Effects of flexible water level management on flood risk in areas outside primary levees around the IJsselmeer and Markermeer

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MSc Thesis Water Management

Effects of flexible water level management on flood risk in areas outside primary levees around the IJsselmeer and Markermeer

by

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Preface

This master thesis investigates effects of flexible water level management on flood risk in areas outside primary levees around the IJsselmeer and Markermeer and will contribute to the development of the Dutch water system to make it more robust and future proof. It was a challenging and extremely interesting research project and I am very proud to present the end results in this report. I learned a lot during this research. Firstly, I experienced how it is to work full-time as an intern at a consultancy and engineering firm and secondly, I learned working with many different computer programmes and how to combine them.

I want to thank my supervisors from the Technical University of Delft. I am grateful to Martine Rutten, Olivier Hoes and Elisa Ragno for asking critical questions, sharing your amazing knowledge and great support. Next, I also like to thank my supervisors Maarten van Dieren and Angelique Vermeulen from WSP for your valuable feedback, motivation and enthusiasm.

Lastly, special thanks goes to my partner Niels who always supported me during the master thesis project. I also want to thank my mam and dad, my grandparents, friends and family for encouraging me throughout my studies at TU Delft!

Enjoy reading my master thesis!

Lisa Goossens

Delft, December 2021

Summary

Since 2019, Rijkswaterstaat has been applying flexible water level management in the IJsselmeer and Markermeer to make the Dutch water system more robust and future proof. The fixed target water level of -0.20 m NAP during summer is replaced by a flexible water level in which the water level can fluctuate between -0.10 and -0.30 m NAP to enlarge the fresh water supply and to anticipate on weather conditions. In the IJsselmeer region, 15,600 hectares of land is located outside primary levees. These areas are mainly pasturelands, recreation areas, nature areas and some buildings and infrastructure areas. By applying flexible water level management, the probability of high water levels increases and therefore flood risk in areas outside primary levees increases. However, the relation between applying flexible water level management and flood risk has not been investigated in detail yet. This research explores this relation further, on smaller scale as well as for the whole IJsselmeer region.

In this research, flood risk is defined as the yearly probability of exceedance of hydraulic loads (lake water level, wind set up and wave run-up) multiplied by the consequences of inundation and is expressed in euros per year. Risk is a set of scenarios, with each a probability and a consequence, and therefore discretization is necessary. Flood risk is computed for three case study areas as well as for the whole IJsselmeer region and a focus group discussion is carried out to discuss water damage mitigation strategies. Hydraulic components are computed for five exceedance probabilities using Hydra-NL, a probabilistic model. To finally determine flood risk, hydraulic loads from Hydra-NL are used in the Waterschadeschatter to calculate water damage. By knowing water damage and the associated exceedance probability, flood risk is computed. However, water levels calculated in Hydra-NL are tens of decimetres higher than occurred water levels and therefore outcomes from Hydra-NL show unrealistic results. Since Hydra-NL forms the base of this research, this uncertainty plays an important role in following analyses.

Case study areas Parkhaven (residential area), Genemuiden (pastureland area) and Schellinkhout (nature and recreation area) are used to show effects of flexible water level management in areas outside primary levees, which are site specific. Comparing components of the hydraulic load for the case study areas, it can be concluded that the lake water level and wave run-up are in general higher when flexible water level management is included and wind set up is lower. Wind set up is lower, because in the wind set up equation the water depth is located in the denominator. When the water depth increases, the wind set up decreases. This observation is also valid for other areas outside primary levees in the IJsselmeer region. In addition, Parkhaven has the largest total flood risk per hectare of the case study areas.

Water damage mitigation strategies were discussed for the case study areas with four experts from WSP in a focus group discussion. The use of mitigation strategies goes beyond the scope of this study, but gives insight in and an overview of possible measures to reduce flood risk. Flood risk for Parkhaven increases by applying flexible water level management, whereas the flood risk for Genemuiden and Schellinkhout does not change significantly. Because water levels are increasing during extreme weather events for the three case study areas, a broader look is given to measures mitigating flood risk. For Parkhaven, the most effective water damage mitigation strategy is reinforcing the current bank protection by elevating the maximum height and making the bank protection less steep to reduce wave run-up, as is substantiated by the focus group. For Genemuiden can be looked at using a different kind of farming, since water damage after destroying meadow hay cannot be neglected. Water damage is almost negligible in the area outside primary levees near Schellinkhout, and it is therefore discouraged to use water damage mitigation strategies.

Extrapolation of case study areas Parkhaven, Genemuiden and Schellinkhout to other areas outside primary levees cannot be done easily, because every area located outside primary levees is different and different thresholds of flooding are encountered. However, the function classes of the case study areas are more or less matching the function classes of other areas outside primary levees in the IJsselmeer region. Still, Parkhaven shows an overestimation regarding water damage compared to other buildings and infrastructure areas outside primary levees. Parkhaven has a residential function, whereas other buildings and infrastructure areas are mostly harbours or parking lots with much lower water damages, which makes extrapolation difficult. The function classes of Genemuiden and Schellinkhout are approximating the function classes appearing in the IJsselmeer region and therefore extrapolation gives more reliable results. By applying flexible water level management the total flood risk for Parkhaven increases with 8%, from 2,500 €/year to 2,700 €/year. For Genemuiden and Schellinkhout, the total flood risk barely changes. Rijkswaterstaat investigates whether it is possible to raise the target water level with 20 cm, with respect to the former water level decree from 1992 during the spring set up, to store even more fresh water into the IJsselmeer region. The total flood risk for Parkhaven by elevating the target water level with 20 cm increases with 175%, from 2,700 €/year to 7,500 €/year, compared to the scenario in which flexible water level management is applied. For Genemuiden and Schellinkhout again the total flood risk does not increase significantly. It can be assumed that the total flood risk in other buildings and infrastructure areas outside primary levees increases, but this increase will be smaller, since Parkhaven shows an overestimation regarding flood risk. Furthermore, it can be assumed that in other pasturelands, recreation areas and nature areas outside primary levees the total flood risk barely changes by applying flexible water level management and by increasing the target water level with 20 cm, since the function classes of Genemuiden and Schellinkhout can be extrapolated.

