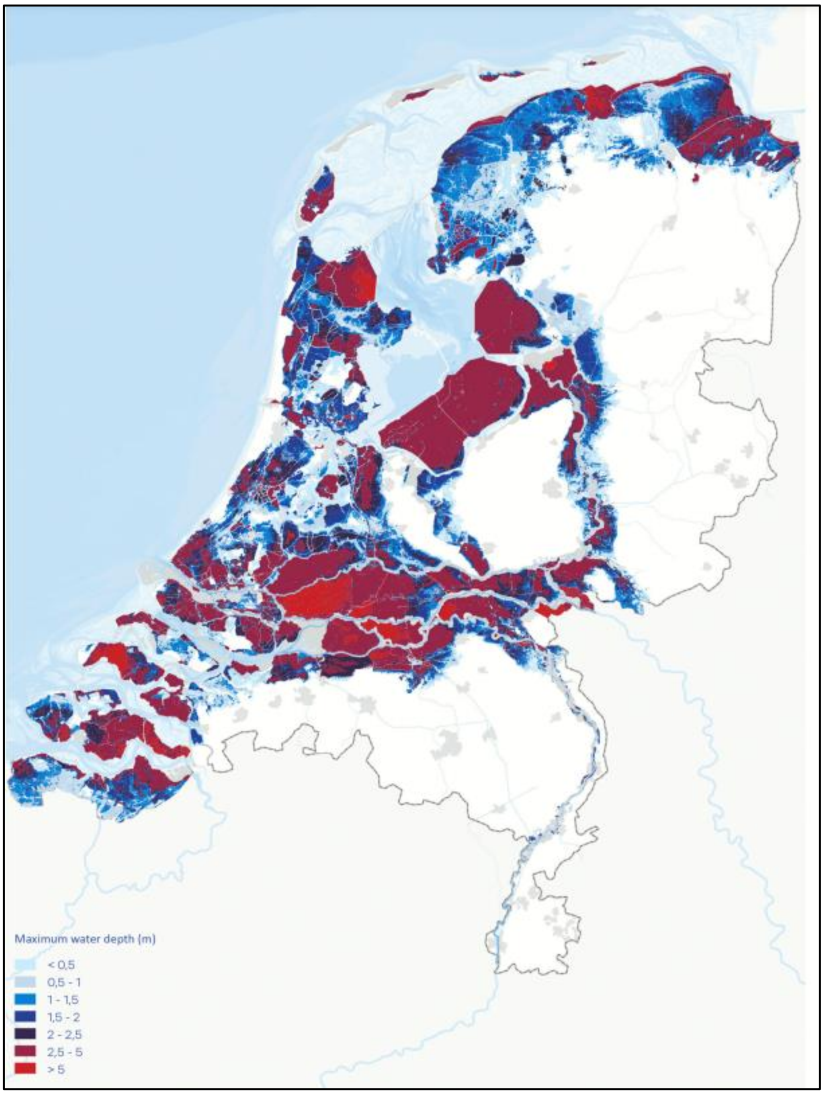
[83] van Berchum, E. C. (2019). Rapid screening and evaluation of flood risk reduction strategies. *Global Facility for Disaster Reduction and Recovery*.

Appendices

Appendix A – Flood defences

The protection against flooding is of vital importance for the Netherlands, since almost 26% of the Netherlands lies below sea level [60] and 60% of the Netherlands is liable to flooding from the sea, lakes and major rivers (See Map 11). In 1953 the southwest of the Netherlands was hit by a disastrous flood that led to loss of human life. In the early 1990s, the rivers in Limburg burst their banks [61]. This is why the Dutch government designed the Delta Programme, aiming:

- to protect the Netherlands from flooding now and in the future,
- to secure sufficient supplies of freshwater and
- to make the country climate proof.



Map 11 60% of the Netherlands is liable to flooding from the sea, lakes and major rivers [62]

Since then, through Delta Programme, the central government, provincial and local authorities and water authorities have worked together with input from civil society and private sector to protect the Netherlands from flooding. During these years, multiple structures as levees, dikes, dunes and barriers have been constructed. Those structures are called flood defences and their primary objective is to provide protection against flood events along coasts, rivers and waterways. Besides the flood defences structures, other measures which lie under the room for the river philosophy have been constructed.

A.1 Categories of flood defences

According to the Flood Defence Act (FDA), in the Netherlands, the flood defences are distinguished in primary and secondary (regional) defences. Primary defences are those that directly or indirectly protect a low-lying area against flooding, from an external load of water. The source of the water load can be the sea or large rivers. The secondary flood defences are dikes or dams with smaller importance and managed by the waterboards.

There are three categories of primary flood defences a, b, and c (Figure 52).

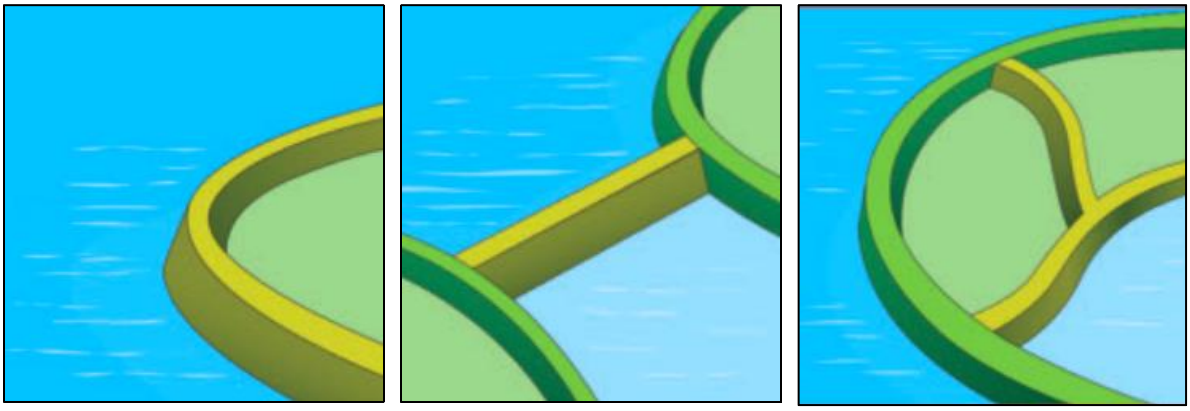


Figure 52 Flood defence category a (left), b (middle) and c (right) [63]

- Flood defences in category a (a defences) include dikes, dunes and hydraulic structures which provide direct protection against the sea, the major rivers, and lakes.
- Flood defences in category b (b defences), such as the Afsluitdijk or the Maeslant storm surge barrier, connect flood defences in either category a or c. Ramspol barrier also belongs in this category b of flood defences.
- Flood defences in category c (c defences) are defences, which provide indirect protection against flood water. An example of these is the flood defences along the North Sea Channel (Noordzeekanaal) [63].

A.2 Types of flood defences

The most important types of flood defences (Figure 53, 54 and 55) are:

Dikes

A dike is a water retaining structure which consists of soil with a sufficient height and strength to be able to withstand the water load under extreme circumstances. The main purpose of a dike is protecting the land behind it against high water.

Dams

A dam is a water retaining structure. The difference between dikes and dams is that the dams are a barrier between two water bodies whereas dikes only have water on one side of the barrier. For example, the Afsluitdijk, which separates IJssel Lake from Wadden Sea, is a dam. Other examples of dams in the Netherlands are the Brouwersdam and the Haringvlietdam, both belonging to Deltaworks concept. In many countries around the world dams are applied in river systems for purposes of water management, energy generation, irrigation or navigation.

Storm Surge Barriers (will be further discussed in Chapter 2.3)
A storm surge barrier is a partially movable flood defence in a river, a lake or an estuary (Figure 53 and 54). A storm surge barrier is most of the time open giving access to navigation and regular water flow. They are only closing during high water levels to prevent flooding of the area behind the barrier. Typical examples of storm surge barriers in the Netherlands are the Maeslant barrier near Hoek van Holland and the Eastern Scheldt storm surge barrier (Oosterschelde barrier). The inflatable storm surge barrier at Ramspol is an innovative barrier, first of its kind protecting the hinterland against highwater levels from IJssel Lake and Vecht River.

Flood walls
A flood wall is a water retaining structure which is built out of concrete, steel or wood. Due to the high horizontal forces to those vertical elements, it is also necessary to have solid foundations.

Dunes
A dune is a hill of sand along the coast, which can be either man made or formed by natural processes. Dunes are getting eroded naturally from waves and wind supplying the beaches with sand. Dunes provide protection against storm surges especially through their large sand volume.

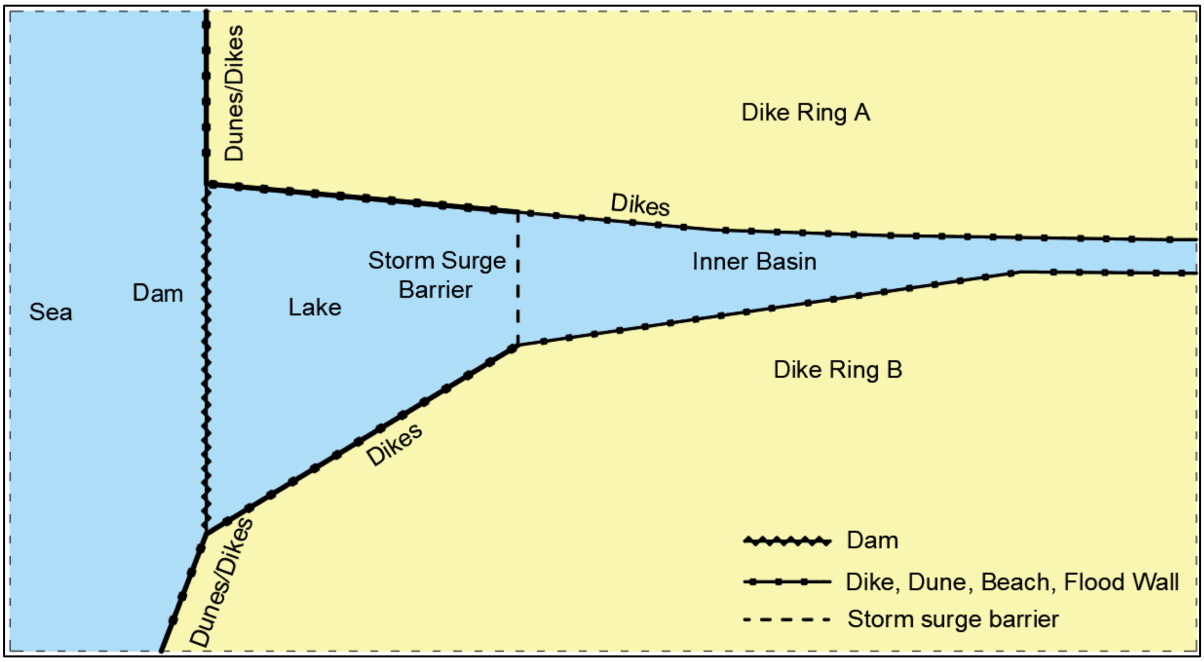


Figure 53 Flood defences at an estuary (dam and storm surge barrier)

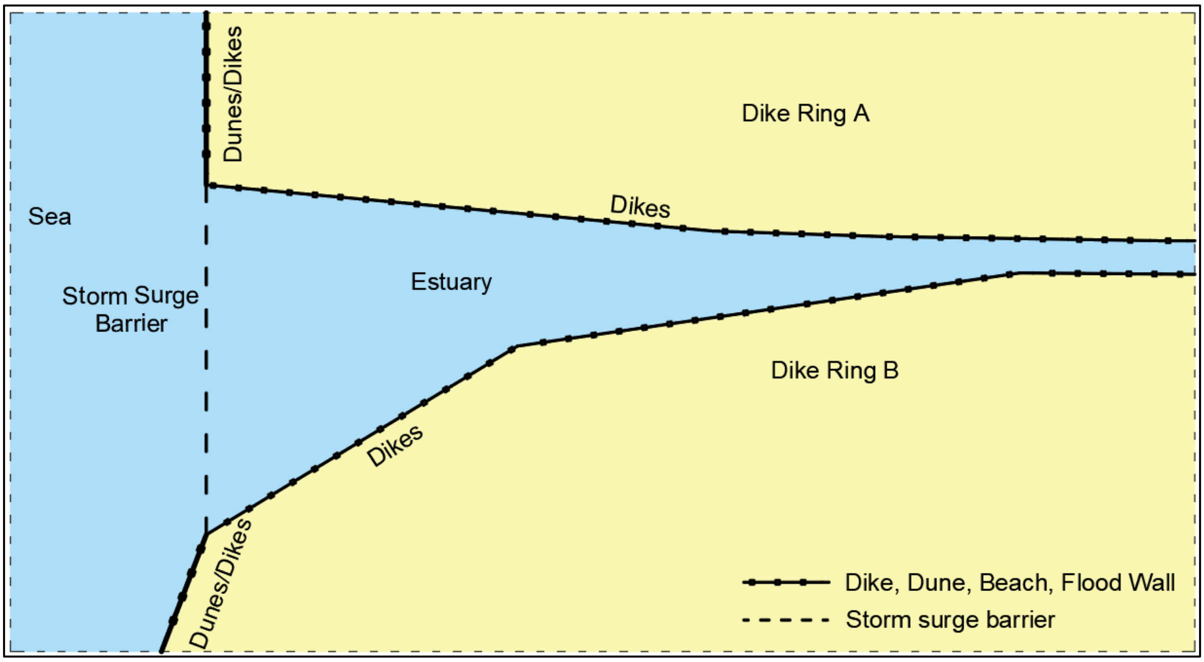


Figure 54 Flood defences at an estuary (storm surge barrier)

A continuous line of flood defences consisting of dikes, dunes, hydraulic structures and natural high ground (Figure 55) is called a dike ring [64].

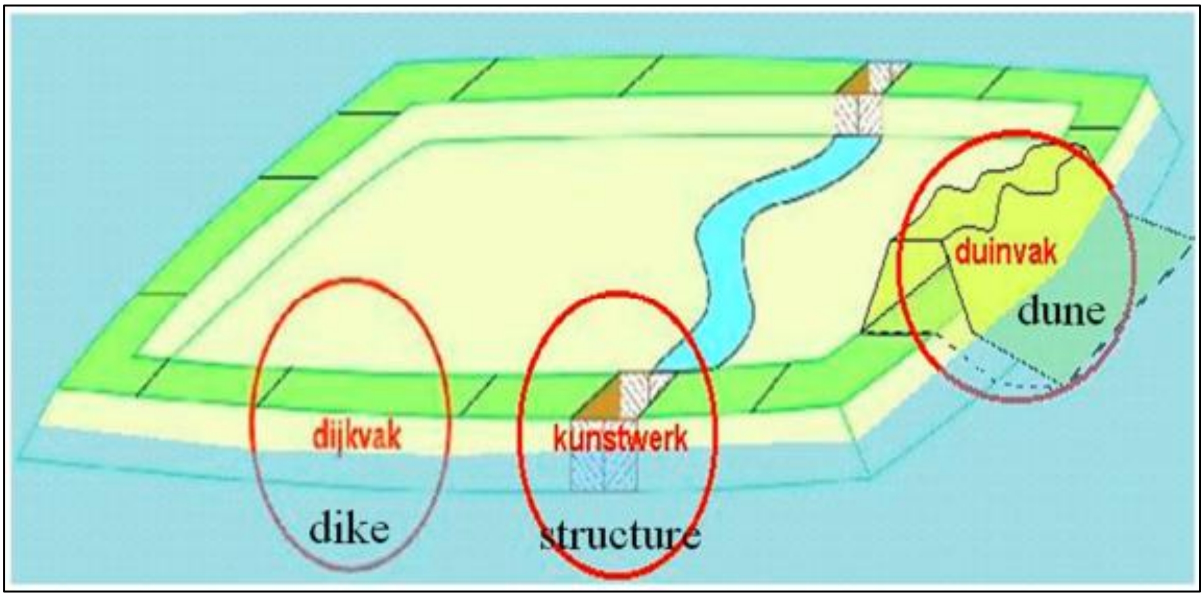


Figure 55 "Dike ring" is a continuous line of flood defences [64]

Apart from the above-mentioned types of flood defences, other measures can be implemented to reduce the probability of flooding. Examples are measures that can be taken in the riverbed to increase the discharge capacity of the river such as increasing the width of the floodplains. These interventions belong to the "Room for the river" concept.

A.3 Types of storm surge barriers

As mentioned, a storm surge barrier is a partially moveable barrier in an estuary, lake or a river branch which can be closed temporarily. The ration of the cross section of the barrier must be large enough to allow sufficient circulation flow during normal conditions. This is a crucial factor for the water ecosystems and quality. A temporary closure is defined as either [65]:

- A closure which is required to protect against flooding the inner area, starting from the moment of closing until the water level outside from the barrier has been dropped sufficiently. Overflow and increased inner water levels are considered.
- A closure required for the maintenance or repair of the barrier.

The main purpose of a barrier during surges is to reduce or prevent the rise of the water level in the protected side and thus sufficiently protect the hinterland area against flooding. Sufficiently regards the maximum permitted water level which is also influenced by river runoff and is determined by the height and safety standards of the dike ring behind the barrier.

Every location which needs a storm surge barrier is different and thus all the barriers are different in between them. Every barrier is especially designed for a specific water system. Although there are no two identical barriers, some types of barriers can be recognized (Figure 56). The basic types of storm surge barriers can be summarised in the following list:

- Inflatable barrier
- Mitre gate
- Horizontal rotating barrier
- Flap gate
- Vertical lifting doors
- Vertical rotating barrier

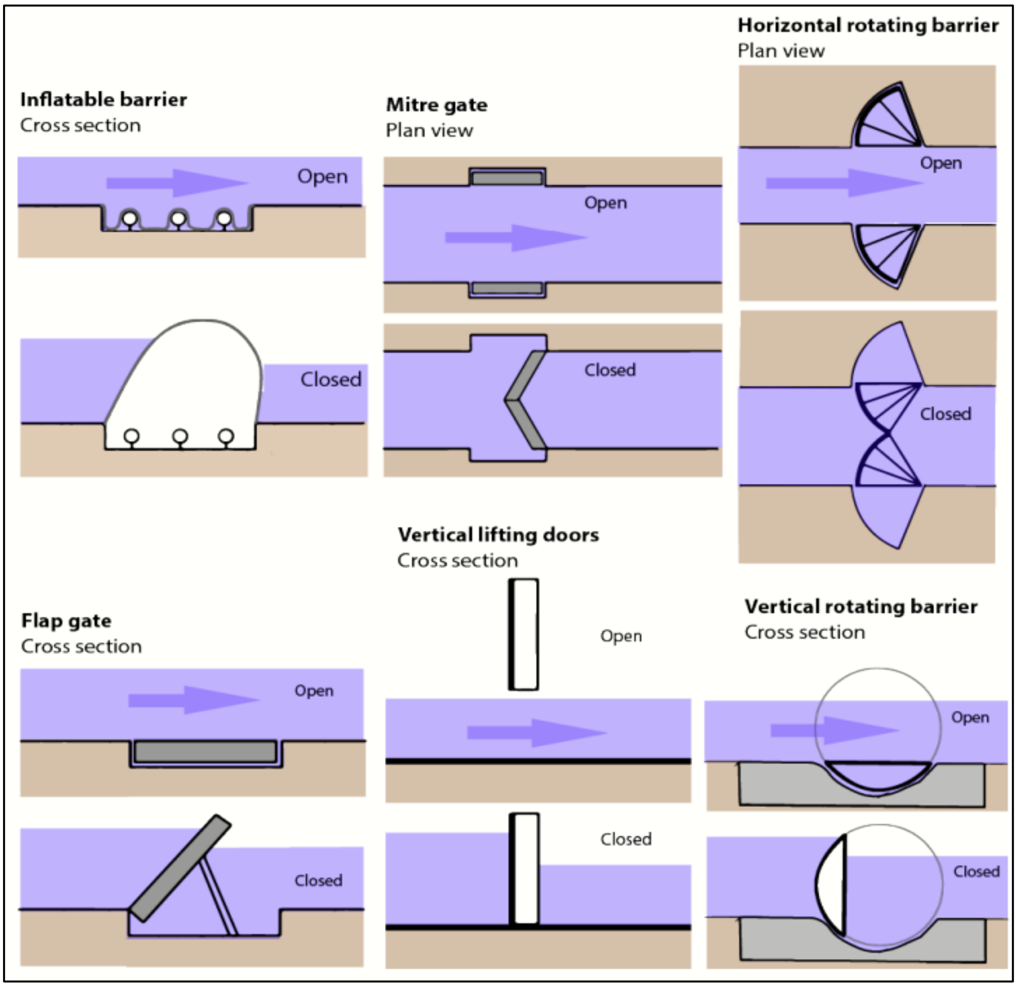


Figure 56 Types of storm surge barriers [66]

A.4 Inflatable storm surge barriers

Inflatable weirs and barriers are designed to regulate high water levels due to storm surge events or high river discharges. An inflatable weir or barrier consist of the foundation, the abutments and the rubber bellow that closes the flow opening after inflation and a facility for supplying with the filling medium (air, water) to the bellows with a controlled manner. In case of high-water events, where protection is needed, water and/or air is inflated into the rubber membrane until the barrier takes its final form. When the water level is below the alarm level, the barrier starts its opening procedure until it is empty of filling medium and getting stored in a sill which is installed in the foundation of the barrier.

A.4.1 States of the inflatable barriers

The main purpose of an inflatable barrier is to close off an opening by inflating the rubber membrane (bellow). The function of the barrier is governed by four different stages:

Stage 1: Inactive

The barrier is in the inactive stage most of the time. The bellow is deflated, and the water flow can be continuous through the opening. The membrane is stored under water in a sill in such a way that navigation still takes place without damaging the membrane.

Stage 2: Inflating

When extreme water levels are expected or has been measured, the bellow will be inflated with the filling medium (air or/and water). During the inflating water and/or air is pumped into the bellow, and it slowly comes up. Depending on the fill material it closes like an upcoming weir (vertical rising) or like horizontal gates.

Stage 3: Inflated

This is the active state of the barrier. The bellow is fully inflated with water and/or air and protects the hinterland from extreme water levels.

Stage 4: Deflating

When the outside water level becomes lower than the threshold level the barrier can be deflated again, since its function is no longer required. The filling medium will be released from the bellow until it is completely empty. Then the membrane will be stored in the sill.

A.4.2 Filling medium

The inflatable barriers are usually filled with water air or a combination of those. The filling medium influences significantly the design of a structure like this (Figure 57). Some of the important aspects of the barrier that are associated to the material that this is filled are:

- The time is needed for the barrier to inflate
- The desired retaining height and required membrane length and internal pressure
- The magnitude of the forces acting in the membrane and on the foundation
- The expected dynamic behaviour of the barrier
- The grade of a controlled inflation and deflation

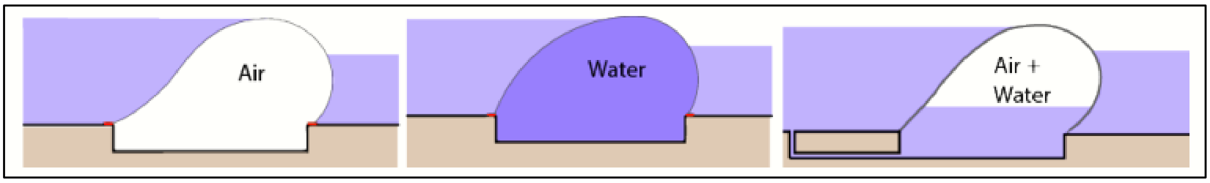


Figure 57 Filling ways of an inflatable barrier. Left: Air, middle: water and right: air and water [53]

A.4.3 Attachment ways of the bellow

The rubber bellow is attached to the foundation and to the abutments when not inflated. The barrier can be single or double attached/anchored to the foundation (Figure 58). Usually, weirs are almost always open and have to retain water only for one flow direction and thus a single row anchorage is sufficient. On the other hand, inflatable barriers are only activated during high water and usually have to retain water in both flow directions and thus the double row of anchorage is required.

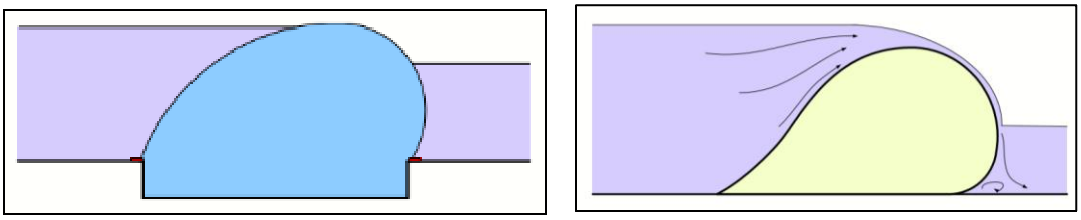


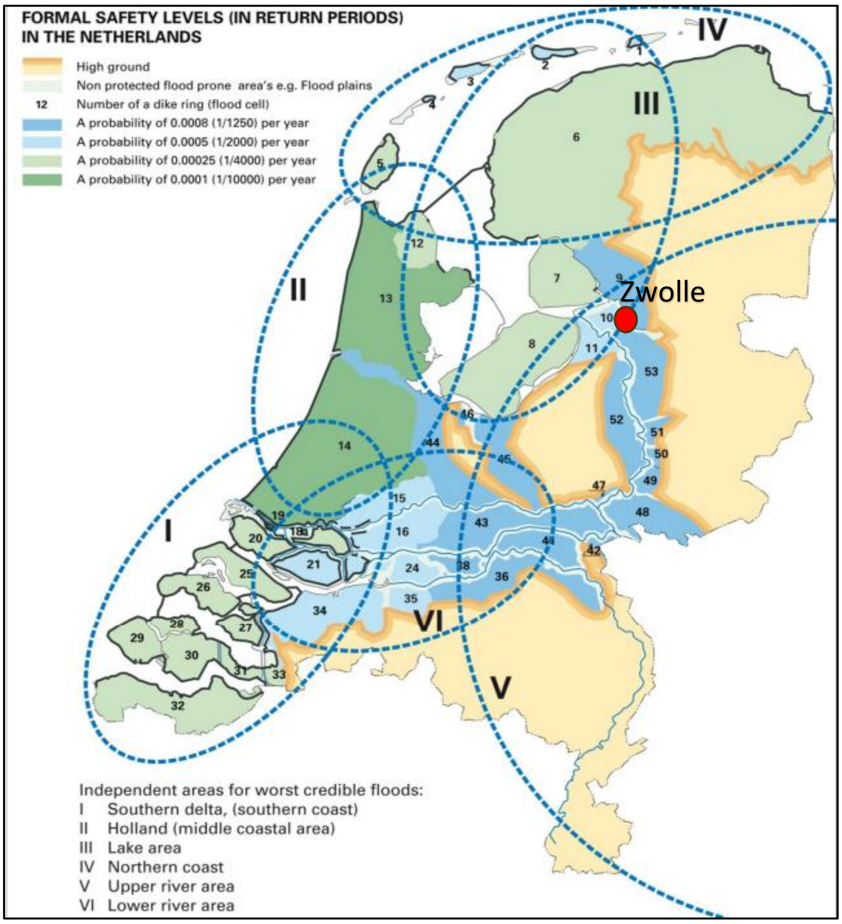
Figure 58 Left: Double row anchored inflatable barrier and right: Single row anchored inflatable barrier [67]

A.5 Dike stretches

The dike stretches which belongs to the dike rings along the Netherlands can be seen in the following Map 12.

Map 12 Levee segment in the Netherlands [22]

The city of Zwolle mainly belongs in the Dike Ring 53 and partially in Dike Ring 10. Looking at the Map 13 which is showing the formal risk of flood defences, it can be seen that the safety level for Dike Rings 53 and 10 are, 1/1250 per year and 1/2000 respectively.



Map 13 Formal risk for flood defences 1996-2017 and the concept of "worst credible floods" [24]

A.6 Assessment of flood defences and flood risk in the Netherlands

Each dike ring is surrounded by a continuous line of flood defences protecting the enclosed area against flooding, but not all the dike rings have the same safety standard. Before 2017, the standard for flood defences was expressed as a water level which the defence structures should be able to withstand and thus the standard focused only on the hydraulic load. The new standard is based on the risk of flooding. The Water Act or Waterwet (in Dutch) supplies safety standards for the primary flood defences. The primary defences are divided into one or more levee segments and each one of them has its own safety standards. Across the entire stretch of the segment, a uniform level of threat, accompanied by fairly similar consequences, exists for a breaching event. The safety standards are represented in terms of an exceedance frequency (number of times per year) of the water level, that this flood defence should be able to withstand.

All the defences which are part of the dike rings must be assessed every 6 years according to "The Water Act" since it must be verified that it is still in line with the safety standards. The Water Act replaced the Flood Defences Act [18], which followed a 5-year assessment strategy and conducted a total of three assessments (1196-2001, 2001-2006 and 2006-2011). The new period of 6-year assessment is in line with the European Flood Risk Directive and assessment will be conducted for the periods 2011-2017, 2017-2023 and so on. For each one of these assessments the Hydraulic Boundary

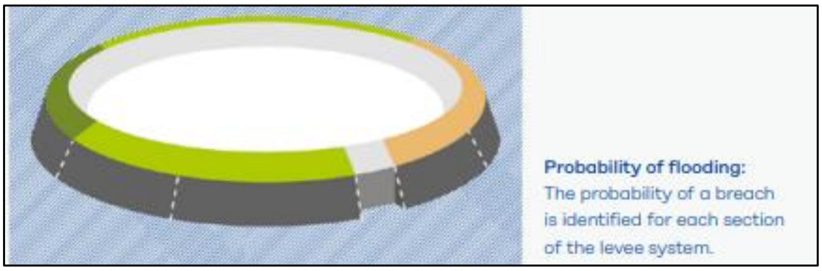
Conditions (HBCs) have been derived and published [19]. The assessment rules are collected in a report which is denoted here as ‘Safety Regulations for the Assessment of Primary Flood Defences’ (the translation of the Dutch title: ’Voorschrift Toetsen op Veiligheid Primaire Waterkeringen,’ see reference [18]). Examples of the strength properties of the dikes are the present crest height of the dike, the thickness and constitution of its revetment. The hydraulic loads acting on the flood defences are determined mainly by the water levels and wind waves at the toe of the flood defences [19].

In order to use the assessment rules, the HBCs are needed. For example, the normative water levels (water levels derived from the normative frequency, reflect the situation at the final year of the assessment), and the wave conditions (significant wave height, wave period, wave direction) relevant with the normative frequency, are important HBCs which are considered. Other types of HBCs are needed, e.g., the (average) time behaviour of the water level thought to be representative during a threatening situation. Some of the HBCs needed for the assessment are provided in a report (in Dutch: het Hydraulische Randvoorwaardenboek [21]), while others are calculated by the computer program Hydra-NL. The two reports containing (part of) the HBCS and the assessment rules [19], together with Hydra-NL, form the main instruments for the 6-yearly assessment of flood defences [19].

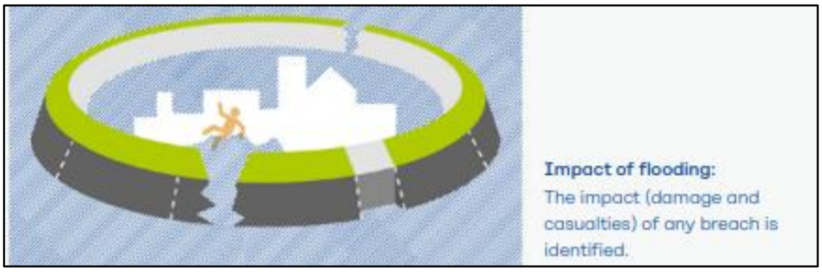
So, summarising, in the 6-yearly assessment of the (primary) flood defences, the following information is needed:

- Characteristics of the flood defences, described/stored in ledgers.
- Assessment rules for all failure models, which are collected in a report, called (after translation) ‘Safety Regulations for the Assessment of Primary Flood Defences’, updated every 6 years.
- Hydraulic Boundary Conditions (HBCs) updated every 6 years. Part of the Hydraulic Boundary Conditions are published in a report and part of them can be calculated with the computer program Hydra-NL.

The risk refers both to the probability and impact (damage and casualties) of flooding (Figure 59). The loss of life has played an important role in updating the safety standards for the flood defences. Specifically, it has been decided that the probability of loss of life because of flooding must not exceed the 1/100 per year in the Netherlands [22].



Probability of flooding:
The probability of a breach is identified for each section of the levee system.



Impact of flooding:
The impact (damage and casualties) of any breach is identified.

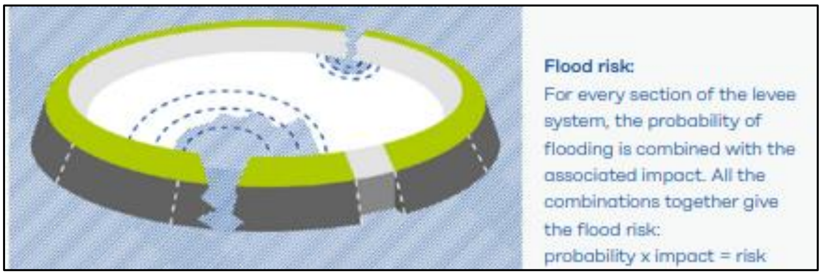


Figure 59 Schematic representation of risk [22]

A.7 Flood defence assessment approach and methods

Until recently, flood risk management was based on a safety-oriented approach where structure measures were designed (e.g., dikes, levees and storm surge barriers) and implemented in order to protect against a design flood height [25]. This approach relies mainly on the quantification of the hazard for a given return period, implies complete flood control and the risk behind the structure is ignored, since the probability of larger events than the design ones is small [26]. Currently, there is a swift to more risk-based approaches in the United States [27, 28 and 29]. The same approach is followed also in the Netherlands. Within the risk-based approach, the interventions on a water system for the reduction of the flood risk, is based on the potential to reduce the annual risk. As previously discussed, the flood risk is given by multiplying the annual probability of flood and the associated consequences. Thus, this approach gives the opportunity for cost benefit analysis of different improvements, where the benefits are expressed as the annual risk reduction [30].

Given the uncertain nature of climate change and its potential impact on flood risk, it is imperative to develop comprehensive flood risk management programs that incorporate robust strategies for the future. To move from risk assessments to the implementation of risk reduction measures, it is crucial to identify effective strategies. Computer-based risk models can aid in this decision-making process by evaluating risks and comparing different strategies. In the case of flood risk, sophisticated simulation models are commonly used. However, these models are resource-intensive, requiring significant time and data to simulate various scenarios and assess flood risk reduction strategies. As an alternative, analytical models offer valuable insights and optimised solutions for resilient and adaptive flood risk reduction strategies. Nonetheless, these models tend to be simplified and focus on specific hazards, such as storm surges, lacking the complexity of real-life situations that involve multiple factors like rainfall and storm surge. For specific examples of analytical optimization models, see [77, 78, 79 and 80].

Appendix B - Information from the visit to Ramspol Barrier

A visit at Ramspol Barrier has been conducted to gain a better understanding of the issues arising during the last years regarding the operation of the barrier and the impact that the closing procedures have on the surrounding areas. This information can only be used as supplementary information and not necessarily as a reliable source, able to influence the decision making, since some of it, reflects personal opinions of Ramspol Barrier's operators.

The engineers operating at the barrier name several issues and concerns. Initially, Ramspol Barrier designed for a frequency of closings low as one time per year. However, during the last years the barrier had more than one closure procedure per year, because of the frequent severe storm events in IJssel Lake. However, this fact does not necessarily imply a trend in the intensity and frequency of storm events. Right now, there is only a limited number of people who are responsible for the closing procedures and thus during long lasting storm events they have to extend their working hours and stay multiple days at the barrier to ensure its successful operation. Moreover, during closing procedures of the barrier, Rijkswaterstaat receives complaints from people of low elevation areas which are getting flooded. Ramspol Barrier has a fully automated closing procedure. This in some cases means that the closing procedure will start for NAP + 0.5 m and an inland flow direction, even if the operators know (having the weather forecast in hand) that by the end of the closing the flow direction and the water level will no longer be dangerous for the area. It is obvious that with this operation scheme (does not involve decision making by the operators) the barrier will have more closing procedures that are needed and thus more flood events in the low elevation areas behind the barrier.

Appendix C – Climate change analysis

In the last years, there has been a lot of discussion and concern over climate change. The continuously increasing temperature of the planet leads to sea level rise, possible higher precipitation and river discharges and more severe weather phenomena (severe storm events). This is visible in many parts of the world including the Netherlands, where a great part of the population lives below sea level. For this reason, there is a growing need for better flood protection.

C.1 Trends in winter precipitation and river discharges

Climate change affects the peak discharges of the Vecht and IJssel River. Discharge from the river IJssel depends on discharge from the river Rhine for which peak discharge will increase between 3% and 19% until 2050 [32]. Since 85% of the incoming water in the IJssel Lake region is determined by the discharge from the IJssel River, this increase in the peak discharge is of high importance for the water level in the lake. The discharge of the Vecht River also depends on the discharge of the Rhine River. The peak discharge of Rhine River is expected to increase according to projections [33] and thus there is a high possibility that the discharge of the Vecht River will be increased.

According to recent research, because of the human influence on climate change there is an increase in winter precipitation in the Northern Hemisphere (including large parts of Western Europe) [34]. The volume of precipitation influences the water level of IJssel Lake, both directly (precipitation in the basin) and indirectly (precipitation upstream to the mountain-river sources). The KNMI’14 scenarios [35], described a further increase in winter precipitation in future for the Netherlands (Figure 60).