The total inundated area, so taking into account all areas outside primary levees in the IJsselmeer region, excluding and including flexible water level management hardly differs. About 90% of the total damage comes from water damage in buildings and infrastructure areas, and then especially from residential areas. Since less than 3% of areas outside primary levees consist of buildings and infrastructure areas and less than 10% of buildings and infrastructure areas consist of residential areas, the flood risk is reduced. Moreover, most computations show overestimations. Water levels computed in Hydra-NL are higher than occurred water levels and the upper boundary of -0.10 m NAP is used to calculate effects of flexible water level management. Because both overestimations are used and there are just a few residential areas, most areas located outside primary levees in the IJsselmeer region will hardly suffer from applying flexible water level management and it should be considered to construct more areas outside primary levees and to use them more intensively.

Samenvatting

Sinds 2019 past Rijkswaterstaat in het IJsselmeer en Markermeer flexibel peilbeheer toe om een robuuste zoetwatervoorziening te creëren. Het vaste streefpeil van -0,20 m NAP in de zomer wordt vervangen door een bandbreedte van -0,10 tot -0,30 m NAP waarbinnen het waterpeil mag fluctueren om te sturen op weersomstandigheden en de vraag naar zoetwater. In het IJsselmeergebied ligt 15.600 hectare land buitendijks. Dit zijn voornamelijk weilanden, recreatiegebieden, natuurgebieden en een paar gebieden met bebouwing en infrastructuur. Bij het toepassen van flexibel peilbeheer neemt de kans op hoge waterstanden en overstroming in buitendijkse gebieden toe. De relatie tussen het toepassen van flexibel peilbeheer en het overstromingsrisico is echter nog niet in detail onderzocht. Dit onderzoek gaat hier verder op in, zowel op kleinere als op grotere schaal.

In dit onderzoek is het overstromingsrisico gedefinieerd als het product van de overschrijdingskans van de hydraulische belasting en de waterschade van de overstroming uitgedrukt in euro's per jaar. Her risico is een reeks van scenario's met elk een overschrijdingskans en een gevolg. Om het overstromingsrisico te bepalen, wordt geïntegreerd over alle overschrijdingskansen. Het overstromingsrisico is berekend voor zowel drie specifieke locaties in het IJsselmeergebied als voor het hele IJsselmeergebied. Daarnaast is een focus groep discussie uitgevoerd waarin maatregelen die waterschade beperken zijn besproken. De hydraulische belasting bestaat uit het meerpeil, de wind opzet en de golfoploop en wordt berekend voor vijf overschrijdingskansen in Hydra-NL, een waarschijnlijkheidsmodel. Hydraulische belastingen uit Hydra-NL worden gebruikt in de Waterschadeschatter om waterschade te bepalen. Na het bepalen van waterschade voor de vijf overschrijdingskansen, kan het overstromingsrisico worden uitgedrukt. De berekende waterstanden in Hydra-NL zijn echter tientallen decimeters hoger dan de opgetreden waterstanden en dit maakt de berekeningen in Hydra-NL minder betrouwbaar. Hydra-NL vormt de basis van dit onderzoek, waardoor deze onzekerheid steeds groter wordt in opeenvolgende analyses.

Buitendijkse gebieden Parkhaven (woonwijk), Genemuiden (weilanden) en Schellinkhout (natuur- en recreatiegebied) laten lokaal de effecten van flexibel peilbeheer zien. Bij het vergelijken van de drie componenten waaruit de hydraulische belasting is opgebouwd, kan worden geconcludeerd dat bij het toepassen van flexibel peilbeheer het meerpeil en de golfoploop hoger zijn en de wind opzet lager. In de vergelijking van de wind opzet staat de waterdiepte in de deler. Als de waterdiepte hoger wordt, wordt de wind opzet lager. Dit geldt ook voor andere buitendijkse gebieden in het IJsselmeergebied. Van de drie gebieden heeft Parkhaven het grootste overstromingsrisico per hectare.

Tijdens een focus groep discussie met vier experts van WSP zijn maatregelen die waterschade beperken besproken voor de drie buitendijkse gebieden. Het onderzoeken van deze maatregelen valt buiten het doel van dit onderzoek, maar geeft een goed overzicht van eventuele maatregelen die genomen kunnen worden om het overstromingsrisico te beperken. Voor Parkhaven neemt het overstromingsrisico toe en voor Genemuiden en Schellinkhout is het verschil in overstromingsrisico niet significant. Aangezien de waterstanden wel hoger worden onder extreme omstandigheden voor de drie gebieden bij het toepassen van flexibel peilbeheer, is in bredere zin gekeken naar maatregelen die waterschade beperken. De meest effectieve maatregel voor Parkhaven, resulterend uit de focus groep discussie, is het versterken, verhogen en flauwer maken van de oeverbescherming. Voor Genemuiden kan een ander type landbouw worden gekozen, aangezien de waterschade van weide hooi niet gering is. Het nemen van maatregelen in Schellinkhout is overbodig, omdat waterschade daar te verwaarlozen is.