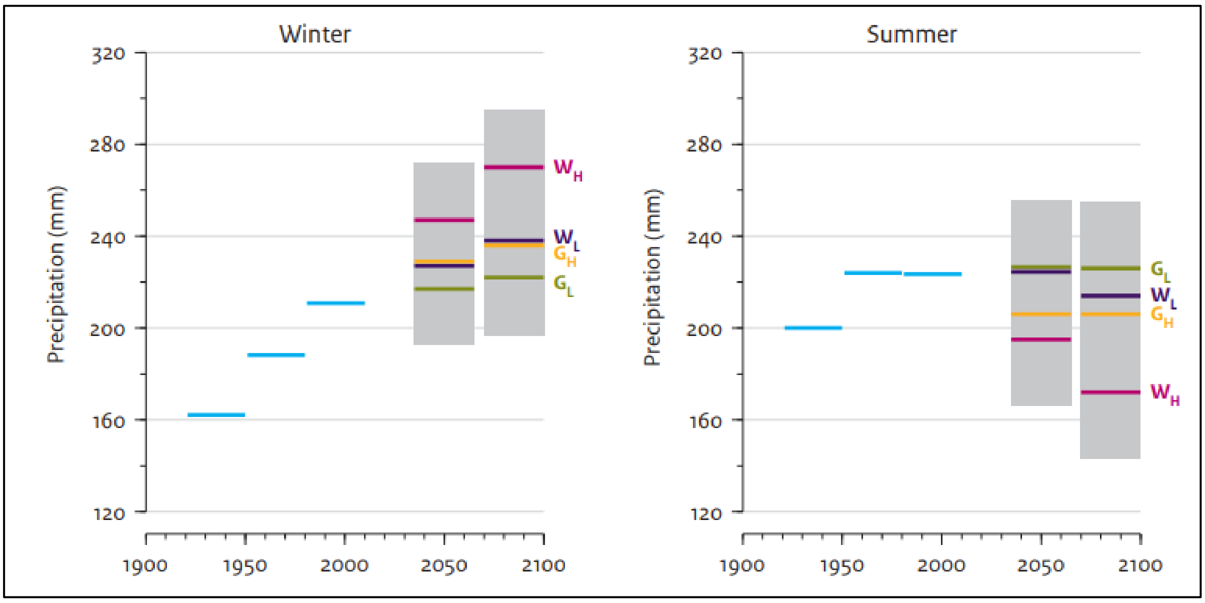


Figure 60 Precipitation climate in the Netherlands: observations and KNMI’14 scenarios for 2050 and 2085 [35]

Precipitation changes since 1950

Increases in the occurrence of low water (usually in summer) and high water (usually in winter) in the Rhine-Meuse basin have a potentially major impact. High and low water are determined by different precipitation characteristics. For high water, the maximum 10-day area precipitation in the winter half-year (October-March) is a commonly used indicator, and for low tide the minimum 90-day area precipitation in the summer half-year (April-September).

Since 1950, the low water indicator (Figure 61, black lines) has shown a steady decrease of -2.7% per ten years. This decrease is slightly stronger than the -2.1 % per ten years average precipitation in the summer half-year in the Rhine basin between 1950 and 2018 (Figure 61). The trend in the high-water indicator (red lines) is less clear. Over the entire period, the relative decrease on average per year is about half as great (-1.4 % per 10 years) as for the low water indicator and is not significant. In line with this and with a decrease in the average discharge in the summer half-year at Lobith in the period 1950-2018, the probability of low water (in summer) in the catchment areas of the Rhine and Meuse will probably be increased gradually. There is no reason to assume that the probability of high water (in winter) in the Rhine-Meuse basin has changed in the past. Significant trends were also not found in a previous study of trends in the highest annual discharge of the Rhine and Meuse [31].

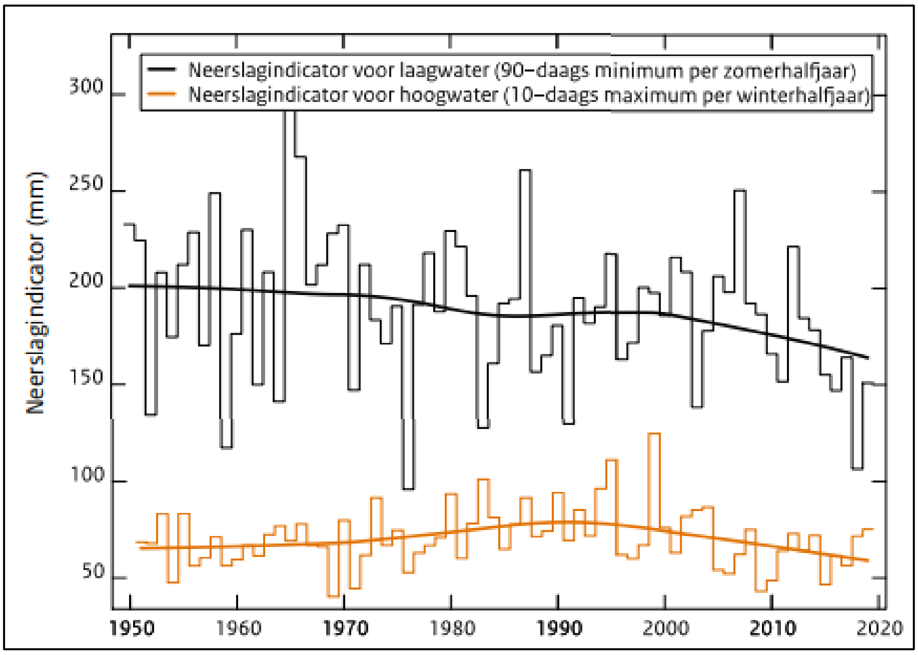


Figure 61 Precipitation indicators for low and high water in the Rhine-Meuse basin per year from 1950. The smooth lines represent the long-term trend. Based on the E-OBS v21.0 e 1950-2019 rainfall data [31]

Future changes in precipitation

The future projections of the precipitation indicators for high and low water show clear differences in Figure 62. While the high-water indicator shows an increase, the low water indicator shows a further decrease, both in particular in the high emission scenario (SSP5-8.5). The projected decrease of the low water indicator under the high emission scenario (albeit with a broad uncertainty band) is therefore a continuation of the observed trend since 1950 (Figure 62). The projected increase in the precipitation indicator for high water has not been seen yet in the observations (the decrease in this indicator is very small).

Changes in other meteorological variables that affect river discharges are also added. For example: the higher evaporation in a warmer climate will further increase the chance of low discharges. It is noted that for high and low water in the Rhine-Meuse basin, in addition to meteorological factors, hydrology and future water management play important role.

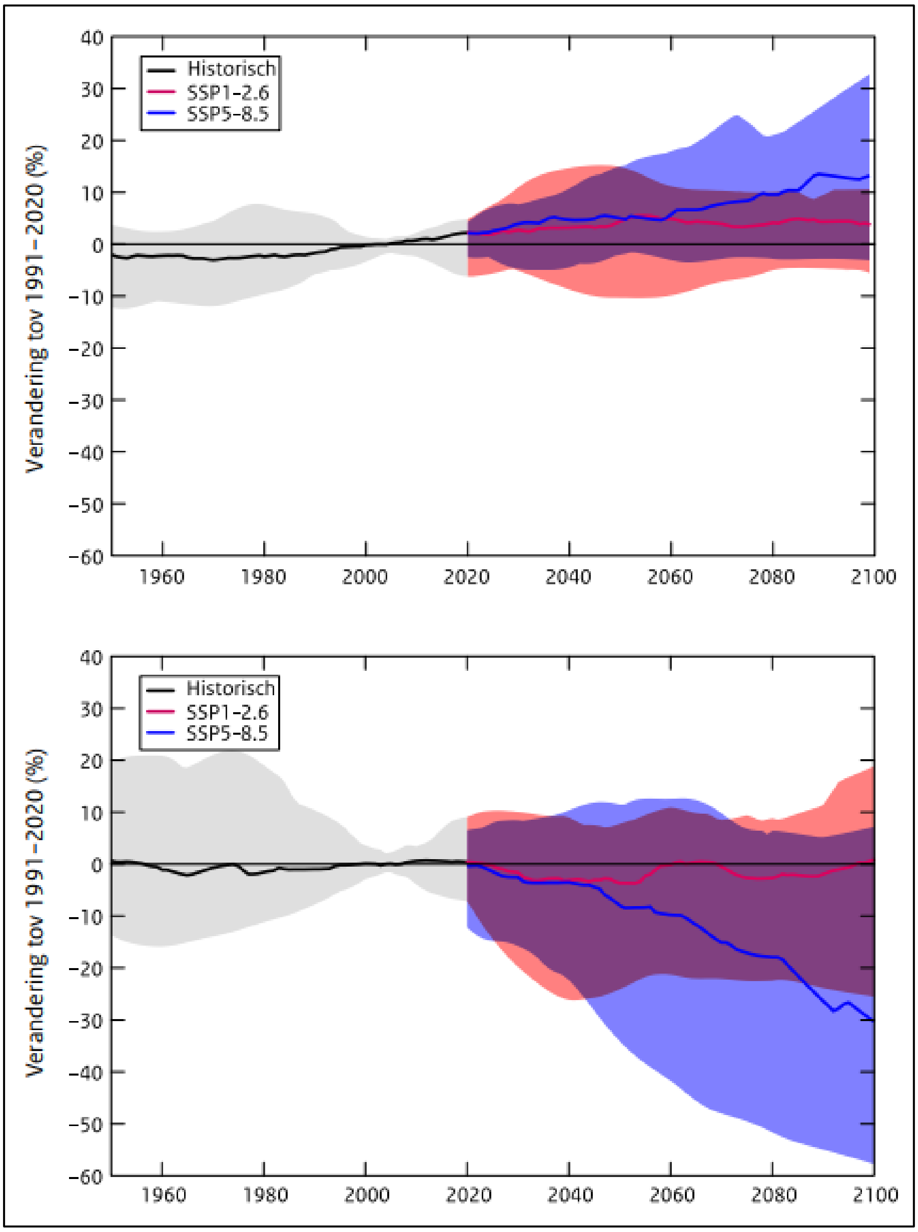


Figure 62 Relative changes per year in the high-water indicator (above) and the low water indicator (below) compared to the average over the period 1991-2020. Black is for the historical period (up to 2020), and the colours are for the future projections under the low (SSP1-2.6; red) and high (SSP5-8.5; blue) emission scenarios. The solid lines are the medians, and the coloured bands the highly probable (90%) range of all climate models used. Based on simulations of 27 CMIP6 climate models [31]

C.2 Trends in summer rainfall

Summer showers are usually intense and short-lived. Sudden extreme summer showers can have a major impact on society. They are associated with strong rises and falls in the air, fuelled by high temperatures at the Earth's surface and heat released by condensation in the cloud. The increase in the absolute amount of moisture in the atmosphere with warming is the main reason that precipitation extremes are increasing. In the Netherlands, an upward trend in moisture in the atmosphere, has been observed [31]. In the summer half-year (April to September), the surface increase is approximately 8% in the period 1951 to 2020. However, this is lower than the 14% [36], expected on the basis of the temperature rise of approximately 2°C at constant relative humidity. The number of days with very humid conditions has also increased: approximately doubling [31].

Because chance plays a major role in where heavy showers occur, a possible trend in precipitation extremes can only be determined by involving several stations in the analysis at the same time. Extremes in daily precipitation in the summer half-year have increased by about 20% in a broad stretch of the coast since 1951 (Figure 63), [31].

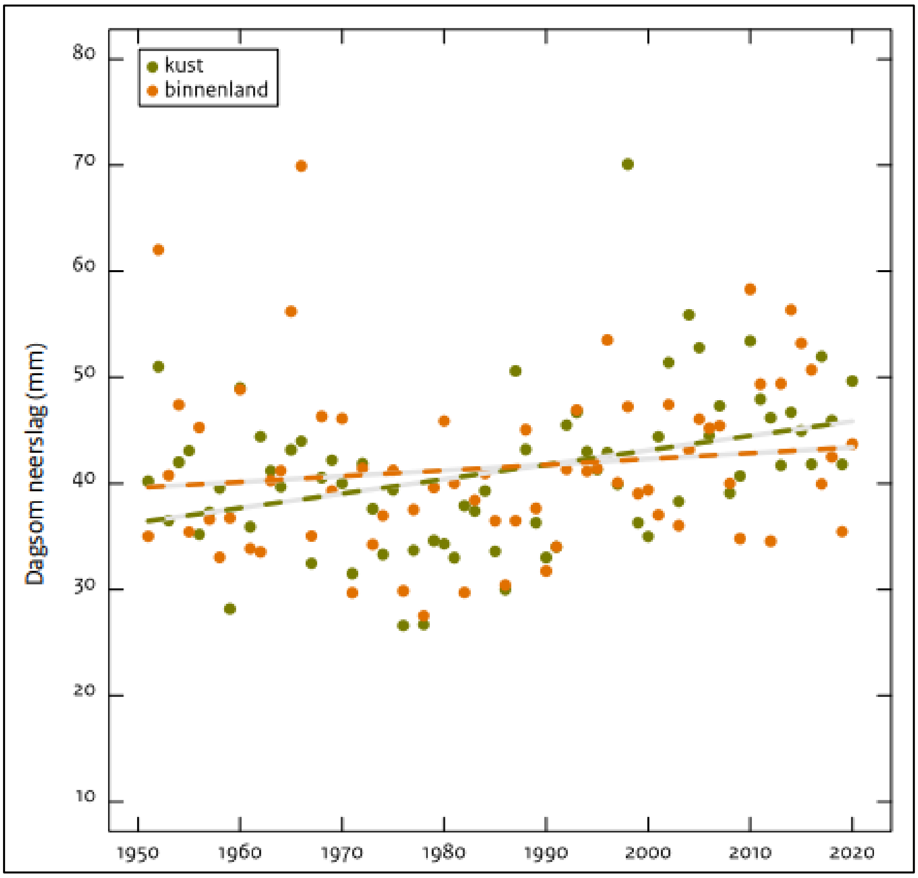


Figure 63 Daily precipitation extremes (recurrence time once every five years, 8-8-hour daily precipitation sums) aggregated over stations in a coastal zone about 50 km wide, and those inland, for the summer half-year (April through September). The lines represent the result of a trend analysis over the entire period. Extremes on the coast are increasing faster than those inland [31]

The precipitation extremes in a shorter time frame (less than a day) have also increased. This is an important measure for flush rain events, where in a short time frame big water volume can be added to the water system and lead to inundation of low-lying areas. In the last thirty years there has been an increase of about 10-15% in precipitation per hour at the extremes that occur about once every ten years or less often per location (Figure 64), [31].

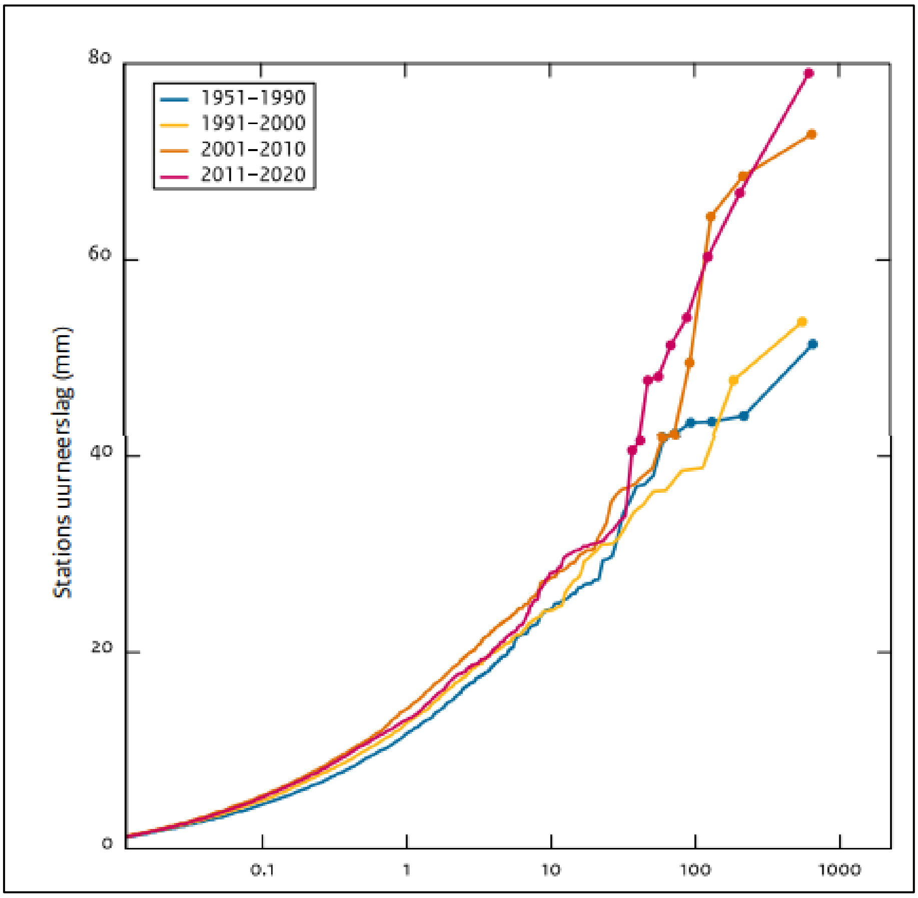


Figure 64 Hourly precipitation in the summer half-year, April to September, for the last ten-year periods, and the period 1951-1990, as a function of return period [31]

C.3 Influence of sea level rise in IJssel Lake

To cope with sea level rise, pumping stations in the Afsluitdijk are being installed and ready for use at the beginning of 2022. The pumping stations are needed, because the flowing of water through the sluices because of gravity, will become harder due to sea level rise. They will guarantee that target water levels can be maintained at least until 2050 [37]. The climate change scenarios in Hydra-NL are also taking into account the lake level rise in lake Ijssel.

The world sea level has risen by about 20 cm from 1901 to 2018. This rise is accelerating between 2006 and 2018 by 3.7 mm per year. This global acceleration of the recent years is not yet visible in the Dutch coast, according KNMI’21. For small areas, such as the North Sea, a longer period is needed to determine changes in the trend due to local effects such as fluctuations in wind and sea currents. Even though sea level rise in the Netherlands has been slightly slower than the global average in recent years, it is certain that the Netherlands will follow the world average. After all, the North Sea is directly connected to the oceans. The sea level will also rise faster and faster in the Netherlands. If parts of the Antarctic Ice Sheet become unstable, that acceleration could increase significantly after 2050 [31].

Since 1901, the total sea level rise off the Dutch coast has been roughly equal to the global sea level rise, namely about 22 cm. This corresponds to a rate of rise of more than 1.8 mm/year. An acceleration of the sea level rise off the Dutch coast is not yet detectable due to the large year-to-year variations in the number of storms, which have a strong influence on the sea level. This gives a standard deviation of the annual mean sea level of 6 cm [31].

The calculation of the sea level rise on the Dutch coast takes into account many factors, including the expansion of the oceans due to warming, self-gravity, the changes in salinity, and the mass loss of glaciers and ice caps in Greenland and Antarctica. Because the melting of the Greenland Ice Sheet hardly contributes to the sea level rise off the Dutch coast, we expect that the rise here will lag slightly behind the global average. The scenarios assume a subsidence of 0.5 mm/year. For the sea level rise on the Dutch coast, each scenario gives both a lower and an upper value, in accordance with the highly probable bandwidth of 90%, Figure 65 [31].

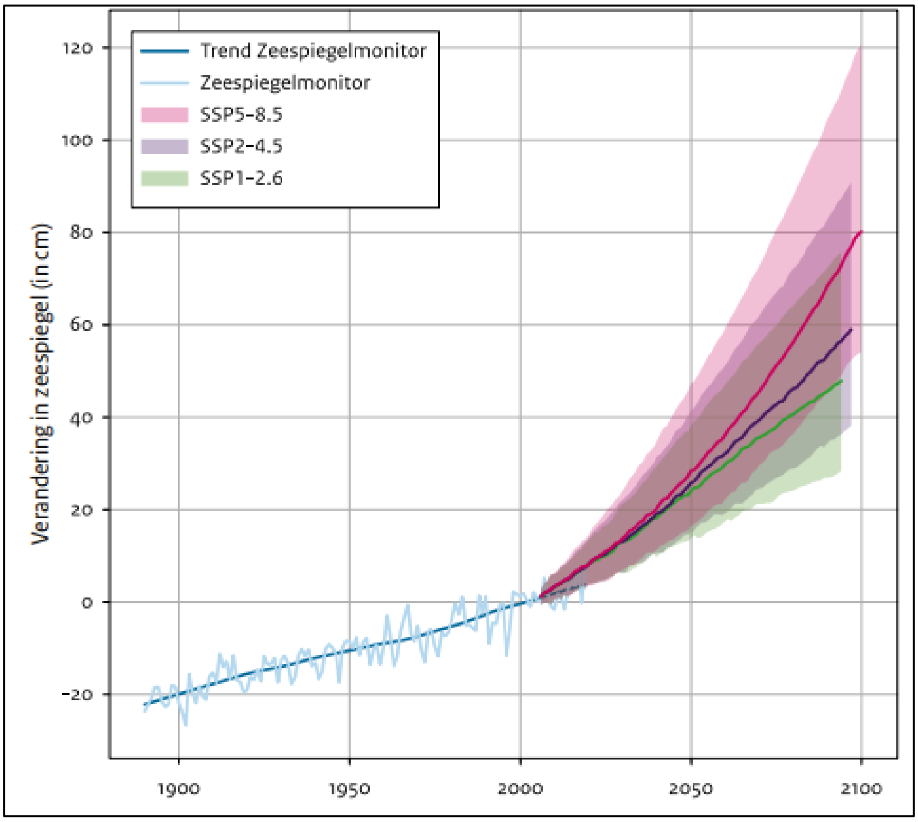


Figure 65 Sea level on the Dutch coast, as observed and according to new projections. The solid lines in green, purple and red indicate the median of those projections. The coloured area is the 90% bandwidth. Zero point of the median lines is at the year 2005, and the bandwidth for this year corresponds to natural variability [31]

The sea level rise for the Dutch coast up to 2300 for a number of scenarios can be seen in the following Figure 66. Sea levels will continue to rise in all emission scenarios, even if the global agreements made in Paris in 2015 are respected and the global temperature rise is limited to a maximum of 2°C.

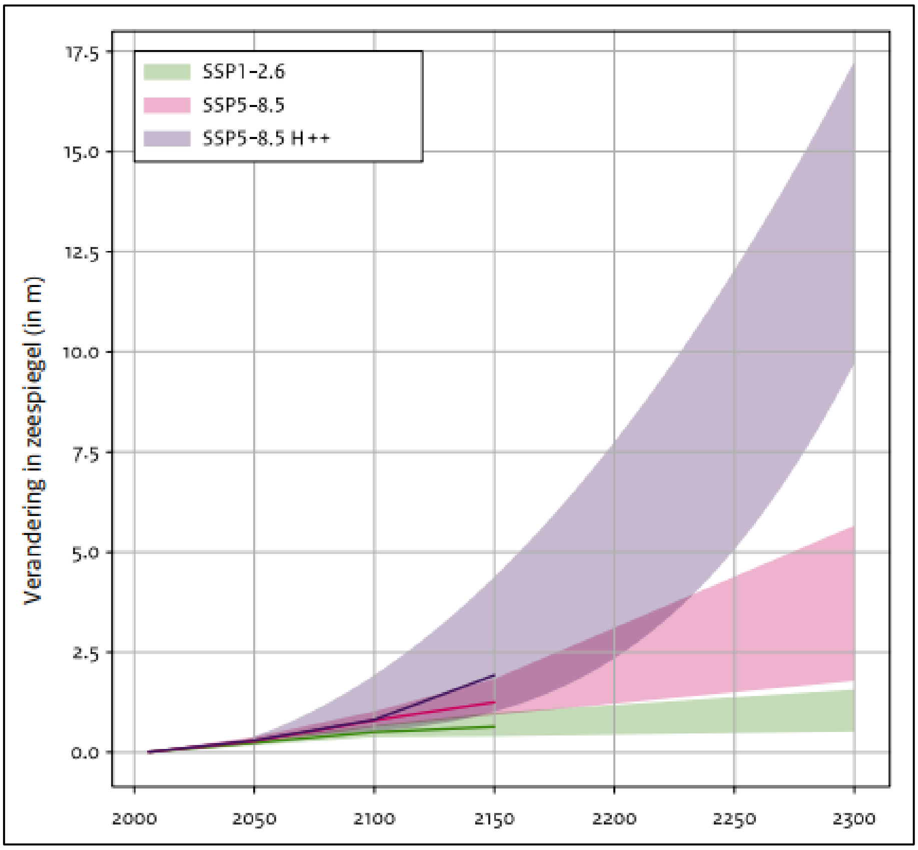


Figure 66 Sea level scenarios for the Dutch coast until 2300 for the SSP1-2.6 and SSP5-8.5 scenarios and SSP5-8.5 including uncertain ice sheet processes such as the collapse of ice cliffs on the edge of Antarctica (SSPS5-8.5 H++). The median lines of those three scenarios can only be calculated up to 2150.The indicated bandwidth in colour corresponds to the likely bandwidth of 67% [31]

C.4 Trends of storminess, wind direction and wind set-up

The wind set-up during storm surges, is determined by the wind strength and wind direction. According to KNMI'21, over the period 1950-2020, the wind climate in the Netherlands and in the North Sea was characterised by a large year-to-year variability and, since the 1990s, by a small decrease in the average wind strength [31]. The projections from the latest generation of climate models (CMIP6) also show only small changes in the wind climate for Western Europe. Over the southern North Sea, Denmark and southern Sweden, there is an area where the maximum wind strength increases (Figure 67), while the rest of the area shows a decrease. The area with the greatest increase is close to the Dutch coast (green dot in Figure 67).

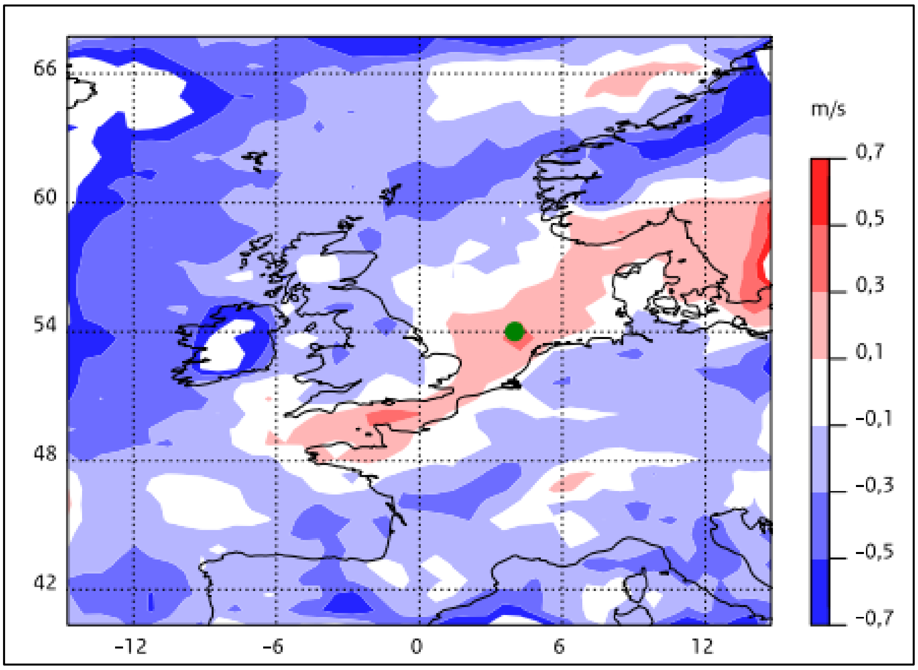


Figure 67 Change of the annual maximum of the wind speed (m/s) in winter (December - February) in Western Europe between 1991-2020 and 2071-2100 based on a high emission scenario (SSP5-8.5). Increase in red, decrease in blue. Shown is the median of 26 CMIP6 models. The green dot indicates the position of the largest increase in the median. Figure 69 shows the development over time at this location [31]

The green dot represents a location of the North Sea near the Wadden Sea and the Afsluitdijk. Storms appears at this region are also influencing the Ijssel Lake by inducing the wind set-up phenomenon. Figure 68 shows the bandwidth of the trends of the wind speeds in all models and their median, for the location with the largest increase (green dot in Figure 67). The increase is due to wind from the south-western direction. Figures 68, 69 and 70, apply to the emission scenario with the greatest climate change at the end of the 21st century (SSP5-8.5). The other scenarios yield similar figures, but with significantly smaller changes [31].

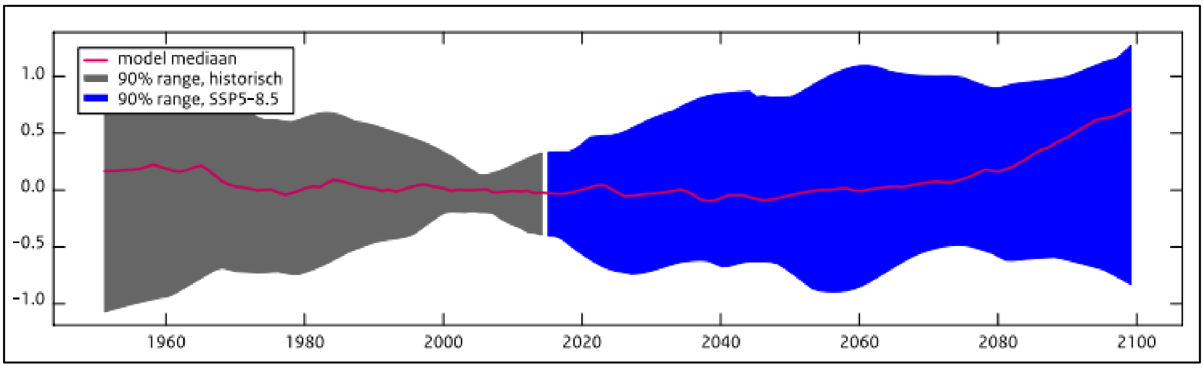


Figure 68 Development of the maximum wind speed at the location of the green dot (of Figure 67) in winter (December-February) for the high emission scenario (SSP5-8.5) based on CMIP6 model simulations (26 models). The deviations from the average in the reference period 1991-2020 are shown. The coloured bands represent the highly probable range (90%) of the 26 climate models, and the red line their median [31]

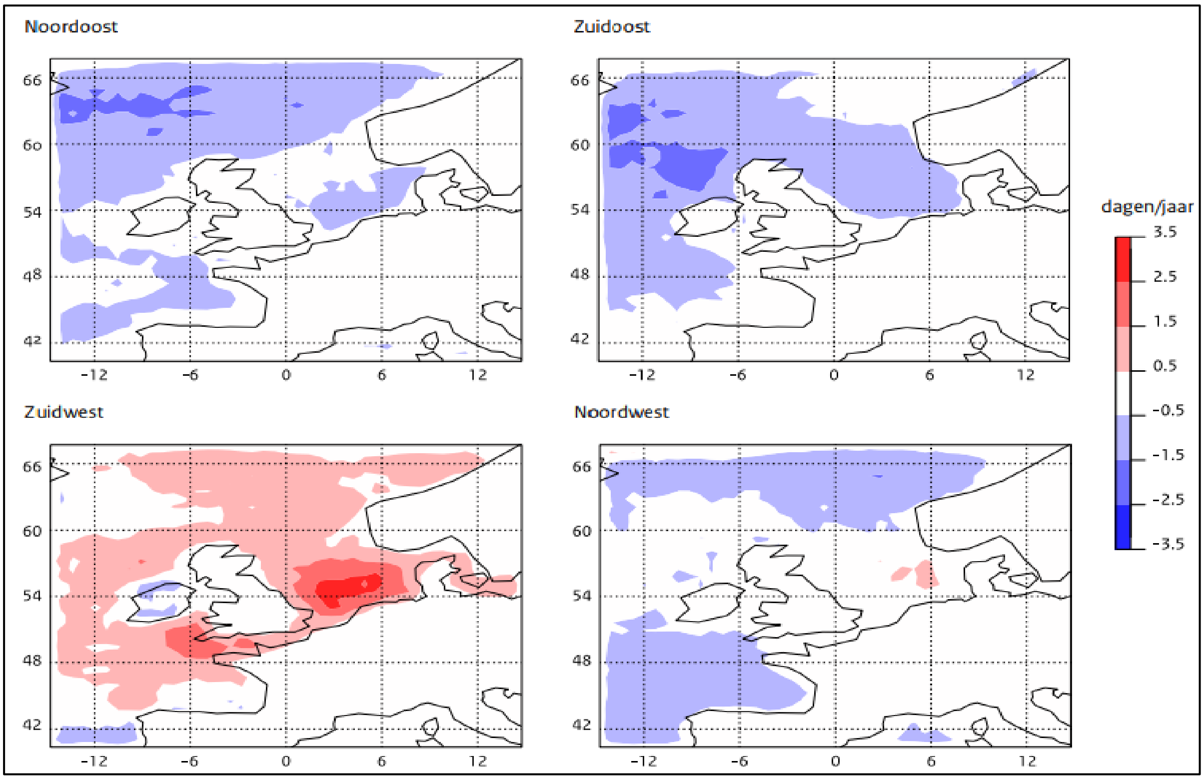


Figure 69 Change between 1991-2020 and 2071-2100 in the number of days per winter (December-February) with a daily average wind speed of more than 11 m/s (40 km/h, wind force 6) and wind direction northeast, southeast, southwest, and northwest in the high emission scenario (SSP5-8.5). Only winds from south-westerly directions show an increase. Shown is the median of 26 climate models [31]

Appendix D - Hydra-NL model

Hydra-NL is a probabilistic model that calculates the statistics of the hydraulic loads (water level, wave conditions, wave overtopping) for the assessment of the primary dikes and structures in the Netherlands. It is consistent with the “Beoordeling en Ontwerpinstrumentarium” (BOI). In the Hydra model, climate scenarios can be implemented, on which design loads can be determined.

D.1 Historic Background of Hydra-NL

First, different programs were needed to do the calculations for different parts of the Dutch water protection systems and thus a different program was being used for fresh and saltwater systems. Hydra-Zoet and Hydra Zout, respectively. Hydra-NL is a combination of the probabilistic assessment programs Hydra-Zoet and Hydra-Zout and constitutes the main probabilistic assessment tool for the flood defences in the Netherlands. Also, some improvements and additions have been made with respect to the previous programs.

The probabilistic model Hydra-Zoet was developed by Chris Geerse [68]. Before the launch of Hydra-Zoet, calculations were made in fresh waters using eight different Hydra models. Relevant in this regard is [69] about Hydra-VIJ, which was used in the Vecht-IJsseldelta. Hydra-B was used for the lower river area. The mathematical background of Hydra-B for the calculation of normative water levels, crest heights or wave conditions for revetments is described in [70] and [71]. Hydra-Zout's probabilistic formulas for calculating normative water levels, crest heights or wave conditions for revetments originate from Chris Geerse (HKV line in water). For water levels in the Oosterschelde, these formulas are based on [72] and the Performance Level Model.

For the purposes of this study, Hydra-NL model will be used. Since the area of interest is in fresh water, Hydra-Zoet is the relative background model for the calculations. Before the implementation of Hydra-Zoet, the models Hydra-B and Hydra-VIJ were being used for these purposes. These two models have been developed by Rijkswaterstaat Waterdienst (the executive arm of the Ministry of Infrastructure and Environment), and HKV Consultants since 1999. Both models have been developed for river deltas, are similar and later became apparent that they can be combined in a more uniform way. The so-called “slow” stochastic variables in these models, as discharges and lake levels, can be modelled using the same type of schematisation. It also turned out that the upper reaches of these rivers, as well as the lakes IJssel and Marker, fitted into the general scheme of this model, meaning that all primary flood defences of the freshwater systems could be included in a single new probabilistic model, the Hydra-Zoet.

The Hydra-NL application was jointly developed by the Water, Traffic and Living Environment Department (WVL) of Rijkswaterstaat, Deltares and HKV line in water. The implementation of Hydra-NL was performed at HKV by Matthijs Duitsland, Bastiaan Kuijper, Guus Rongen, Rolf Waterman and Johan Ansink. The supervision from Deltares was provided by Hans de Waal and Huib Tanis and the guidance from Rijkswaterstaat by Robert Slomp and Thomas van Walsem.

D.2 Purpose of Hydra-NL

Hydra-NL is a probabilistic assessment program for the safety of the primary flood defences along the main water systems in the Netherlands, specifically for the rivers Rhine and Meuse and their branches as well as the river Vecht, for the lakes (IJssel Lake and Marker Lake) and for the coast.

Hydra-NL model can be used to calculate water levels, significant wave heights, spectral wave periods, peak periods, hydraulic load levels, overtopping discharges and wave conditions at the revetment for specified return periods. In addition, illustration points, percentiles, breakdowns and contributions to overloading can be calculated.

Dike height assessment

In order to assess the height of the dike a water level calculation or a calculation for the hydraulic load level must be selected. When calculating the hydraulic load level for a given return period, two failure mechanisms are available. Those are: 2% wave run-up and the combined wave overtopping and overflow failure mechanism. The second mechanism can specify a critical overtopping flow.

Illustration points, contributions, percentiles, and breakdowns

The illustration points and contributions of the different wind directions and, for example, the different scenarios of a storm surge barrier can be provided as additional information in the assessment.

In some cases, illustration points can also be conditionally calculated for the discharge flow. These illustration points are used for the river engineering assessments for the granting of permits in accordance with the Water Act for relatively minor river engineering measures. For major interventions in the river system, such as the Kampen bypass (Reevediep), this method offers insufficient mathematical accuracy. The calculation method of the illustration points conditional on the discharge is described in [73,74].

In addition - if relevant - percentiles and breakdowns of wind, lake level, sea water level and discharge can also be calculated with Hydra-NL. The percentiles of discharge and lake level are important for deriving normative water level trends. All breakdowns provide insight into the behaviour of the water system and are especially useful in analysing and interpreting the results.

Wave conditions for dike revetment assessment

In addition to assessing the height of a dike, Hydra-NL also allows you to calculate the wave parameters for the dike revetment with which the revetment must be assessed. Hydra-NL provides these wave conditions by calculating illustration points. The revetment module in Hydra-NL is based on the advice from [75], in which the normative wave conditions are calculated for each water level. This type of calculation is referred to as the "custom Q variant."

Additional calculation options

Region-specific, Hydra-NL contains extra calculation options. This includes, for example, the dike ring calculations (not for revetments) and the calculation of the fragility curve. Regions are mentioned within the context of Hydra-NL water systems. The water systems can be divided into several types.

D.3 Hydra-NL, types of water systems

Hydra-NL can conduct calculations for eight types of water systems:

1. *Rivier_naar_zee_met_SVK* (River discharging to the sea)

   In this water system belongs only the lower river area. For this water system important parameters are the sea water level, the Rhine and Meuse River discharges and the Europoort storm surge barrier.