Extrapolatie van de drie buitendijkse gebieden Parkhaven, Genemuiden en Schellinkhout naar andere buitendijkse gebieden in het IJsselmeergebied is niet gemakkelijk, aangezien elk buitendijks gebied anders is en bij verschillende waterstanden overstroomt. Het type landgebruik van de gekozen, buitendijkse gebieden komt wel aardig overeen met het type landgebruik in andere buitendijkse gebieden. Woonwijk Parkhaven toont echter een overschatting wat betreft waterschade vergeleken met andere buitendijkse gebieden met bebouwing en infrastructuur. Andere gebieden met bebouwing en infrastructuur bestaan namelijk vaak alleen uit een parkkeerplaats of een haven wat veel minder waterschade veroorzaakt. Dit maakt extrapolatie van gebieden met bebouwing en infrastructuur lastig. Het type landgebruik van Genemuiden en Schellinkhout komt wel overeen met het type landgebruik van andere buitendijkse gebieden in het IJsselmeergebied en kan daarom wel worden geëxtrapoleerd. Bij het toepassen van flexibel peilbeheer neemt het overstromingsrisico in Parkhaven met 8% toe, van 2.500 €/jaar naar 2.700 €/jaar. Voor Genemuiden en Schellinkhout verandert het overstromingsrisico nauwelijks. Rijkswaterstaat onderzoekt of er meer zoetwater kan worden vastgehouden in het IJsselmeergebied door middel van het verhogen van het streefpeil met 20 cm ten opzichte van het voormalige peilbesluit uit 1992 tijdens de voorjaarsopzet. Voor Parkhaven neemt bij het verhogen van het streefpeil met 20 cm het overstromingsrisico toe met 175%, van 2.700 €/jaar naar 7.500 €/jaar, vergeleken met de situatie waarin flexibel peilbeheer wordt toegepast. Voor Genemuiden en Schellinkhout verandert het overstromingsrisico minimaal. Er kan worden aangenomen dat in andere buitendijkse gebieden met bebouwing en infrastructuur het overstromingsrisico toeneemt, maar niet zoveel als in Parkhaven, aangezien Parkhaven een overschatting laat zien van de waterschade vergeleken met andere buitendijkse gebieden met bebouwing en infrastructuur. Voor buitendijkse weilanden, natuur- en recreatiegebieden kan worden aangenomen dat het overstromingsrisico amper verandert bij het toepassen van flexibel peilbeheer en voor het scenario waarbij het streefpeil wordt verhoogd met 20 cm, omdat het landgebruik van Genemuiden en Schellinkhout wel kan worden geëxtrapoleerd.

Bij het analyseren van de effecten van flexibel peilbeheer op alle buitendijkse gebieden in het IJsselmeergebied, kan worden geconcludeerd dat het overstroomde gebied, met en zonder flexibel peilbeheer, amper verschilt. Verder ontstaat ongeveer 90% van de totale waterschade in gebieden met bebouwing en infrastructuur en dan voornamelijk in woonwijken. Minder dan 3% van de buitendijkse gebieden bestaat uit gebieden met bebouwing en infrastructuur en minder dan 10% van de gebieden met bebouwing en infrastructuur bestaat uit woonwijken. Bovendien zijn er in de berekeningen overschattingen gemaakt. De waterstanden verkregen uit Hydra-NL zijn hoger dan de opgetreden waterstanden en de bovengrens van flexibel peilbeheer is gebruikt om de effecten van flexibel peilbeheer inzichtelijk te maken. Hieruit kan worden geconcludeerd dat de meeste buitendijkse gebieden in het IJsselmeergebied weinig last hebben van flexibel peilbeheer en er moet worden overwogen om meer buitendijkse gebieden aan te leggen en die intensiever te gebruiken.

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List of Symbols

D	Damage	[€]
h	Water depth	[m]
W	Wind set up	[m]
κ	Friction constant kappa	[-]
u_{10}	Wind velocity at 10 meters height	[m/s]
g	Gravitational constant	[m/s^2]
F	Fetch length	[m]
ϕ	Angle between land and wind	[°]
$R_{u2\%}$	Wave run-up height exceeded by 2% of incoming waves	[m]
H_{m0}	Wave height	[m]
γ_b	Influence factor for berm	[-]
γ_f	Influence factor for roughness	[-]
γ_β	Influence factor for oblique wave attack	[-]
$\xi_{m-1.0}$	Breaker parameter	[-]
β	Angle of wave attack	[°]
B	Width of berm	[m]
d_b	Vertical difference between middle of berm and water level	[m]
L_{berm}	Characteristic berm length	[m]
r_b	Influence of width of berm	[-]
r_{db}	Vertical difference between still water level and middle of berm	[-]
R	Total flood risk	[€/y]
D	Water damage	[€]
T	Return period	[year]

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1. Introduction

In this chapter the introduction is presented. Section 1.1 discusses the research context and section 1.2 deals with the problem statement. In section 1.3 the main research question is formulated and described and the relevance of this project is emphasized.

1.1 Research context

The climate is changing, the need for fresh water becomes larger and there is ever more economic value to protect. About 30% of the Netherlands depends on fresh water from the IJsselmeer and Markermeer (Rijkswaterstaat, 2015). Because of this balance of interest, the water level decree from 1992 has been revised and resulted in a new water level decree for the IJsselmeer and Markermeer which is operative since 2019 to enlarge the fresh water supply and to better maintain target water levels. In this new water level decree, a flexible water level management is applied. Flexible water level management means that the water level can fluctuate between -0.10 m and -0.30 m NAP during the summer period (April – September) instead of maintaining the water level at -0.20 m NAP. The water level of -0.40 m NAP during the winter period (October – March) will stay unchanged at least until 2050 to make water drainage to the region easier and to ensure water safety, as is stated in the Delta Decision (Rijkswaterstaat, 2018).

The current water level decree offers the manager the opportunity to respond to extreme weather conditions by lowering the water level when heavy precipitation events are expected to guarantee water safety, and increasing the water level when a dry period is forecasted to increase the fresh water buffer (Rijkswaterstaat, 2018). A fresh water buffer of 20 cm in the IJsselmeer and Markermeer can be realised and contains 400 million m^3 of extra available fresh water, which can be used for various functions. Approximately 18% of the fresh water buffer is used for drinking water purposes (Rijkswaterstaat, 2015), and this fresh water buffer is expected to be sufficient until at least 2050 (Rijkswaterstaat, 2018).

In this research only the IJsselmeer and Markermeer are included, so not the Veluwerandmeren. This is done, because the water level in the Veluwerandmeren stays unchanged during summer with respect to the former water level decree. Applying flexible water level management affects many factors. The most important affected factors are flood risk for areas outside primary levees, fauna living next to the lake, water quality and groundwater levels. The change in groundwater levels due to the implementation of flexible water level management is not taken into account, because groundwater fluxes are negligibly small (Boderie et al., 2012). Furthermore, next to this study, a parallel research is executed about effects of flexible water level management on breeding birds by a trainee from Rijkswaterstaat. Therefore, impact on fauna is only discussed superficially. In addition, as a result of flexible water level management, water quality can be affected due to changing temperatures and changing nutrient content. However, these effects are negligibly small according to the Environmental Impact Report (Jaspers et al., 2017). Therefore, this research focusses on the change in water levels in the IJsselmeer and Markermeer and the change in flood risk for areas outside primary levees by applying flexible water level management.