2. *Rivier_naar_meer_met_SVK* (River discharging to lake)

In this water system belongs only the Vecht and Issel Delta. For this water system the important parameters are the water level of IJssel Lake, the discharge of IJssel and Vecht River and the Ramspol storm surge barrier.

3. *Meer* (Lake)
   In this type of water system, the water systems IJssel Lake, Marker Lake, Veluwerand Lakes, Grevelingen and Veerse Lake are included. For these water systems, the important parameters are the lake water level and the wind characteristics.

4. *Rivier* (River)
   In this type of water system, the upper area of the rivers is included. In the upper river area, only the river discharge and the wind characteristics are important.

5. *Rivier_Zee_Keringen* (River, sea and barrier)
   Only the Hollandsche IJssel water system belongs to the water system type *Rivier_Zee_Keringen*. This water system type has similarities with the water system type *River_naar_Zee_met_SVK* and is an extension thereof. The failure of the Hollandsche IJsselkering is included as an extra option. In this water system type, the fragility curve can be calculated with conditional exceedance probabilities given the water level.

6. *Rivier_Zee_Meer_Kering* (River, sea, lake and barrier)
   Only the Volkerak-Zoommeer water system belongs to the water system type *Rivier_Zee_Meer_Kering*. This water system type has similarities with the water system type *River_naar_Zee_met_SVK*. In addition to the influence of the sea water level, the Rhine and Maas discharges and the Europoort storm surge barrier, the water level on the Volkerak-Zoommeer also influences the water levels in this area.

7. *Estuarium_met_Kering* (Estuary with barrier)
   Only the Oosterschelde water system belongs to the water system type *Estuarium_met_Kering*. In the Oosterschelde, water levels are not only dependent on the wind and sea water levels, but also on the Oosterscheldekering, the storm surge duration and the tidal phase (the time difference between the moment of the tidal crest and the moment of the maximum of the wind set-up). Regarding the Eastern Scheldt storm surge barrier, water levels are influenced by the closing method of this barrier (strategic closure or emergency closure) and the number of gate failures of this barrier (where no gate failure is also a possibility; this number of 'failing gates' even has the greatest chance).

8. *Zee* (Sea)
   The water system Zee includes the water system Hollandse Kust, Waddenzee and Western Scheldt. For these water systems, only the sea water level and the wind characteristics are important parameters.

The first six water system types form the fresh water of Hydra-NL and the last two water system types form the salt water. For the salt waters, no dike calculation is available.

D.4 User modes

Hydra-NL has three user modes:

1. Review mode

This mode aims at assessing flood defences in the context of the Statutory Assessment Toolbox (Wettelijk BeoordelingsInstrumentarium) 2017 (WBI2017). The assessment per dike section takes place with prescribed statistics.

2. Design mode

This mode focuses on the design of flood defences within the framework of the Design Instruments (OntwerpInstrumentarium) 2014 (OI2014). The design takes place with prescribed climate scenarios.

3. Test mode

This mode is provided to be used by a specialist. There is an extensive input and output capability.

D.5 Physical models

Hydra-NL uses input generated by physical models to calculate water levels and wave variables. For a probabilistic model as this, the load level must be known for a lot of combinations, since these combinations should cover the entire range of circumstances occurring in reality. A few thousand combinations must be considered for the more complex water systems. In the probabilistic part of the model Hydra-NL, proper probabilities are assigned to the combinations of boundary conditions (and ones obtained by interpolation), eventually providing the exceedance frequencies of load levels.

Water levels

To generate water levels corresponding to a set of boundary conditions for a given water system in Hydra-NL, two hydrodynamic models are used, the 2-dimensional model WAQUA and the 1-dimensional model SOBEK. When using these models, a program called Baseline is used to convert GIS-data into a database with all the physical characteristics of the lake and/or river bottoms and shores. Next, using this database, a WAQUA (2-d) schematisation or SOBEK ‘lay out’ (1-d) is built. For the most recent Hydraulic Boundary Conditions, WAQUA has been used for the lakes, Vecht and IJssel delta and the upper rivers.

The model WAQUA, being a 2-d model, has the advantage of being more accurate than the 1-d model SOBEK, especially for the wider channels and the lakes. Also, it can accurately represent the effect of the centrifugal force in the river bends in contrast to SOBEK. However, the disadvantages of WAQUA are that it requires much more information to build the model and is much more time consuming and demands more computer capacity and time than SOBEK is.

Wind waves

To calculate the hydraulic load on a dike, wave variables are needed. These variables usually are *the significant wave height*, *the peak period* and *the wave direction*. These variables are calculated with the 1-d wave growth formulas of Bretschneider. Only for Lake IJssel and Lake Marker a 2-d model has been used. However, it is possible to use wave variables which have been derived with 2d wave models. When using Bretschneider formula, the wave direction is taken equal to the wind direction, which is not the case when a 2d wave model is being used. Hydra-NL is using the 2-d wave model SWAN for large water bodies as the lakes. If the 2-d wave model SWAN is used instead of Bretschneider, no effective fetches and bottom levels are needed, since this kind of information is contained in the 2- dimensional schematisation of the SWAN model.

The Bretschneider formulas can be used to calculate wave variables, in which the flood defence and its surroundings are treated in a simplified manner, using only effective fetches and bottom levels for each direction. Another possibility is to use a 2-d (or 3-d) model to calculate the wave variables. The need for such a model becomes more important if the wind waves threatening the dike are higher, for example in the case of larger bodies of water such as lakes and wider channels. A 2-d model will also perform better than a 1-d model if the surroundings of the flood defence is complex. Next to this, a 2-d model allows, among other things, to consider the effect of current velocities on the waves, and better modelling of diffraction, refraction and energy dissipation.

Transformation from open water to the toe of the dike

In the previous sections, discussed how the wave variables for open water can be derived using a wave model (1-d or 2-d). As the waves approach the shore, they get transformed because of the influence of the bottom, and the variables at the toe of the structures (dikes) will differ from the open water. To derive this wave transformation a module needs to be chosen (dam or foreshore).

Hydraulic load levels

If the failure mechanism wave overtopping is used, the wave variables at the toe of the dike must be transformed into a hydraulic load level on the dike. This load level, in NAP+ metres, depends on the wave variables, but also on the allowed critical overtopping discharge q_{crit}. For the calculation of the wave overtopping height, the module PC-Overslag is used.

D.6 Schematic structure of the model

The diagram follows, concerns the calculation of the hydraulic load level for the failure mechanism of wave overtopping, for a shore location with wave variables obtained with the 1-dimensional Bretschneider formulas. An overview of how HYDRA-NL works can be found in the following Figure 70.

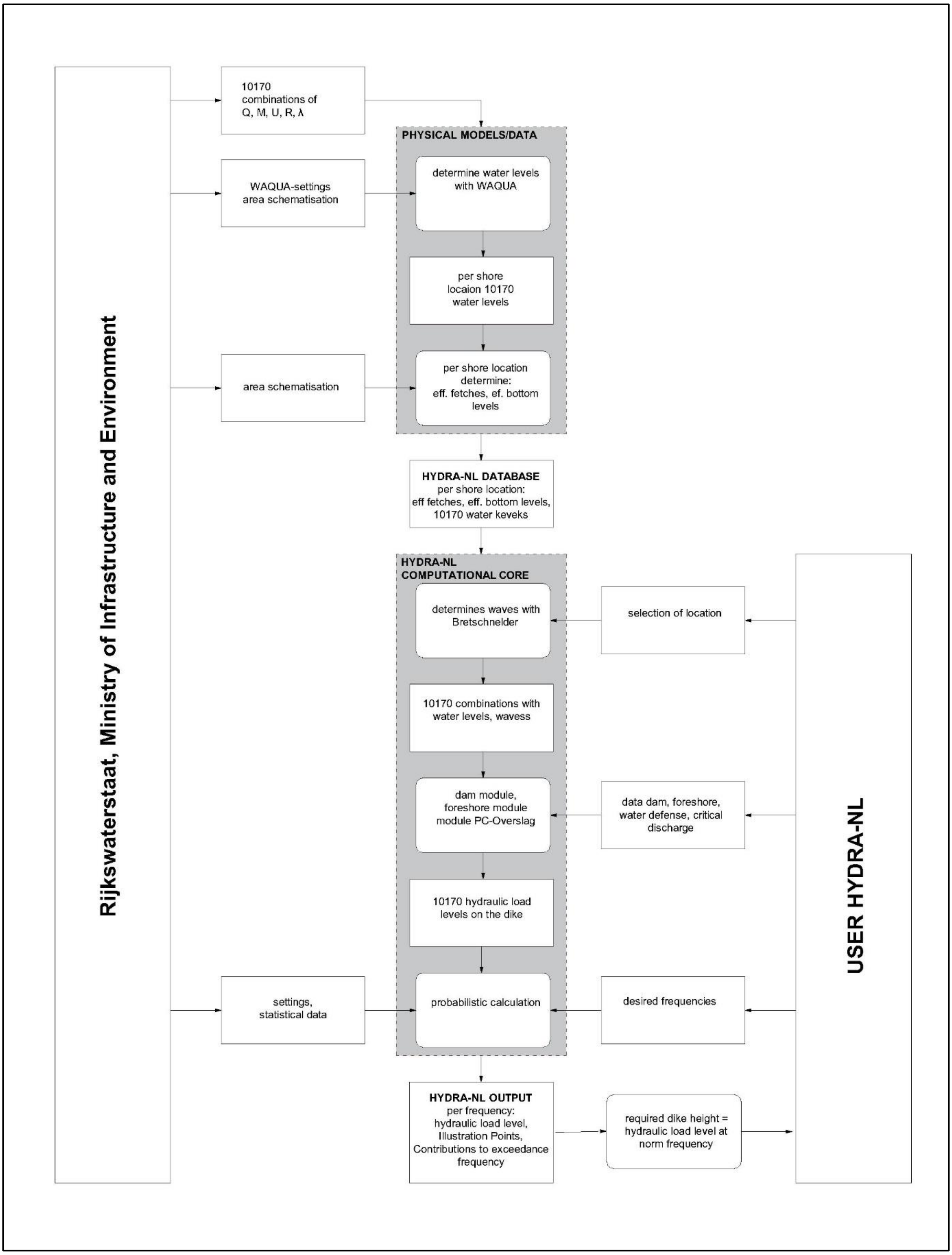


Figure 70 Diagram for a shore location in the Vecht and IJssel delta, for failure mechanism wave overtopping. The barrier state here is denoted by λ. [19]

The structure of the diagram can be explained as follows. All the data delivered by the Ministry of Infrastructure and Environment, are used as input for the model (left block of the diagram). For the assessment of the flood defences the user must import data which are relevant with the location considered (right block of the diagram). The block in the middle of the diagram shows the flow of the data and at which point the probabilistic calculation is executed in the model.

PHYSICAL MODELS/DATA
At this stage is being described the water level calculations and location-specific data for fetches and bottom levels. For a total of 10170 combinations of boundary conditions, for different values of discharges Q, sea levels M, wind speeds U, wind directions R and barrier states λ, water levels have been calculated with hydrodynamic models such as WAQUA, for many locations throughout the area. For these locations also effective fetches and bottom levels (required for the Bretschneider formulas), are determined.

HYDRA-NL DATABASE
The data for the shore locations are stored in a database. (Block: HYDRA-NL DATABASE) The size of this database is not small and thus it has been divided into several sub-databases for each dike ring to be assessed and is distributed from the Ministry of Infrastructure and Environment to the users of the HYDRA model.

HYDRA-NL COMPUTATIONAL CORE
This block represents the actual model core of Hydra-NL (the former data are only input for the model). In advance of the probabilistic calculation executed in this block, the available data must be used to calculate the hydraulic load level in every one of the 10170 combinations. First, for every combination the wave variables Hs and Tp are calculated with Bretschneider. At this stage of the program, water levels and waves are known as ‘open water’ near the toe of the dike. If necessary, they are transformed by the dam and/or foreshore module, to water levels and waves directly in front of the dike toe. The module PC-Overslag transforms the conditions at the toe of the dike to a hydraulic load level on the dike. The load levels in this block not only depend on the data stored in the Hydra-Zoet database, but also on the information supplied by the user of the program. In addition to the information for a possible dam and/or foreshore, these contain the dike orientation, the geometry of the dike (shoulders/berms, slopes and their roughness) and the critical wave overtopping discharge.

At this point of the program the load levels are known for all the 10170 combinations. Using the probability distributions of discharges, sea levels, wind speeds, wind directions and barrier states, a probabilistic calculation now yields the hydraulic load levels at the user-specified (normative) exceedance frequencies.

HYDRA-ZOET OUTPUT
In this block the most relevant output of the model is shown. Next to the hydraulic load levels just mentioned, this output contains Illustration Points and contributions to the exceedance frequencies.

STATISTIC DATA
The statistic data that is being used for Hydra-NL (Hydra-Zoet case for Vecht and IJssel Delta) are the following:

1. Lake IJssel
    1.1 Trapezium parameters: base duration B, minimum lake level mmin, peak duration b(s).
    1.2 Exceedance probability P(S>s), from which f(s) follows by differentiation.
2. Vecht discharge

2.1. Trapezium parameters: base duration B, minimum discharge qmin, peak duration b(k).

2.2. Exceedance probability P(K>k), from which f(k) follows by differentiation.

3. Correlations between Vecht and Lake IJssel

   3.1. Value for the phase φ between the discharge and the lake level trapezia.

   3.2. Value for the standard deviation σ in the (transformed) model CS used for the bivariate density f (k, s), which has marginals f(k) and f(s). Recall that the model CS was treated in section 7.2.

4. Wind

   4.1. Exceedance probabilities P(U>u|r) for the 12-hourly maximum wind speed U, given wind direction R = r (where r = NNE, NE..., N).

   4.2. Probabilities g(r) for the wind directions r.

D.7 Hydra-NL model used in this thesis

The model Hydra-NL can be used for the purpose of this study, to calculate water levels for different return periods for multiple calculation points in the area of interest. As can be seen below Figures 71, 72 and 73, the current situation and a newly designed situation can be assessed.

Hydra-NL can be used as an assessment tool to evaluate the current situation. For the rivers, lakes and the sea, the model uses all kinds of statistical information, and many calculated water levels and wave variables, provided through physical models such as WAQUA and SWAN. Using the Hydra-model for the current safety levels, i.e., the norm frequencies, the normative water levels and required (or desired) dike heights can be determined. A required dike height can then be compared to the existing dike height. A scheme for the assessment of the current situation can be seen in Figure 71.

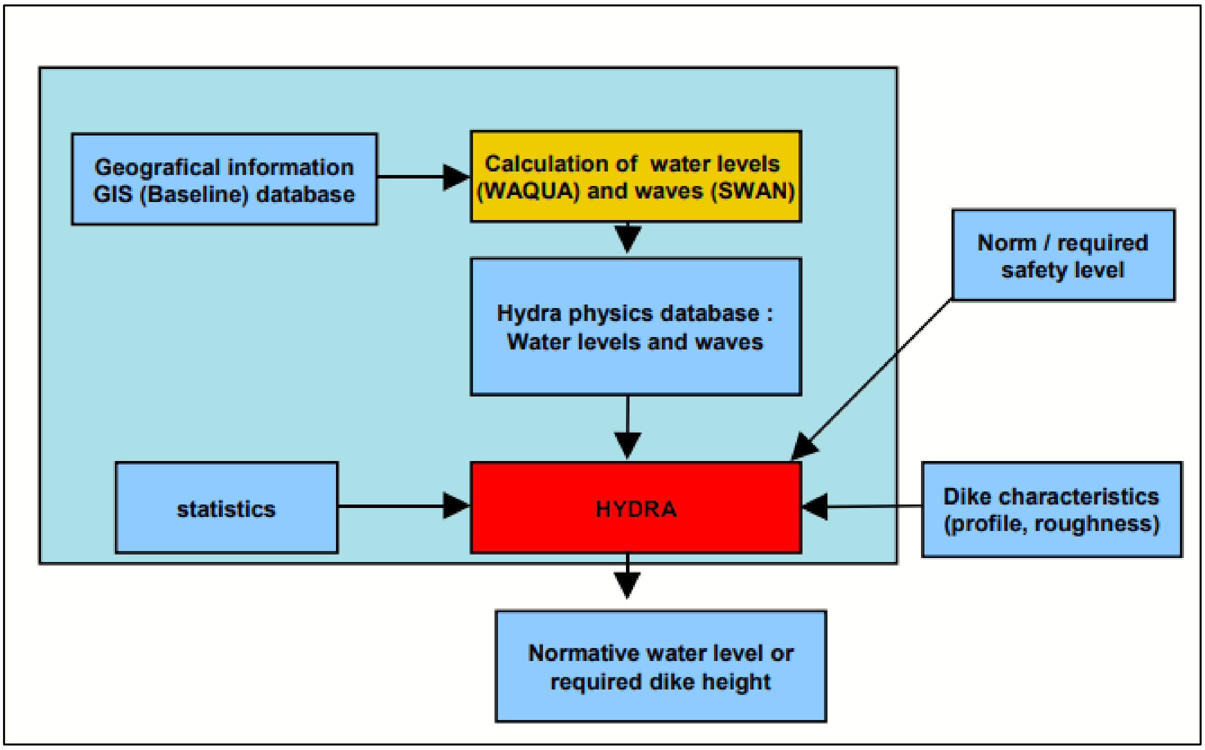


Figure 71 Hydra Zoet, as used in the assessment of the current situation [19]

Instead of considering a single safety level (norm frequency), the Hydra model can also determine the water levels and hydraulic load levels for an entire range of exceedance frequencies, yielding so-called frequency lines for water levels and hydraulic load levels Figure 72.