1.2 Problem statement

The relation between applying flexible water level management and the change in flood risk in areas outside primary levees around the IJsselmeer and Markermeer has not yet been investigated in detail. In the Environmental Impact Report (Jaspers et al., 2017) is stated that flood risk in areas outside primary levees will increase during the spring set up and during summer when the upper boundary of the bandwidth is maintained. However, the Environmental Impact Report does not explain why the flood risk is increasing and how the increase is determined. Therefore, more research is needed to determine flood risk on smaller scale as well as for the whole IJsselmeer region. This research will built on the Environmental Impact Report and will examine effects of flexible water level management in relation to the hydraulic components; lake water level, wind set up and wave run-up and to financial damage.

1.3 Research objective

More information should be gathered about effects of flexible water level management for areas outside primary levees in the IJsselmeer region regarding flood risk, since this topic is not fully understood yet. By applying flexible water level management negative effects may arise from high water levels. Therefore, it is important to determine what kind of areas will be impacted and how flood risk will change by applying flexible water level management. Hence, the main research question is:

What are the effects of flexible water level management regarding flood risk of areas outside primary levees around the IJsselmeer and Markermeer?

Three case study areas are chosen to show the effects of flexible water level management in areas outside primary levees which are site specific. Next, hydraulic loads are computed for the case study areas in Hydra-NL and are uploaded into the Waterschadeschatter, a tool to compute water damage, to finally determine flood risk. Lastly, the case study areas are extrapolated to other areas outside primary levees in the IJsselmeer region.

2. System description

In this chapter the bigger picture is presented. Section 2.1 discusses the IJsselmeer region. The hydrological compartments, components of the water balance and the function classes of areas outside primary levees are described. Furthermore, section 2.2 explains how flexible water level management works and section 2.3 describes the importance of buffering fresh water in the IJsselmeer region. Lastly, section 2.4 describes the possibility to retain even more fresh water into the IJsselmeer region by elevating the target water level with 20 centimetres.

2.1 The IJsselmeer region

The IJsselmeer region is one of the biggest lake districts in Northwest-Europe and has a water surface of 2,000 km^2. It is divided into three hydrological compartments, which can be seen in the *Figure 2.1*.

1. IJsselmeer (including Ketelmeer, Zwarte Meer, Vossemeer, Revemeer and Reevediep).
2. Markermeer (including IJmeer, Eemmeer, Nijkerkernauw and Gooimeer).
3. Veluwerandmeren (Nuldernauw, Veluwemeer and Drontermeer).

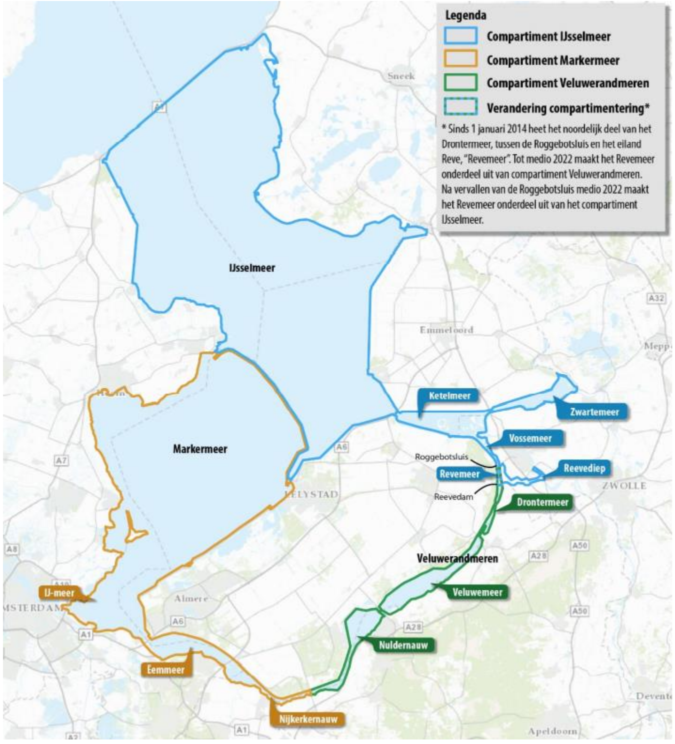


Figure 2.1: Hydrological compartments in the IJsselmeer region (Rijkswaterstaat, 2018).

The largest inflow of water comes from the river IJssel. Smaller rivers flowing into the IJsselmeer and Markermeer are het Meppelerdiep, de Eem and de Laak. Furthermore, sluices at the boundaries of the hydrological compartments also drain into the IJsselmeer region. The total land surface that drains into the IJsselmeer and Markermeer is around 20,000 km^2 as can be seen in *Figure 2.4* (Rijkswaterstaat, 2015). Fluxes going out are controlled by sluices, discharge by gravity in the Afsluitdijk and water drained into the North Sea Channel. In *Table 2.1*, components of the water balance are presented for the IJsselmeer region. Groundwater fluxes written in italics are neglected in this research, because groundwater fluxes are 1,000 times smaller than other fluxes used in this research (Boderie et al., 2012).

*Table 2.1: Components of the water balance for the IJsselmeer region. *Not considered in this research.*

Fluxes IN	**Fluxes OUT**
Precipitation	Evaporation
Discharge from de IJssel, het Meppelerdiep, de Eem and de Laak.	Water release under the influence of gravity into the Waddenzee in the Afsluitdijk.
Sluices at boundaries of hydrological compartments.	Inlets and sluices at boundaries of hydrological compartments.
*Infiltration and percolation**	*Seepage**

In *Figure 2.2* and *Figure 2.3* the ingoing and outgoing fluxes are presented in percentages for both the IJsselmeer and Markermeer. A big difference between the water balance of the IJsselmeer and Markermeer is that the main incoming flux for the IJsselmeer depends on discharge from the IJssel and the incoming water flux for the Markermeer is mainly determined by precipitation. Furthermore, the outgoing flux for the IJsselmeer mainly depends on the amount of freshwater discharged by gravity into the Waddenzee and the outgoing flux for the Markermeer mainly depends on the evaporation rate.

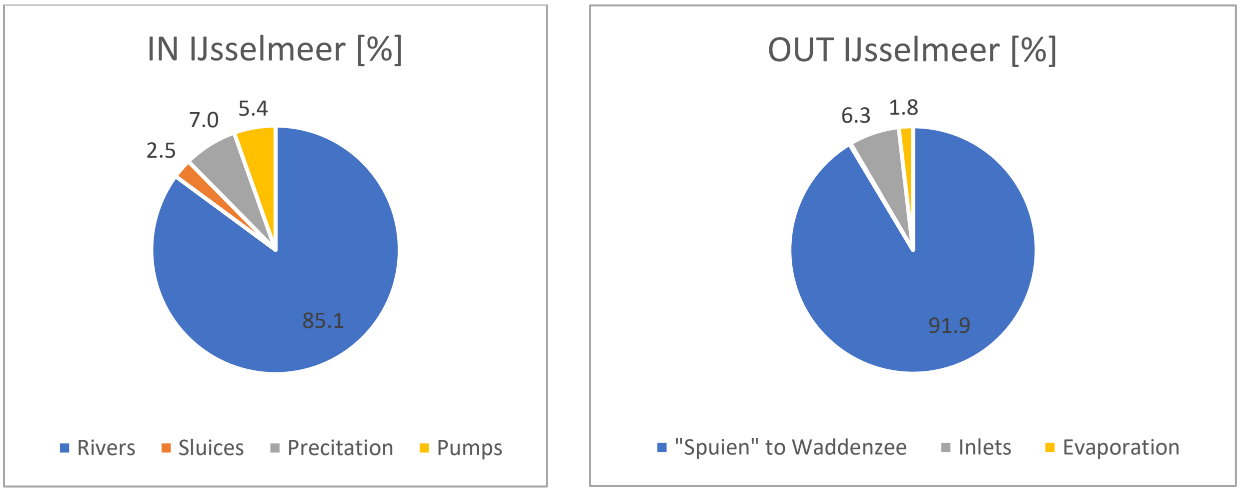


Figure 2.2: Ingoing (left) and outgoing (right) water fluxes for the IJsselmeer (WSP, 2020).

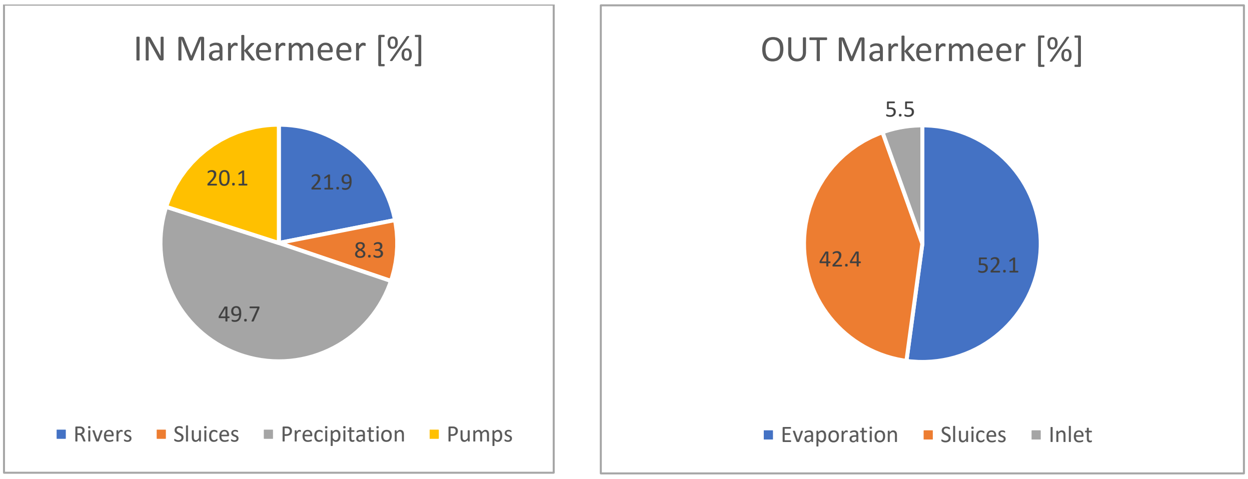


Figure 2.3: Ingoing (left) and outgoing (right) water fluxes for the Markermeer (WSP, 2020).

The IJsselmeer region is the largest fresh water basin in the Netherlands. More than 30% of the Netherlands is dependent on fresh water from this basin (Jaspers et al., 2017). During summer, fresh water is distributed to the surrounding areas, as can be seen in *Figure 2.4*.

Figure 2.4: Drainage area (left) and water supply of IJsselmeer region (right) (Rijkswaterstaat, 2015).

The water supply area of the IJsselmeer region overlaps with nine water authorities. The nine water authorities are Hoogheemraadschap Amstel, Gooi en Vecht; Hoogheemraadschap Hollands Noorderkwartier; Waterschap Drents Overijsselse Delta; Waterschap Vallei & Veluwe; Waterschap Vechtstromen; Waterschap Hunze en Aa's; Waterschap Noorderzijlvest; Waterschap Zuiderzeeland and Wetterskip Fryslân (Rijkswaterstaat, 2016). Every water authority has their own sluices and inlets. Important hydraulic structures are the Oranjesluizen, the Houtribsluizen, the Lorentzsluizen, the Stevinsluizen and pumping station Zeeburg.

In the IJsselmeer region 15,600 ha is located between the water and the primary flood defences, as can be seen in *Figure 2.5,* and are called areas outside primary levees in this research. These areas concern in particular pasturelands, recreation areas, nature areas and some buildings and infrastructure areas (Rijkswaterstaat, 2018). Buildings and infrastructure areas outside primary levees contain in particular parking lots, harbours, campsites, catering businesses, buildings with a water related function and occasionally some residential areas. Nature areas outside primary levees are mostly grasslands. In *Figures 2.6* and *2.7,* the function classes of areas outside primary levees are shown and *Figure 2.8* presents examples of buildings and infrastructure areas.

Starting with buildings and infrastructure areas outside primary levees, the largest areas are Schokkerhaven located along the Ketelmeer, Parkhaven located along the IJsselmeer and Huizen situated along the Gooimeer. There are just a few buildings and infrastructure areas outside primary levees, but many more pasturelands. Two relatively big pastureland areas outside primary levees are the area near Genemuiden and the Warkumerwaard. Looking to recreation areas outside primary levees, Mukkum beach is relatively large, but also Schellinkhout has a beach with many visitors during summer. Last but not least, the largest nature areas outside primary levees are located along het Zwarte Meer and the river Vecht.