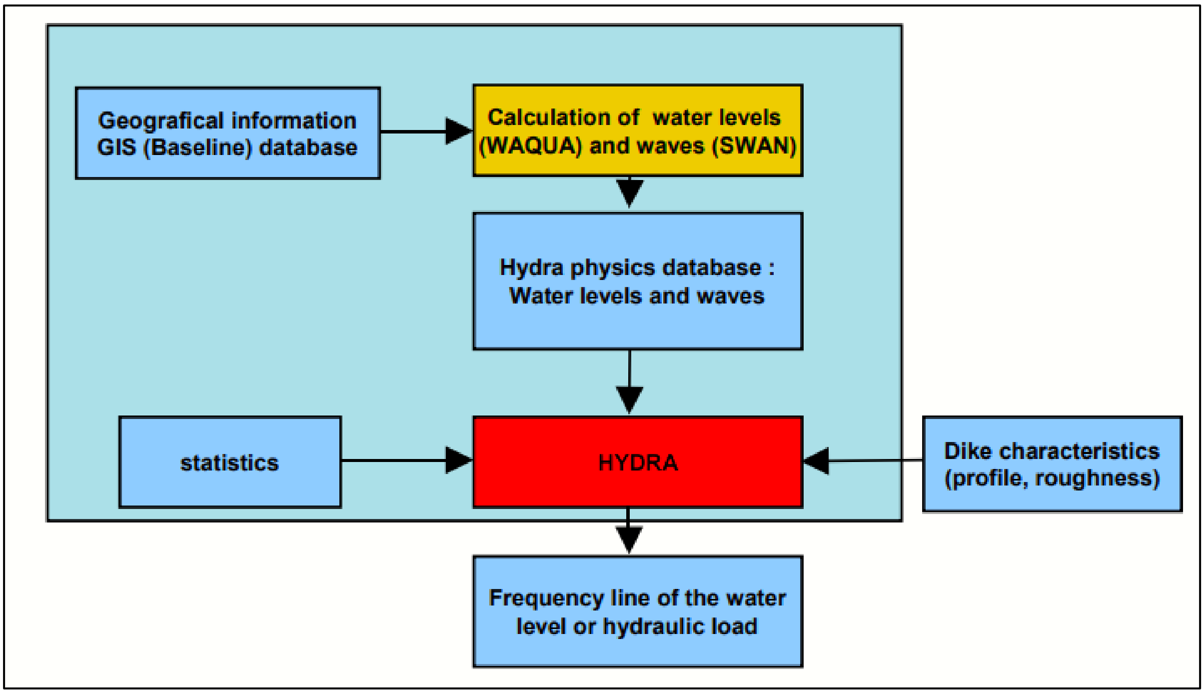


Figure 72 Hydra-Zoet, providing for the current situation frequency lines for water levels and hydraulic load levels [19]

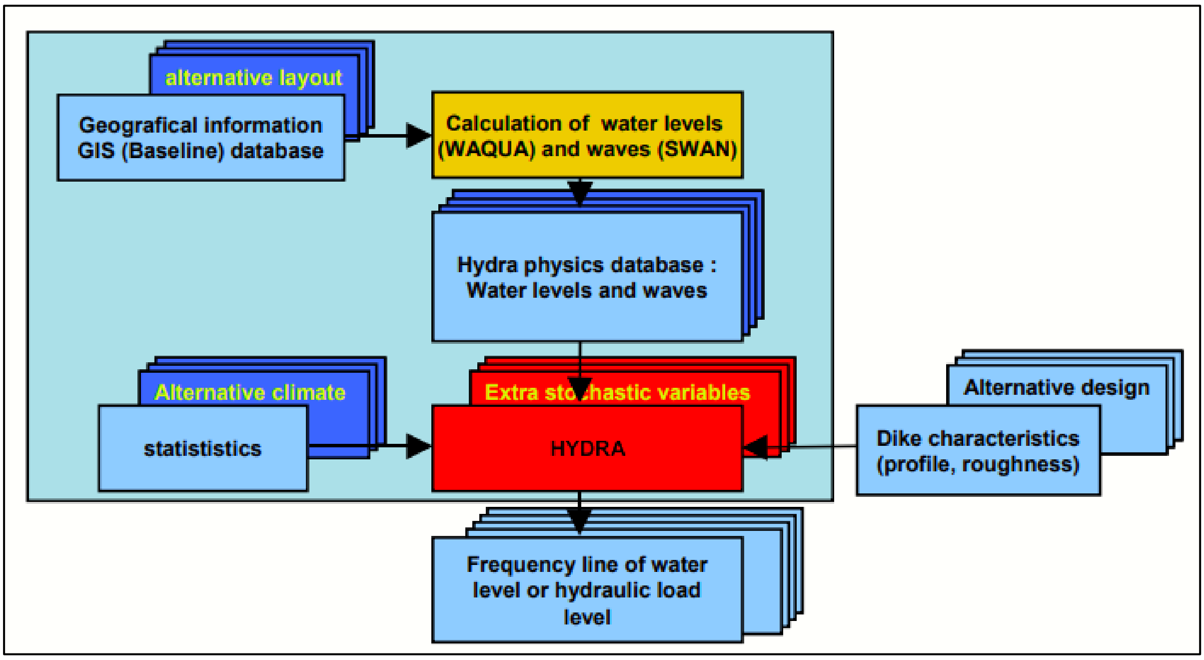


Figure 73 Hydra-Zoet, providing frequency lines for water levels and hydraulic load levels for policy design studies [19]

When considering new enclosure dams or changes in the riverbed, changes of the input of Hydra-Zoet are necessary, leading to different “physical databases” of water levels and waves, also, different dike characteristics might have to be used. When considering alternative climate scenarios, changes to the statistical input become necessary. For all kinds of policy studies, such changes to Hydra-Zoet will be necessary, leading to the scheme of Figure 73, where also extra random variables are indicated that could be necessary. For the purposes of this thesis one or more of the existing current databases will be used, to introduce alternative design ideas.

Appendix E - Protected species

There are several species that are protected under Dutch and European laws in the water system. **Fishes** which protected and have been drastically declined drastically due to overfishing, habitat loss, and other factors are:

European eel (Anguilla anguilla): The European eel is a critically endangered fish species. The eel is an important commercial and recreational fishery species in the IJssel Lake and its surrounding waters.

River lamprey (Lampetra fluviatilis): The river lamprey is a primitive, eel-like fish. It is an important food source for many predatory fish species in the Ketel Lake. The River lamprey is a parasitic fish species that is found in the IJssel Lake, as well as in the rivers that flow into it, such as the IJssel River.

Sea lamprey (Petromyzon marinus): The sea lamprey is another primitive fish species. In the IJssel Lake region, Sea lampreys can be found in the deeper areas of the lake, as well as in the rivers and streams that flow into it. They are typically found in areas with a strong flow of water and suitable substrate for spawning and ammocoete development.

Gudgeon (Gobio gobio): The gudgeon is a small, bottom-dwelling fish species. It is an important prey species for predatory fish in the Ketel Lake.

Bullhead (Cottus gobio): Is a small freshwater fish species that can be found in the IJssel Lake region, as well as in many other lakes, rivers, and streams throughout Europe. Bullheads are typically found in shallow, rocky areas of streams and rivers, where they feed on small invertebrates and other aquatic organisms. In the IJssel Lake, Bullheads can be found in the rivers and streams that flow into the lake, such as the IJssel River and its tributaries. They are also found in many of the smaller streams and creeks that feed into these larger rivers.

European sturgeon (Acipenser sturio): The European sturgeon is a critically endangered fish species. Reintroduction efforts are currently underway in the IJssel Lake and its tributaries.

Atlantic salmon (Salmo salar): The Atlantic salmon is a migratory fish species. Atlantic salmon are typically found in the rivers that flow into the IJssel Lake, such as the IJssel River and its tributaries. Efforts have been made to reintroduce Atlantic salmon to the IJssel Lake region, including the construction of fish ladders and other measures to help the fish migrate upstream to their spawning grounds. However, the population of Atlantic salmon in the IJssel Lake remains relatively small, and the fish are not typically found within the lake itself.

There are several **bird species** that breed or feed in IJssel Lake and are under protection. These species have been affected by habitat loss, disturbance, and pollution.

Common tern (Sterna hirundo): Common tern is a protected bird species that breeds on the sandbanks and islands in IJssel Lake.

Black tern (Chlidonias niger): The Black tern is a migratory bird species that breeds in the wetlands around the IJssel Lake. They are dependent on these habitats for nesting and feeding, and are considered to be of conservation concern throughout Europe.

*Little tern (Sternula albifrons***):** The Little tern is a small migratory bird species that breeds on sandy beaches and in salt marshes around the IJssel Lake. Low water levels could impact the availability of suitable nesting sites and prey, and could also increase the risk of predation and disturbance by humans and other animals.

Eurasian spoonbill (Platalea leucorodia): The Eurasian spoonbill is a large wading bird that is found in the wetlands and marshes around the IJssel Lake. They are dependent on these habitats for feeding, and low water levels could reduce the availability of prey species such as fish and invertebrates.

Osprey (Pandion haliaetus)**:** Osprey is a protected bird of prey that breeds in the wetlands surrounding IJssel Lake.

Great crested grebe (Podiceps cristatus): Great crested grebe is a protected bird species that breeds in the wetlands and shallow waters of IJssel Lake. The species is vulnerable to disturbance and habitat loss.

Eurasian spoonbill (Platalea leucorodia): The Eurasian spoonbill is a large wading bird that is found in the wetlands and marshes around the IJssel Lake. They are considered to be of conservation concern, as they are dependent on these habitats for feeding and nesting.

Common redshank (Tringa totanus): The Common redshank is a wading bird species that is found in wetland habitats throughout Europe, including the IJssel Lake region. They feed on small fish and invertebrates, and low water levels could reduce the availability of these food sources.

Other animals which are in danger in the water system are:

Freshwater pearl mussel (Margaritifera margaritifera): Freshwater pearl mussel is an endangered species that is protected under both national and international legislation. The species is dependent on clean, unpolluted water and is an indicator of high water quality.

Many insect species, such as the *Marsh Fritillary butterfly (Euphydryas aurinia)* are also endangered on the dikes of Zwarte Water River due to habitat loss and fragmentation.

European otter (Lutra lutra): The European otter is a semi-aquatic mammal species that is listed as 'near threatened' on the IUCN Red List. The species is dependent on wetland habitats around the IJssel Lake for food and shelter, and is vulnerable to habitat loss and degradation.

Great pond snail (Lymnaea stagnalis) and *River nerite (Theodoxus fluviatilis)* are snail species known to be sensitive to pollution and habitat degradation, which can affect their populations. It is important to maintain and protect the quality of wetland habitats around the IJssel Lake to ensure the survival of these and other snail species.

There are several **plant species** that are in danger in wetlands around the IJssel Lake. The species is in decline in many areas due to habitat loss and degradation. Efforts are being made to conserve these and other endangered plant species in wetlands around the IJssel Lake, including habitat restoration and management, research and monitoring programs, and public education and awareness campaigns. Some examples include:

Water soldier (Stratiotes aloides): The water soldier is a submerged aquatic plant that is listed as 'vulnerable' on the Dutch Red List of vascular plants. The species is in decline in many areas due to habitat loss and degradation.

Marsh gentian (Gentiana pneumonanthe): The marsh gentian is a flowering plant species that is listed as 'vulnerable' on the Dutch Red List of vascular plants. The species is dependent on wetland habitats around the IJssel Lake and is vulnerable to habitat loss and degradation.

Bogbean (Menyanthes trifoliata): Bogbean is a plant species that is listed as 'vulnerable' on the Dutch Red List of vascular plants. The species is typically found in wetland habitats around the IJssel Lake.

Floating water plantain (Luronium natans): The floating water plantain is a rare and threatened aquatic plant species that is found in wetland habitats around the IJssel Lake. The species is listed as 'vulnerable' on the Dutch Red List of vascular plants.

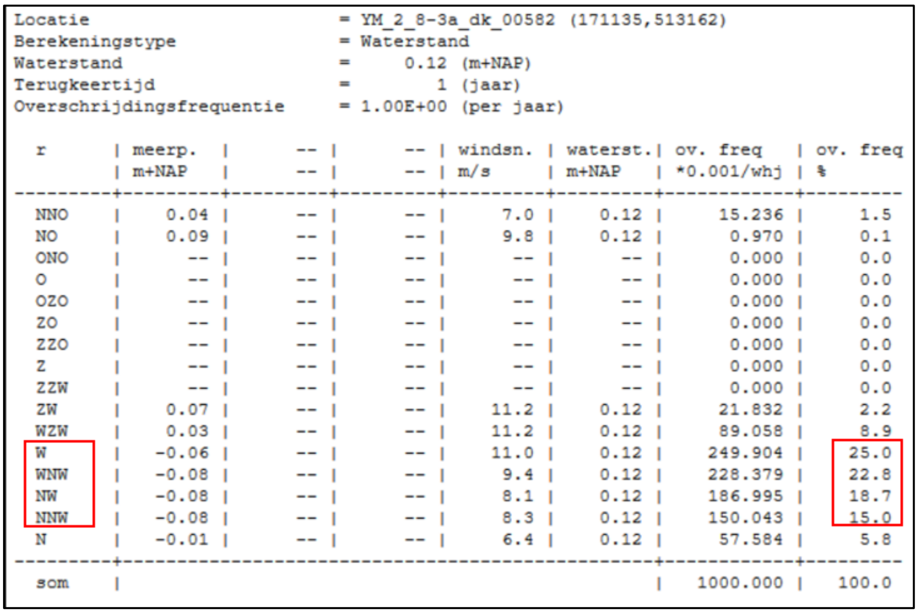
Meadow clary (Salvia pratensis): Is a flowering plant that is listed as 'vulnerable' on the Dutch Red List of vascular plants.

Fen orchid (Liparis loeselii): is a rare and threatened orchid species that is found in wetlands around the IJssel Lake. The species is listed as 'endangered' on the Dutch Red List of vascular plants and is threatened by habitat loss and degradation due to drainage, land-use changes, and development.

It is important to protect and restore the habitats of these species and to reduce pollution and other threats to ensure their survival in IJssel Lake.

Appendix F - Calculations

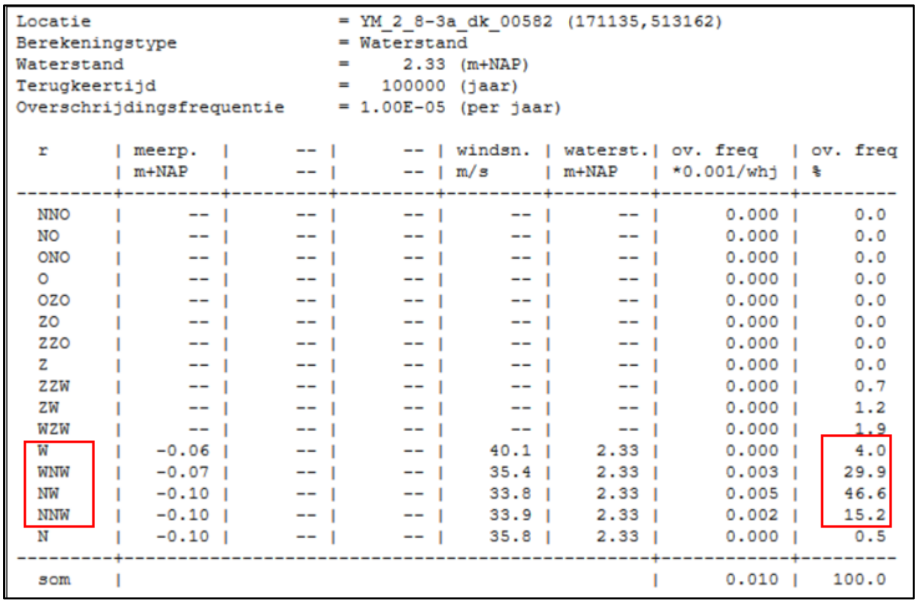
F.1 Calculations for identify the important wind direction per improvement



```
Locatie                          = YM_2_8-3a_dk_00582 (171135,513162)
Berekeningstype                  = Waterstand
Waterstand                       =      0.12 (m+NAP)
Terugkeertijd                    =         1 (jaar)
Overschrijdingsfrequentie        = 1.00E+00 (per jaar)

  r       | meerp.   |       -- |       -- | windsn.  | waterst.| ov. freq    | ov. freq
          | m+NAP    |       -- |       -- | m/s      | m+NAP   | *0.001/whj  | %
---------+---------+---------+---------+---------+---------+------------+---------
  NNO     |     0.04 |       -- |       -- |      7.0 |    0.12 |     15.236 |     1.5
  NO      |     0.09 |       -- |       -- |      9.8 |    0.12 |      0.970 |     0.1
  ONO     |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  O       |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  OZO     |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  ZO      |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  ZZO     |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  Z       |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  ZZW     |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  ZW      |     0.07 |       -- |       -- |     11.2 |    0.12 |     21.832 |     2.2
  WZW     |     0.03 |       -- |       -- |     11.2 |    0.12 |     89.058 |     8.9
  W       |    -0.06 |       -- |       -- |     11.0 |    0.12 |    249.904 |    25.0
  WNW     |    -0.08 |       -- |       -- |      9.4 |    0.12 |    228.379 |    22.8
  NW      |    -0.08 |       -- |       -- |      8.1 |    0.12 |    186.995 |    18.7
  NNW     |    -0.08 |       -- |       -- |      8.3 |    0.12 |    150.043 |    15.0
  N       |    -0.01 |       -- |       -- |      6.4 |    0.12 |     57.584 |     5.8
---------+-----------------------------------------------------+------------+---------
  som     |                                                    |   1000.000 |   100.0
```

Figure 74 Hydra-NL calculation results and important wind directions, return period 1



```
Locatie                          = YM_2_8-3a_dk_00582 (171135,513162)
Berekeningstype                  = Waterstand
Waterstand                       =      2.33 (m+NAP)
Terugkeertijd                    =    100000 (jaar)
Overschrijdingsfrequentie        = 1.00E-05 (per jaar)

  r       | meerp.   |       -- |       -- | windsn.  | waterst.| ov. freq    | ov. freq
          | m+NAP    |       -- |       -- | m/s      | m+NAP   | *0.001/whj  | %
---------+---------+---------+---------+---------+---------+------------+---------
  NNO     |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  NO      |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  ONO     |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  O       |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  OZO     |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  ZO      |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  ZZO     |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  Z       |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.0
  ZZW     |       -- |       -- |       -- |       -- |      -- |      0.000 |     0.7
  ZW      |       -- |       -- |       -- |       -- |      -- |      0.000 |     1.2
  WZW     |       -- |       -- |       -- |       -- |      -- |      0.000 |     1.9
  W       |    -0.06 |       -- |       -- |     40.1 |    2.33 |      0.000 |     4.0
  WNW     |    -0.07 |       -- |       -- |     35.4 |    2.33 |      0.003 |    29.9
  NW      |    -0.10 |       -- |       -- |     33.8 |    2.33 |      0.005 |    46.6
  NNW     |    -0.10 |       -- |       -- |     33.9 |    2.33 |      0.002 |    15.2
  N       |    -0.10 |       -- |       -- |     35.8 |    2.33 |      0.000 |     0.5
---------+-----------------------------------------------------+------------+---------
  som     |                                                    |      0.010 |   100.0
```

Figure 75 Hydra-NL calculation results and important wind directions, return period 10000

Table 35 Parameters used for the calculation of wind set-up with the wind set-up formula for WNW wind direction

Parameter	Value	Unit
g=	9.81	[ms-2]
κ=	0.0000034	[-]
F_W=	42200	[m]
d_{mW}=	4.0	[m]

Table 36 Calculations of wind set-up and water level in Ketelbrug with wind set-up formula for WNW wind direction

WNW							
Return period	Frequency	Water level Hydra-NL	Initial lake water level Hydra-NL	Wind set-up Hydra-NL	Wind speed	Wind set-up formula	
						Wind set-up	Water level
[Years]	[1/Years]	[m]	[m]	[m]	[m/s]	[m]	[m]
1	1/ 1	0.13	-0.08	0.21	9.4	0.16	0.08
5	1/ 5	0.37	-0.06	0.43	16.2	0.49	0.43
10	1/ 10	0.47	-0.07	0.54	17.8	0.59	0.52
50	1/ 50	0.72	-0.08	0.80	21.3	0.85	0.77
100	1/ 100	0.84	-0.08	0.92	22.7	0.96	0.88
500	1/ 500	1.15	-0.09	1.24	26.0	1.26	1.17
1000	1/ 1000	1.31	-0.07	1.38	27.2	1.38	1.31
5000	1/ 5000	1.68	-0.10	1.78	30.5	1.74	1.64
10000	1/ 10000	1.84	-0.09	1.93	31.7	1.88	1.79
50000	1/ 50000	2.19	-0.08	2.27	34.4	2.21	2.13
100000	1/ 100000	2.33	-0.07	2.40	35.4	2.33	2.26