Water authorities are the most important stakeholders using fresh water from the IJsselmeer region. The water authorities arrange the fresh water division for agriculture, drinking water and industry. Furthermore, there are two power plants, ENGIE Maxima and Vattenfall, using fresh water from the IJsselmeer region as cooling water. In addition, PWN (drinking water company for the province Noord-Holland) extracts water from the IJsselmeer to supply Noord-Holland with drinking water.

Figure 2.5: Areas located outside primary levees.

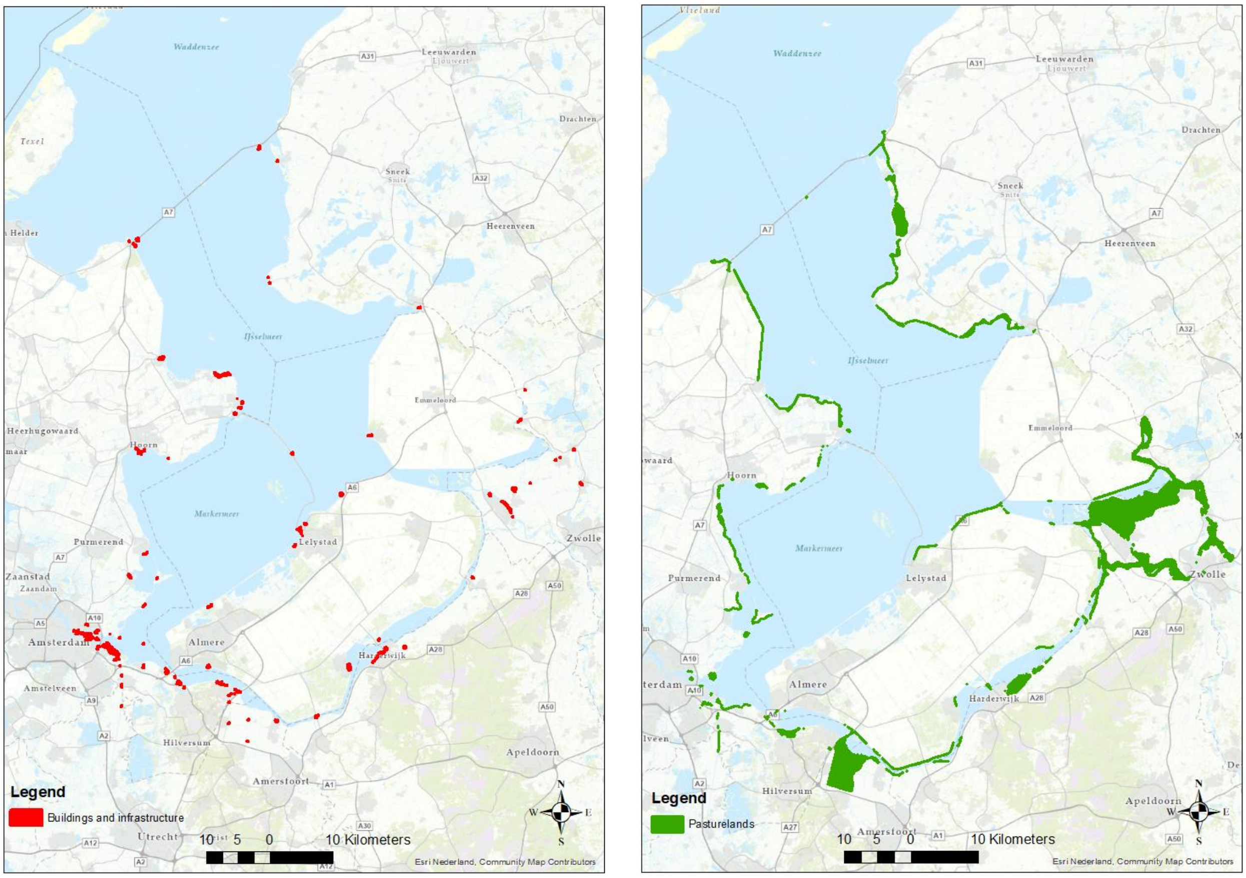


Figure 2.6: Buildings and infrastructure areas (left) and pasturelands (right) outside primary levees.

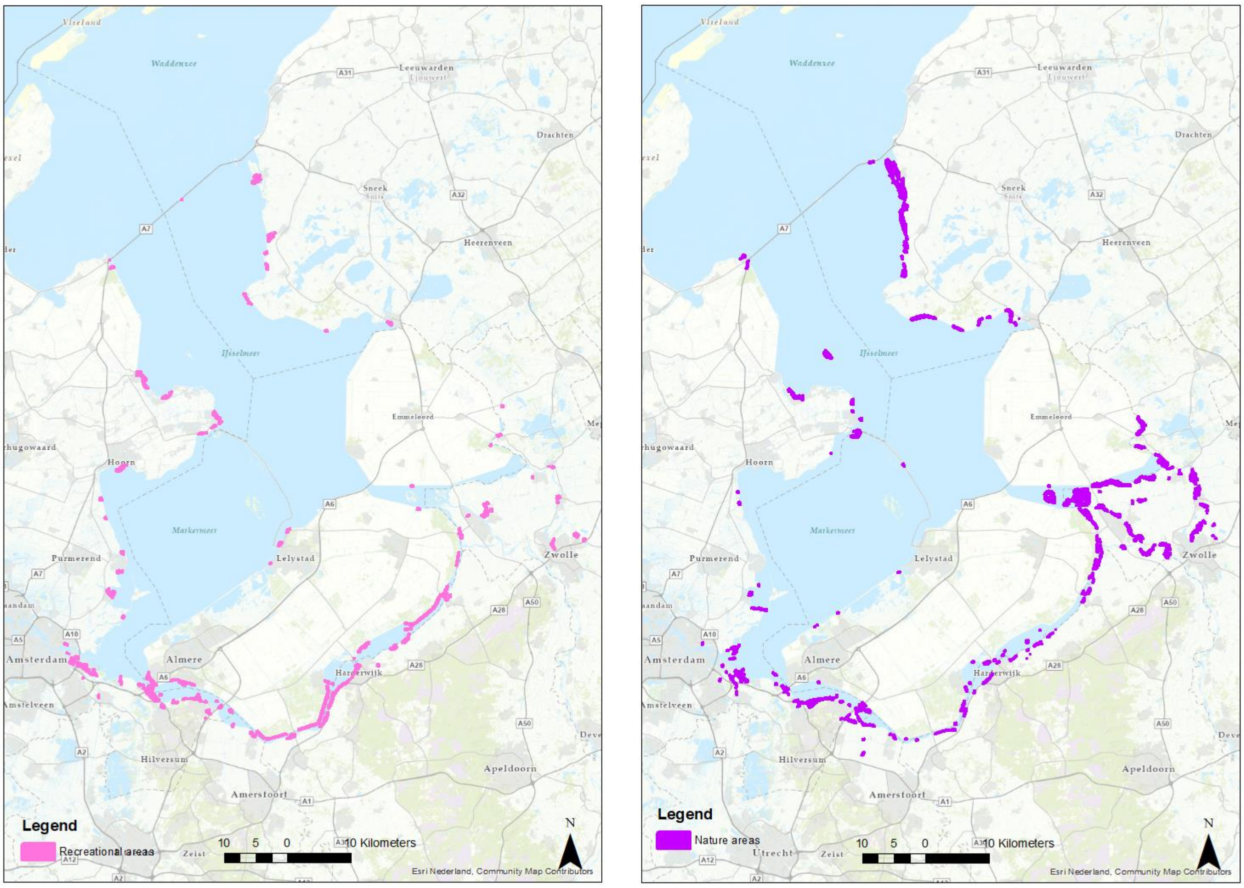


Figure 2.7: Recreation areas (left) and nature areas (right) outside primary levees.

Figure 2.8: Examples of buildings and infrastructure areas (Google maps, 2021).

2.2 Flexible water level management

The fixed target water level of -0.20 m NAP during summer is replaced by a flexible water level management in which the water level can fluctuate inside a bandwidth. In early spring, so the end of the winter period, the water level set up reaches -0.10 m NAP, which is called the spring set up. In the IJsselmeer, the spring set up last about 2 weeks. However, in the Markermeer, the spring set up only last a couple of days because otherwise negative effects will arise for water safety. From April until August, an average water level of -0.20 m NAP is aimed for, but can fluctuate between -0.10 m and -0.30 m NAP depending on weather conditions. From August until September, the target water level of -0.30 m NAP is tried to be maintained, but can fluctuate depending on occurring circumstances. During the winter period (October – March) the target water level is -0.40 m NAP, but can fluctuate between -0.05 m NAP and -0.40 m NAP. The target water levels and bandwidths for the IJsselmeer and Markermeer can be seen in *Figures 2.9* and *2.10.*

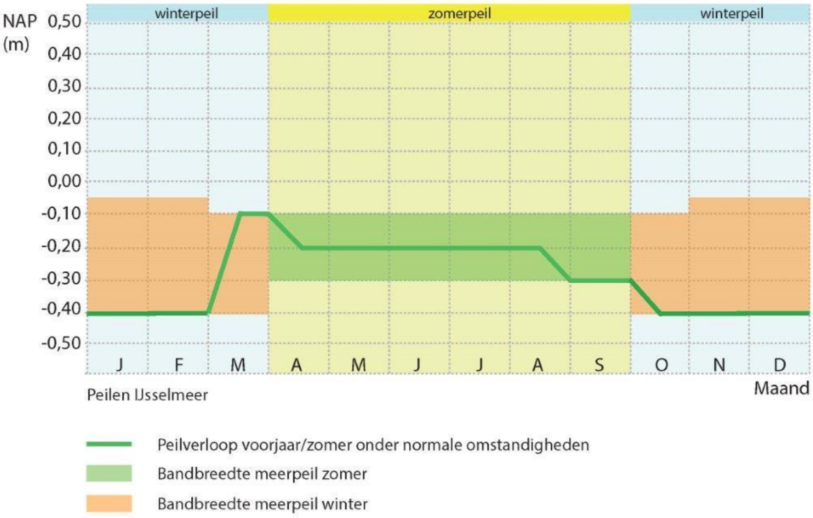


Figure 2.9: Target water levels and bandwidths for the IJsselmeer by applying flexible water level management (Rijkswaterstaat, 2018).

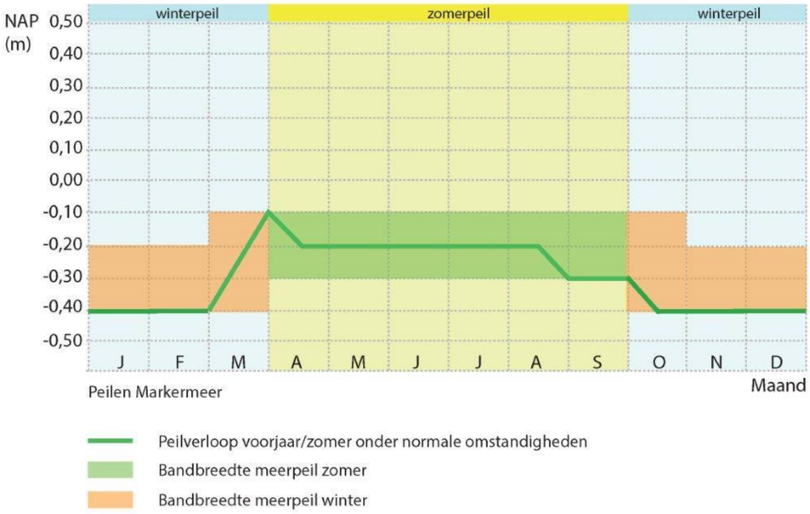


Figure 2.10: Target water levels and bandwidths in the Markermeer by applying flexible water level management (Rijkswaterstaat, 2018).

Also variable water level components can be applied. The spring set up can be delayed when heavy precipitation events or high river discharges are forecasted to lower the probability of flooding. Furthermore, the fresh water buffer can be maintained for a longer period and the fresh water buffer can be deployed and created again. Lastly, the summer water level of -0.20 m NAP can be kept at the beginning of the winter period.