Table 37 Parameters used for the calculation of wind set-up with the wind set-up formula for NW wind direction

Parameter	Value	Unit
g=	9.81	[ms-2]
κ=	0.0000034	[-]
F_W=	52000	[m]
d_{mW}=	4.4	[m]

Table 38 Calculations of wind set-up and water level in Ketelbrug with wind set-up formula for NW wind direction

NW							
Return period	Frequency	Water level Hydra-NL	Initial lake water level Hydra-NL	Wind set-up Hydra-NL	Wind speed	Wind set-up by formula	
						Wind set-up	Water level
[Years]	[1/Years]	[m]	[m]	[m]	[m/s]	[m]	[m]
1	1/ 1	0.13	-0.08	0.21	8.1	0.13	0.05
5	1/ 5	0.37	-0.07	0.44	15.4	0.49	0.42
10	1/ 10	0.47	-0.08	0.55	16.8	0.59	0.51
50	1/ 50	0.72	-0.07	0.79	20.0	0.83	0.76
100	1/ 100	0.84	-0.07	0.91	21.4	0.95	0.88
500	1/ 500	1.15	-0.07	1.22	24.5	1.25	1.18
1000	1/ 1000	1.31	-0.09	1.40	25.9	1.40	1.31
5000	1/ 5000	1.68	-0.08	1.76	28.9	1.74	1.66
10000	1/ 10000	1.84	-0.10	1.94	30.2	1.91	1.81
50000	1/ 50000	2.19	-0.10	2.29	32.7	2.24	2.14
100000	1/ 100000	2.33	-0.10	2.43	33.8	2.39	2.29

Table 39 Parameters used for the calculation of wind set-up with the wind set-up formula for NNW wind direction

Parameter	Value	Unit
g=	9.81	[ms-2]
κ=	0.0000034	[-]
F_W=	51500	[m]
d_{mW}=	4.4	[m]

Table 40 Calculations of wind set-up and water level in Ketelbrug with wind set-up formula for NNW wind direction

NNW							
						Wind set-up formula	
Return period	Frequency	Water level Hydra-NL	Initial lake water level Hydra-NL	Wind set-up Hydra-NL	Wind speed	Wind set-up	Water level
[Years]	[1/Years]	[m]	[m]	[m]	[m/s]	[m]	[m]
1	1/ 1	0.13	-0.08	0.21	8.3	0.14	0.06
5	1/ 5	0.37	-0.06	0.43	15.3	0.48	0.42
10	1/ 10	0.47	-0.08	0.55	16.8	0.58	0.50
50	1/ 50	0.72	-0.07	0.79	20.2	0.84	0.77
100	1/ 100	0.84	-0.07	0.91	21.5	0.95	0.88
500	1/ 500	1.15	-0.07	1.22	24.6	1.25	1.18
1000	1/ 1000	1.31	-0.08	1.39	26.0	1.40	1.32
5000	1/ 5000	1.68	-0.08	1.76	29.0	1.74	1.66
10000	1/ 10000	1.84	-0.10	1.94	30.4	1.92	1.82
50000	1/ 50000	2.19	-0.10	2.29	32.8	2.23	2.13
100000	1/ 100000	2.33	-0.10	2.43	33.9	2.39	2.29

Table 41 Cumulative results of wind set-up calculated for the 4 dominant wind directions by Hydra-NL and wind set-up formula

Return period	W		WNW		NW		NNW	
	Wind set-up Hydra-NL	Wind set-up (formula)	Wind set-up Hydra-NL	Wind set-up (formula)	Wind set-up Hydra-NL	Wind set-up (formula)	Wind set-up Hydra-NL	Wind set-up (formula)
	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]
1	0.19	0.18	0.21	0.17	0.21	0.13	0.21	0.14
5	0.42	0.47	0.43	0.49	0.44	0.49	0.43	0.48
10	0.53	0.58	0.54	0.59	0.55	0.59	0.55	0.59
50	0.78	0.82	0.80	0.85	0.79	0.83	0.79	0.84
100	0.92	0.96	0.92	0.97	0.91	0.95	0.91	0.96
500	1.23	1.26	1.24	1.28	1.22	1.25	1.22	1.25
1000	1.37	1.37	1.38	1.39	1.40	1.40	1.39	1.40
5000	1.76	1.74	1.78	1.76	1.76	1.74	1.76	1.75
10000	1.91	1.87	1.93	1.90	1.94	1.91	1.94	1.93
50000	2.25	2.20	2.27	2.22	2.29	2.24	2.29	2.25
100000	2.39	2.34	2.40	2.35	2.43	2.39	2.43	2.40

Table 42 Analytical calculations of water level for interventions 1-3 and 6-9 for NNW direction

	(NNW) wind direction	Wind speed [m/s]										
	Improvement	10	12	14	16	18	20	22	24	26	28	30
Water level [m]	0 Curent situation	0.20	0.29	0.40	0.52	0.66	0.81	0.98	1.17	1.37	1.59	1.83
	1 Breakwater	0.05	0.07	0.10	0.13	0.17	0.21	0.25	0.30	0.35	0.40	0.46
	2 Afsluitdijk II	0.10	0.14	0.19	0.24	0.31	0.38	0.46	0.55	0.65	0.75	0.86
	3 Reclamation land	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.05
	6 Increase pump capacity at Afsluitdijk	0.01	0.11	0.22	0.34	0.49	0.65	0.83	1.02	1.24	1.47	1.71
	7 Pump installation at Marker Lake	0.11	0.20	0.31	0.43	0.57	0.73	0.90	1.10	1.30	1.53	1.77
	8 Deepening of Ijssel Lake	0.17	0.24	0.32	0.42	0.54	0.66	0.80	0.95	1.12	1.30	1.49
	9 Vegetation land	0.04	0.13	0.26	0.36	0.48	0.61	0.77	0.92	1.10	1.57	1.83

Table 43 Analytical calculations of water level for interventions 1-3 and 6-9 for NW direction

	(NW) wind direction	Wind speed [m/s]										
	Improvement	10	12	14	16	18	20	22	24	26	28	30
Water level [m]	0 Curent situation	0.20	0.29	0.40	0.52	0.66	0.82	0.99	1.18	1.38	1.61	1.84
	1 Breakwater	0.03	0.05	0.06	0.08	0.11	0.13	0.16	0.19	0.22	0.26	0.30
	2 Afsluitdijk II	0.08	0.12	0.16	0.21	0.27	0.34	0.41	0.48	0.57	0.66	0.76
	3 Reclamation land	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07
	6 Increase pump capacity at Afsluitdijk	0.01	0.11	0.22	0.35	0.50	0.66	0.84	1.04	1.25	1.48	1.73
	7 Pump installation at Marker Lake	0.11	0.20	0.31	0.44	0.58	0.74	0.91	1.11	1.32	1.54	1.79
	8 Deepening of Ijssel Lake	0.17	0.24	0.33	0.43	0.54	0.67	0.81	0.96	1.13	1.31	1.50
	9 Vegetation land	0.04	0.13	0.26	0.37	0.49	0.62	0.77	0.93	1.11	1.59	1.84

Table 44 Analytical calculations of water level for interventions 1-3 and 6-9 for WNW direction

	(WNW) wind direction	Wind speed [m/s]										
	Improvement	10	12	14	16	18	20	22	24	26	28	30
Water level [m]	0 Curent situation	0.18	0.26	0.36	0.47	0.59	0.73	0.88	1.05	1.24	1.43	1.65
	1 Breakwater	0.03	0.04	0.06	0.08	0.10	0.12	0.14	0.17	0.20	0.23	0.27
	2 Afsluitdijk II	0.12	0.17	0.23	0.30	0.38	0.47	0.57	0.68	0.80	0.93	1.07
	3 Reclamation land	0.02	0.02	0.03	0.04	0.05	0.06	0.08	0.09	0.11	0.12	0.14
	6 Increase pump capacity at Afsluitdijk	-0.01	0.08	0.18	0.29	0.42	0.57	0.73	0.91	1.10	1.31	1.53
	7 Pump installation at Marker Lake	0.09	0.17	0.27	0.38	0.51	0.65	0.81	0.98	1.17	1.37	1.59
	8 Deepening of Ijssel Lake	0.15	0.21	0.29	0.37	0.47	0.59	0.71	0.84	0.99	1.15	1.32
	9 Vegetation land	0.02	0.09	0.23	0.32	0.43	0.54	0.68	0.83	0.97	1.17	1.63

Table 45 Analytical calculations of water level for interventions 1-3 and 6-9 for W direction

	(W) wind direction	Wind speed [m/s]										
	Improvement	10	12	14	16	18	20	22	24	26	28	30
Water level [m]	0 Curent situation	0.14	0.20	0.27	0.36	0.45	0.56	0.68	0.80	0.94	1.09	1.26
	1 Breakwater	0.05	0.07	0.09	0.12	0.15	0.18	0.22	0.26	0.31	0.36	0.41
	2 Afsluitdijk II	0.14	0.20	0.27	0.36	0.45	0.56	0.68	0.80	0.94	1.09	1.26
	3 Reclamation land	0.14	0.20	0.27	0.36	0.45	0.56	0.68	0.80	0.94	1.09	1.26
	6 Increase pump capacity at Afsluitdijk	-0.04	0.03	0.11	0.20	0.31	0.43	0.56	0.70	0.86	1.03	1.21
	7 Pump installation at Marker Lake	0.05	0.11	0.19	0.28	0.38	0.49	0.62	0.75	0.90	1.06	1.23
	8 Deepening of Ijssel Lake	0.09	0.13	0.18	0.23	0.29	0.36	0.43	0.52	0.61	0.70	0.81
	9 Vegetation land		0.04	0.11	0.22	0.30	0.40	0.50	0.61	0.73	0.86	0.99

Table 46 Wind direction causing the highest water level per improvement

Wind direction causing the maximum water level per improvement												
Wind direction	Improvement	Wind speed [m/s]										
		10	12	14	16	18	20	22	24	26	28	30
NW	0 Curent situation	0.20	0.29	0.40	0.52	0.66	0.82	0.99	1.18	1.38	1.61	1.84
NNW	1 Breakwater	0.05	0.07	0.10	0.13	0.17	0.21	0.25	0.30	0.35	0.40	0.46
W	2 Afsluitdijk II	0.14	0.20	0.27	0.36	0.45	0.56	0.68	0.80	0.94	1.09	1.26
W	3 Reclamation land	0.14	0.20	0.27	0.36	0.45	0.56	0.68	0.80	0.94	1.09	1.26
NW	6 Increase pump capacity at Afsluitdijk	0.01	0.11	0.22	0.35	0.50	0.66	0.84	1.04	1.25	1.48	1.73
NW	7 Pump installation at Marker Lake	0.11	0.20	0.31	0.44	0.58	0.74	0.91	1.11	1.32	1.54	1.79
NW	8 Deepening of Ijssel Lake	0.17	0.24	0.33	0.43	0.54	0.67	0.81	0.96	1.13	1.31	1.50
NW	9 Vegetation land	0.04	0.13	0.26	0.37	0.49	0.62	0.77	0.93	1.11	1.59	1.84

F.2 Analytical calculations of the water levels for improvements 1-3 and 6-9

Analytical calculations of water levels for different return periods with wind set-up formula. Improvements 1-3 and 6-9. Calculations in Ketelbrug and transformation of the results to the "calculation point of interest" in the city of Zwolle, through applying the correlation factor.

Table 47 Parameters used for the calculation of the water levels for different return periods with the wind set-up formula. Improvements 1-3 and 6-9.

		g=	9.81	[ms-2]						
		κ=	3E-06	[-]						
NW	0	Current situation								
NNW	1	Breakwater	$F_{NNW(1)}$=	11000	[m]	$d_{mNNW(1)}$	3.7	m		
W	2	Afsluitdijk II	$F_{W(2)}$=	14500	[m]	$d_{mW(2)}$=	1.8	m		
W	3	Reclamation land	$F_{W(6)}$=	14500	[m]	$d_{mW(6)}$=	1.8	m		
NW	6	Pump capacity Afsluitdi	F_{NW}=	52000	[m]	$d_{mNW(4)}$=	4.2	m		
NW	7	Pump station Markerm	F_{NW}=	52000	[m]	$d_{mNW(4)}$=	4.3	m		
NW	8	Lake deepening	F_{NW}=	52000	[m]	$d_{mNW(4)}$=	5.4	m		
NW	9	Vegetation area	F_{NW}=	52000	[m]	d_{mNW}=	4.4	m	C_M=	Table xx

Table 48 Water level at Ketelbrug [Hydra-NL], wind speed and initial lake level [Hydra-NL], per wind direction

Return period	Ketelbrug								
	0. Current situation / Hydra-NL								
	Water level	West wind direction		Westnorthwest wind direction		Northwest wind direction		Northnorthwest wind direction	
		Wind speed	Initial lake level	Wind speed	Initial lake level	Wind speed	Initial lake level	Wind speed	Initial lake level
[Years]	[m]	[m/s]	[m]	[m/s]	[m]	[m/s]	[m]	[m/s]	[m]
1	0.13	11.00	-0.06	9.40	-0.08	8.10	-0.08	8.30	-0.08
2.5	0.29	15.90	-0.03	14.90	-0.07	12.60	-0.03	11.20	0.02
5	0.37	18.00	-0.05	16.20	-0.06	15.40	-0.07	15.30	-0.06
7.5	0.42	19.30	-0.06	17.20	-0.08	16.20	-0.08	16.10	-0.06
10	0.47	19.90	-0.06	17.80	-0.07	16.80	-0.08	16.60	-0.05
25	0.61	22.30	-0.07	19.80	-0.07	18.50	-0.06	18.50	-0.04
50	0.72	23.80	-0.06	21.30	-0.08	20.00	-0.07	20.20	-0.07
75	0.79	24.70	-0.05	22.10	-0.08	20.80	-0.08	21.00	-0.08
100	0.84	25.60	-0.08	22.70	-0.08	21.40	-0.07	21.50	-0.07
250	1.01	27.70	-0.07	24.50	-0.07	23.20	-0.08	23.40	-0.08
500	1.15	29.30	-0.08	26.00	-0.09	24.50	-0.07	24.60	-0.07
750	1.24	30.10	-0.07	26.70	-0.08	25.40	-0.09	25.60	-0.09
1000	1.31	30.70	-0.06	27.20	-0.07	25.90	-0.09	26.00	-0.08
2500	1.52	32.80	-0.07	29.10	-0.08	27.80	-0.10	27.90	-0.10
5000	1.68	34.40	-0.08	30.50	-0.10	28.90	-0.08	29.00	-0.08
7500	1.78	35.30	-0.08	31.20	-0.09	29.70	-0.10	29.90	-0.10
10000	1.84	35.80	-0.07	31.70	-0.09	30.20	-0.10	30.40	-0.10
25000	2.04	37.80	-0.10	33.40	-0.10	31.60	-0.09	31.70	-0.08
50000	2.19	38.90	-0.06	34.40	-0.08	32.70	-0.10	32.80	-0.10
75000	2.27	39.60	-0.07	35.00	-0.08	33.40	-0.10	33.50	-0.10
100000	2.33	40.10	-0.06	35.40	-0.07	33.80	-0.10	33.90	-0.10

The following Table 49, is a continuation of Table 48.

Table 49 Calculated wind set-up and water levels for the improvements 1-3 and 6-9 by wind set-up formula, for different return periods and the dominant wind direction per improvement

Ketelbug																
1. Breakwater		2. Afsluitdijk II		3. Land reclamation		6. Pump capacity Afsluitdijk		7. Pump station Markermeerdijk		8. Lake deepening		9. Vegetation area		
Wind. Dir.	NNW	Wind. Dir.	W	Wind. Dir.	W	Wind. Dir.	NW	Wind. Dir.	NW	Wind. Dir.	NW	Wind. Dir.	NW	
Wind set-up	Water Level	Wind set-up	Water Level	Wind set-up	Water Level	Wind set-up	Water Level	Wind set-up	Water Level	Wind set-up	Water Level	Wind set-up	Reduction factor Cm	Water Level
[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[-]	[m]
0.04	-0.02	0.17	0.11	0.17	0.11	0.14	-0.12	0.14	-0.02	0.11	0.05	0.14	1.00	-0.06
0.06	0.03	0.36	0.33	0.36	0.33	0.34	0.11	0.34	0.21	0.27	0.24	0.33	0.46	0.15
0.12	0.07	0.47	0.42	0.47	0.42	0.52	0.27	0.51	0.36	0.40	0.35	0.49	0.32	0.29
0.14	0.08	0.54	0.48	0.54	0.48	0.57	0.31	0.56	0.40	0.44	0.38	0.55	0.29	0.33
0.14	0.08	0.57	0.51	0.57	0.51	0.62	0.36	0.60	0.44	0.48	0.42	0.59	0.27	0.37
0.18	0.11	0.72	0.65	0.72	0.65	0.74	0.47	0.73	0.56	0.58	0.51	0.71	0.26	0.46
0.21	0.15	0.82	0.76	0.82	0.76	0.87	0.61	0.85	0.69	0.68	0.62	0.83	0.24	0.57
0.23	0.18	0.88	0.83	0.88	0.83	0.95	0.70	0.92	0.77	0.73	0.68	0.90	0.23	0.64
0.24	0.16	0.96	0.88	0.96	0.88	1.00	0.72	0.98	0.80	0.77	0.69	0.95	0.23	0.66
0.29	0.22	1.11	1.04	1.11	1.04	1.18	0.91	1.15	0.98	0.91	0.84	1.12	0.21	0.81
0.32	0.24	1.25	1.17	1.25	1.17	1.31	1.03	1.28	1.10	1.01	0.93	1.25	0.21	0.91
0.35	0.28	1.32	1.25	1.32	1.25	1.41	1.14	1.38	1.21	1.09	1.02	1.35	0.20	1.01
0.36	0.30	1.36	1.30	1.36	1.30	1.47	1.21	1.44	1.28	1.14	1.08	1.40	0.19	1.07
0.41	0.34	1.56	1.49	1.56	1.49	1.70	1.43	1.66	1.49	1.31	1.24	1.62	0.01	1.53
0.44	0.36	1.73	1.65	1.73	1.65	1.83	1.55	1.78	1.60	1.41	1.33	1.74	0.01	1.64
0.47	0.39	1.82	1.74	1.82	1.74	1.94	1.66	1.89	1.71	1.50	1.42	1.85	0.01	1.76
0.49	0.42	1.86	1.79	1.86	1.79	2.00	1.73	1.96	1.79	1.55	1.48	1.91	0.00	1.84
0.53	0.43	2.11	2.01	2.11	2.01	2.19	1.89	2.14	1.94	1.69	1.59	2.09	0.00	1.99
0.57	0.51	2.19	2.13	2.19	2.13	2.35	2.09	2.29	2.13	1.82	1.76	2.24	0.00	2.18
0.59	0.52	2.28	2.21	2.28	2.21	2.45	2.18	2.39	2.22	1.90	1.83	2.34	0.00	2.27
0.61	0.55	2.32	2.26	2.32	2.26	2.51	2.25	2.45	2.29	1.94	1.88	2.39	0.00	2.33

The following Table 50, is a continuation of Table 49.

Table 50 Estimation of the correlation factor between the point of interest at Ketelbrug and the "calculation point of interest" in the city of Zwolle, for improvements 1-2 and 6-9

			Correlation factor calculated for each water level at Ketelbrug						
Water Level		Factor	Improvements						
Ketelbrug	Zwolle		1	2	3	6	7	8	9
0.13	0.55	4.408		4.478	4.478				
0.29	0.94	3.283		3.079	3.079	4.492	3.849	3.633	4.254
0.37	1.07	2.884	4.771	2.700	2.700	3.416	2.974	2.974	3.283
0.42	1.13	2.663	4.750	2.483	2.483	3.150	2.761	2.822	3.079
0.47	1.17	2.512	4.694	2.394	2.394	2.946	2.596	2.687	2.884
0.61	1.30	2.149	4.527	2.053	2.053	2.491	2.277	2.405	2.543
0.72	1.38	1.916	4.205	1.850	1.850	2.134	1.970	2.128	2.240
0.79	1.42	1.799	4.010	1.742	1.742	1.962	1.823	1.989	2.072
0.84	1.45	1.721	4.143	1.678	1.678	1.916	1.787	1.966	2.041
1.01	1.54	1.518	3.758	1.489	1.489	1.642	1.557	1.721	1.760
1.15	1.61	1.392	3.619	1.377	1.377	1.502	1.441	1.609	1.644
1.24	1.65	1.328	3.353	1.325	1.325	1.400	1.350	1.506	1.524
1.31	1.68	1.286	3.236	1.289	1.289	1.348	1.305	1.459	1.466
1.52	1.78	1.171	3.017	1.184	1.184	1.219	1.187	1.328	1.164
1.68	1.85	1.104	2.917	1.116	1.116	1.159	1.135	1.270	1.118
1.78	1.90	1.070	2.790	1.082	1.082	1.112	1.092	1.224	1.076
1.84	1.94	1.052	2.700	1.065	1.065	1.084	1.067	1.191	1.052
2.04	2.06	1.011	2.645	1.017	1.017	1.042	1.032	1.139	1.022
2.19	2.19	1.003	2.399	1.006	1.006	1.008	1.006	1.076	1.003
2.27	2.30	1.012	2.363	1.005	1.005	1.003	1.007	1.055	1.012
2.33	2.39	1.024	2.297	1.011	1.011	1.010	1.016	1.043	1.025

The following Table 51, is a continuation of Table 52.

Table 51 Transformation of the calculated water level at Ketelbrug to water levels at the "calculation point of interest" in Zwolle, through applying the correlation factor, for improvements 1-2 and 6-9

Zwolle						
1. Breakwater	2. Afsluitdijk II	3. Land reclamation	6. Pump capacity Afsluitdijk	7. Pump station at Marker Lake	8. Lake deepening	9. Vegetation area
NNW	W	W	NW	NW	NW	NW
Water level						
[m]						
	0.51	0.51				
	1.01	1.01	0.51	0.79	0.86	0.63
0.35	1.12	1.12	0.91	1.06	1.04	0.95
0.36	1.19	1.19	0.99	1.11	1.09	1.01
0.39	1.23	1.23	1.05	1.15	1.12	1.06
0.49	1.34	1.34	1.18	1.27	1.22	1.16
0.65	1.40	1.40	1.31	1.36	1.31	1.28
0.73	1.44	1.44	1.37	1.41	1.36	1.33
0.67	1.47	1.47	1.38	1.42	1.36	1.34
0.82	1.56	1.56	1.49	1.52	1.45	1.43
0.86	1.62	1.62	1.55	1.58	1.50	1.49
0.93	1.65	1.65	1.60	1.64	1.54	1.53
0.96	1.68	1.68	1.63	1.67	1.57	1.57
1.03	1.77	1.77	1.74	1.77	1.65	1.79
1.06	1.84	1.84	1.79	1.82	1.69	1.84
1.10	1.88	1.88	1.84	1.87	1.74	1.89
1.13	1.91	1.91	1.88	1.91	1.76	1.94
1.14	2.05	2.05	1.97	2.00	1.82	2.03
1.22	2.14	2.14	2.11	2.15	1.89	2.19
1.24	2.22	2.22	2.19	2.24	1.93	2.29
1.26	2.29	2.29	2.27	2.33	1.96	2.39

This table is a part of the cumulative Table 18 in the Chapter 5: Assessment Results and Selection

F.3 Analytical calculations of the water levels for improvements 4-5

Analytical calculations of water levels for different return periods with wind set-up formula and Hydra-NL calculations for Ramspol Barrier. Improvements 4-5. The water level at Ramspol has been calculated as the difference of the calculated water levels from Hydra-NL, reduced by the wind set-up at Ketelbrug, since those improvements are blocking the influence of wind set-up in IJssel Lake to Ketel Lake. Calculations in Ramspol and transformation of the results to the “calculation point of interest” in the city of Zwolle, through applying the correlation factor.

Table 52 Parameters used for the calculations of water level at Ramspol

wind dir.	W	
g=	9.81	[ms-2]
κ=	3.4E-06	[-]
Fw=	11000	[m]
d=	4.5	[m]

Table 53 Analytical calculation of water level at Ramspol for improvements 4 and 5 and transformation of the water levels at Ramspol to water levels at Zwolle by applying the correlation factor

Return period	Water level at Ramspol Barrier (Hydra-NL)	Wind set up at ketelbrug (wind set up formula)	Water level at Ramspol (Hydra-NL - wind set up at Ketelbrug)		Water level at Zwolle	Correlation factor beteen Ramspol and Zwolle	Correlation factor		Water level at zwolle	
			4. Outflow	5. Ramspol Barrier II			4. Outflow	5. Ramspo	4. Outflow	5. Ramspol
[Years]	[m]	[m]	[m]	[m]	[m]	[-]	[-]	[-]	[m]	[m]
1	0.23	0.17	0.06	0.56	0.55	2.375	2.661	1.832	0.15	1.02
2.5	0.47	0.36	0.11	0.61	0.94	1.985	2.569	1.729	0.29	1.06
5	0.63	0.47	0.16	0.66	1.07	1.702	2.490	1.652	0.40	1.09
7.5	0.73	0.54	0.19	0.69	1.13	1.549	2.443	1.609	0.47	1.11
10	0.80	0.57	0.23	0.73	1.17	1.464	2.382	1.552	0.55	1.13
25	1.02	0.72	0.30	0.80	1.30	1.278	2.271	1.462	0.67	1.17
50	1.18	0.82	0.36	0.86	1.38	1.166	2.166	1.409	0.78	1.21
75	1.28	0.88	0.40	0.90	1.42	1.112	2.105	1.379	0.84	1.24
100	1.35	0.96	0.39	0.89	1.45	1.074	2.122	1.387	0.82	1.23
250	1.58	1.11	0.46	0.96	1.54	0.973	1.998	1.325	0.93	1.28
500	1.76	1.25	0.51	1.01	1.61	0.912	1.923	1.289	0.97	1.30
750	1.87	1.32	0.55	1.05	1.65	0.882	1.838	1.257	1.02	1.32
1000	1.95	1.36	0.59	1.09	1.68	0.862	1.778	1.234	1.04	1.34
2500	2.20	1.56	0.63	1.13	1.78	0.809	1.695	1.202	1.07	1.36
5000	2.38	1.73	0.66	1.16	1.85	0.778	1.662	1.185	1.09	1.37
7500	2.49	1.82	0.67	1.17	1.90	0.762	1.639	1.175	1.10	1.38
10000	2.57	1.86	0.70	1.20	1.94	0.754	1.589	1.156	1.12	1.39
25000	2.79	2.11	0.68	1.18	2.06	0.739	1.625	1.170	1.11	1.38
50000	2.96	2.19	0.77	1.27	2.19	0.740	1.492	1.113	1.16	1.42
75000	3.06	2.28	0.78	1.28	2.30	0.751	1.482	1.108	1.16	1.42
100000	3.14	2.32	0.82	1.32	2.39	0.761	1.446	1.089	1.18	1.43

These last 2 rows of Table 55 are a part of the cumulative Table 18 in the Chapter 5: Assessment Results and Selection.

F.4 Analytical calculations of the water levels for improvements 12-16

Analytical calculations of water levels for different return periods with lake level formula and Hydra-NL calculations for Zwarte Lake. Improvements 12-16. The water level at the calculation point in Zwarte Lake, has been calculated as the difference of the calculated water levels from Hydra-NL, reduced by the reduction in water level calculated by the lake level formula. Calculations in Zwarte Lake and transformation of the results to the “calculation point of interest” in the city of Zwolle, through applying the correlation factor.

Table 54 Parameters used for the calculation of the water level in Zwarte Lake for improvements 12-16

Parameter	Unit	0. Current situation	12. Pump Installation at Ramspol	13 Extension of Vollenhover channel	14. Size up Zwarte Lake	15. Faster closure procedure	16. Closure procedure at a lower level
A	[m2]	21500000	21500000	21500000	32250000	21500000	21500000
Qout	[m3/s]	no	40	100	no	no	no
T	[sec]	43200	43200	43200	43200	43200	43200
ho	[m]	0.00	0.00	0.00	0.00	-0.05	-0.10

Table 55 Calculation of the water level at Zwarte Lake by applying the reduction of water level because of the interventions (lake-level formula) to the calculated from Hydra-NL water levels, at the calculation point in Zwarte Lake, for improvements 12-16

Return period	Water level at Zwarte Lake (Hydra-NL)	River Discharge	Wind speed	12. Pump Station at Ramspol	13. Vollenhover channel	14. Size up Zwarte Lake	15. Faster closure procedure	16. Closure procedure at a lower level
				Water level at Zwarte Lake				
[Years]	[m]	[m^3/s]	[m^2/s]	[m]				
1	0.43							
2.5	0.67	100	16.8	0.58	0.46	0.44	0.62	0.57
5	0.77	130	18.1	0.68	0.56	0.51	0.72	0.67
7.5	0.82	130	19.0	0.74	0.62	0.54	0.77	0.72
10	0.85	145	19.4	0.77	0.65	0.57	0.80	0.75
25	0.96	160	21.1	0.88	0.76	0.64	0.91	0.86
50	1.03	161	22.3	0.95	0.83	0.69	0.98	0.93
75	1.07	159	23.1	0.99	0.87	0.72	1.02	0.97
100	1.10	160	23.7	1.02	0.90	0.74	1.05	1.00
250	1.19	175	25.2	1.11	0.99	0.79	1.14	1.09
500	1.24	164	26.4	1.16	1.04	0.83	1.19	1.14
750	1.27	173	26.9	1.19	1.07	0.85	1.22	1.17
1000	1.30	164	27.5	1.21	1.09	0.86	1.25	1.20
2500	1.38	183	29.0	1.30	1.18	0.92	1.33	1.28
5000	1.47	250	29.3	1.39	1.27	0.98	1.42	1.37
7500	1.53	250	30.3	1.45	1.33	1.02	1.48	1.43
10000	1.59	250	31.1	1.50	1.38	1.06	1.54	1.49
25000	1.75	175	35.0	1.67	1.55	1.17	1.70	1.65
50000	1.86	175	36.5	1.78	1.66	1.24	1.81	1.76
75000	1.92	188	37.5	1.84	1.72	1.28	1.87	1.82
100000	1.99	180	39.0	1.91	1.79	1.33	1.94	1.89

Table 56 Estimation of the correlation factor for each calculated water level at Zwarte Lake, for improvements 12-16

Water level at Zwolle (Hydra-NL)	Correlation Factor between water levels at Zwarte Lake and Zwolle	Correlation factor for the different improvements for intermediate water levels				
		12. Pump Station at Ramspol	13. Vollenhover channel	14. Size up Zwarte Lake	15. Faster closure procedure	16. Closure procedure at a lower level
[m]	[-]	[-]	[-]	[-]	[-]	[-]
0.55	1.284					
0.94	1.412	1.369	1.303	1.292	1.385	1.358
1.07	1.395	1.409	1.357	1.328	1.403	1.412
1.13	1.382	1.400	1.385	1.347	1.394	1.403
1.17	1.377	1.393	1.404	1.360	1.386	1.398
1.30	1.359	1.373	1.396	1.398	1.367	1.376
1.38	1.333	1.360	1.380	1.408	1.350	1.363
1.42	1.322	1.347	1.374	1.403	1.336	1.354
1.45	1.311	1.336	1.369	1.400	1.327	1.343
1.54	1.290	1.309	1.348	1.388	1.302	1.315
1.61	1.291	1.296	1.330	1.380	1.291	1.301
1.65	1.294	1.291	1.322	1.377	1.291	1.294
1.68	1.297	1.290	1.314	1.376	1.291	1.290
1.78	1.290	1.297	1.293	1.366	1.294	1.295
1.85	1.263	1.332	1.293	1.351	1.278	1.290
1.90	1.238	1.267	1.294	1.336	1.257	1.273
1.94	1.221	1.249	1.288	1.326	1.238	1.257
2.06	1.178	1.199	1.232	1.295	1.191	1.204
2.19	1.179	1.179	1.203	1.291	1.179	1.178
2.30	1.195	1.179	1.186	1.295	1.183	1.179
2.39	1.198	1.193	1.179	1.294	1.198	1.188

Table 57 Calculation of the water level in the "calculation point of interest" in Zwolle, by applying the correlation factor for improvements 12-16

Return period	Water level at the "calculation point" of interest in Zwolle				
	12. Pump Station at Ramspol	13. Vollenhover channel	14. Size up Zwarte Lake	15. Faster closure procedure	16. Closure procedure at a lower level
[Years]	[m]	[m]	[m]	[m]	[m]
1					
2.5	0.80	0.60	0.57	0.85	0.77
5	0.96	0.77	0.68	1.00	0.94
7.5	1.03	0.85	0.73	1.07	1.01
10	1.07	0.91	0.77	1.11	1.05
25	1.20	1.06	0.89	1.24	1.18
50	1.29	1.15	0.97	1.33	1.27
75	1.34	1.20	1.00	1.37	1.32
100	1.37	1.23	1.03	1.40	1.35
250	1.45	1.33	1.10	1.49	1.43
500	1.51	1.39	1.14	1.54	1.49
750	1.54	1.42	1.17	1.58	1.52
1000	1.57	1.44	1.19	1.61	1.54
2500	1.68	1.52	1.25	1.72	1.66
5000	1.85	1.64	1.32	1.81	1.76
7500	1.84	1.72	1.37	1.87	1.83
10000	1.88	1.78	1.40	1.90	1.87
25000	2.00	1.91	1.51	2.03	1.99
50000	2.10	1.99	1.60	2.13	2.07
75000	2.17	2.04	1.66	2.22	2.15
100000	2.28	2.11	1.72	2.33	2.25

These last 5 rows of Table 57 are a part of cumulative Table 19 in the Chapter 5: Assessment Results and Selection.

Table 58 Calculation of water level for different return period in the city of Zwolle, for multiple values of pump capacity at Ramspol Barrier

	12. Pump station at Ramspol / different pump capacity [m3/s]					
Return period	40	60	80	100	150	200
[Years]	Water level at the calculation point of interest at Zwolle [m]					
2.5	0.80	0.73	0.67	0.60	0.45	
5	0.96	0.90	0.83	0.76	0.60	0.45
7.5	1.03	0.98	0.92	0.85	0.69	0.53
10	1.07	1.03	0.97	0.91	0.74	0.58
25	1.20	1.15	1.11	1.06	0.92	0.75
50	1.29	1.25	1.20	1.15	1.02	0.88
75	1.34	1.30	1.25	1.20	1.08	0.95
100	1.37	1.33	1.28	1.23	1.11	0.99
250	1.45	1.41	1.38	1.34	1.22	1.10
500	1.51	1.47	1.43	1.39	1.28	1.16
750	1.54	1.50	1.46	1.42	1.32	1.20
1000	1.57	1.53	1.48	1.44	1.34	1.22
2500	1.68	1.62	1.58	1.53	1.42	1.32
5000	1.85	1.72	1.68	1.63	1.52	1.41
7500	1.84	1.80	1.75	1.71	1.59	1.48
10000	1.88	1.85	1.81	1.76	1.65	1.54
25000	2.00	2.06	2.05	1.97	1.84	1.73
50000	2.10	2.06	2.06	2.06	1.98	1.84
75000	2.17	2.12	2.06	2.06	2.06	1.90
100000	2.28	2.21	2.16	2.11	2.06	2.06

F.5 Analytical calculations of the water levels for improvement 19

Table 59 Analytical calculations of water levels at Zwolle for the new river cross section for improvement 19

Water level (Hydra-NL)	Depth (4 + Water Level)	Width of the main channel	Calculated Discharge (normal flow depth formula (12))	Flood plain Width	Depth at main channel (complex normal flow depth formula(13))	Water level at Zwolle
[m]	[m]	[m]	[m^3/s]	[m]	[m]	[m]
0.55	4.55	80	243.27	250		0.55
0.94	4.94	80	275.03	250		0.94
1.07	5.07	80	285.79	250	5.055	1.06
1.13	5.13	80	291.05	250	5.009	1.01
1.17	5.17	80	294.81	250	5.013	1.01
1.30	5.30	80	305.90	250	5.213	1.21
1.38	5.38	80	312.33	250	5.258	1.26
1.42	5.42	80	316.00	250	5.283	1.28
1.45	5.45	80	318.45	250	5.299	1.30
1.54	5.54	80	326.38	250	5.351	1.35
1.61	5.61	80	332.59	250	5.390	1.39
1.65	5.65	80	336.42	250	5.413	1.41
1.68	5.68	80	339.10	250	5.430	1.43
1.78	5.78	80	347.92	250	5.483	1.48
1.85	5.85	80	354.90	250	5.523	1.52
1.90	5.90	80	359.00	250	5.547	1.55
1.94	5.94	80	362.29	250	5.566	1.57
2.06	6.06	80	374.07	250	5.631	1.63
2.19	6.19	80	385.98	250	5.695	1.70
2.30	6.30	80	396.03	250	5.748	1.75
2.39	6.39	80	404.64	250	5.793	1.79

This last row of table 59 is a part of the cumulative Table 19 in the Chapter 5: Assessment Results and Selection

F.6 Analytical calculations of the water levels for improvement 17 and Improvement 20

For the Improvements 17 Rising of the dikes which represents the current situation of the water level (influence to the water level) and Improvement 20. Increased reliability of Ramspol Barrier the water levels have been directly derived through the calculation of Hydra-NL.

Table 60 Calculation of Hydra-NL for the water level at the calculation point of interest in Zwolle for improvements 12 and 20

Water level at Zwolle	
17 (0)	20
Increase the height of the dikes	Increase Ramspol Barrier reliablity
[m]	[m]
0.55	0.55
0.94	0.94
1.07	1.06
1.13	1.01
1.17	1.01
1.30	1.21
1.38	1.26
1.42	1.28
1.45	1.30
1.54	1.35
1.61	1.39
1.65	1.41
1.68	1.43
1.78	1.48
1.85	1.52
1.90	1.55
1.94	1.57
2.06	1.63
2.19	1.70
2.30	1.75
2.39	1.79

Those results from Table 60 can be found in the cumulative Table 19 in the Chapter 5: Assessment Results and Selection