Rijkswaterstaat is regulating the water level in the IJsselmeer and Markermeer. The water level increases when less water is drained into the Waddenzee than is discharged into the IJsselmeer region. However, the water level drops when more water is released under the influence of gravity into the Waddenzee (Rijkswaterstaat, 2016). This water release under the influence of gravity into the Waddenzee is the most important management component. During winter, water levels are directed towards the prevention of high water levels. During summer, the water level is controlled by supply and demand.

Controlling of water levels is done automatically and water levels can be raised or lowered with approximately 2 cm/day during favourable conditions (RWS, email, October 28 2021). Several locations around the IJsselmeer measure the water level with different weighting factors and an average water level is determined. Moreover, the discharge from the IJssel is measured together with water levels in the Waddenzee. The decision to increase or lower the water level in the IJsselmeer, by opening valves to release water under the influence of gravity, is made by a decision support system (Rijkswaterstaat, 2018). This system takes into account the weather forecast from the KNMI with a forecasting horizon of one week, the average water level in the IJsselmeer, the discharge from the IJssel and the water level in de Waddenzee. For most of the time, the water level is controlled automatically during regular circumstances. However, for unlikely scenarios like an heavy storm of two weeks with northerly winds, human actions take over the decision support system (Rijkswaterstaat, 2018).

2.3 Fresh water supply IJsselmeer region

Due to climate change, longer periods of droughts are expected in the Netherlands. Temperatures are rising, periodically there will be less precipitation and discharge of rivers decrease. Because of decreasing water discharge in the Dutch rivers, salt water intrudes further into the Netherlands. Nowadays, a large part of fresh water is discharged via the main rivers to reduce the inflow of salt water. However, more fresh water is needed to counteract salt water intrusion. Therefore, the fresh water supply is revisited. It is considered to let salt water intrude further into the Netherlands, and instead of using fresh water to reduce incoming salt water, the fresh water will follow a different route (Slim Water Management, 2021). Via river IJssel, fresh water will flow into the IJsselmeer and Markermeer and from there it will also flow to the western part of the Netherlands. Since also the western part of the Netherlands will then make use of the fresh water buffer, more water should be stored (Slim Water Management, 2021). Therefore, Rijkswaterstaat investigates possibilities to retain more fresh water into the IJsselmeer region.

2.4 Elevating target water level with 20 centimetres

Rijkswaterstaat investigates possibilities to retain more fresh water into the IJsselmeer region by elevating the target water level with 20 centimetres with respect to the former water level decree from 1992 during the spring set up. In *Figure 2.11* the differences between applying flexible water level management and elevating the target water level with 20 centimetres can be seen.

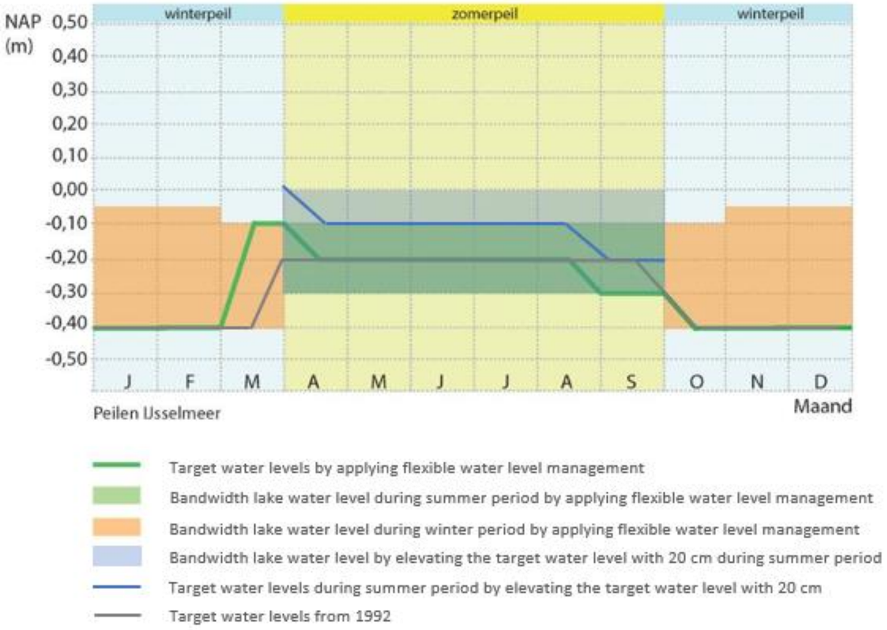


Figure 2.11: Target water levels and bandwidths in the IJsselmeer by elevating the target water level with 20 centimetres.

3. Theory

This chapter presents the theory that is required in this research. Section 3.1 shows an analysis of occurred water levels. Furthermore, section 3.2 presents the contribution of lake water level components during a storm and section 3.3 discusses the components which determine high water levels. Section 3.4 explains the theory behind flood risk. Lastly, in section 3.5 the theory behind the Waterschadeschatter is explained and section 3.6 elaborates on the use of Hydra-NL.

3.1 Water level analysis

Water levels from 2010 to 2019 are gathered by Rijkswaterstaat and can be seen in *Figures 3.1* and *3.2.* Lake water levels from measurement stations Den Oever binnen, Kornwerderzand binnen, Lemmer, Ramspolbrug, Houtrib Noord and Krabbersgat Noord are used to calculate interpolated water levels in the IJsselmeer and lake water levels from measurement stations Krabbersgat Zuid, Houtrib Zuid, Hollandse Brug, Edam, Meetpaal 42 and Meetpaal 43 are interpolated for the Markermeer. Unfortunately, water level data for the Markermeer from 2015 until 2018 is missing and therefore a gap is present. Since 2019, flexible water level management is applied. Before flexible water level management was active, the water level during summer was tried to be maintained at -0.20 m NAP and during winter at -0.40 m NAP. It is valuable to understand how water levels were fluctuating before the current water level decree was applied. *Figure 3.1* and *Figure 3.2* give insight in occurred water levels. The grey line represents the interpolated lake water level and the 90 percentile and 10 percentile water levels during the summer period are shown as well. Only the period when the water level is fluctuating around -0.20 m NAP during summer is taken into account for the calculation of the percentiles. So the transition periods from winter to summer and from summer to winter are not included.

Having a closer look to both figures, the interpolated lake water level in the IJsselmeer shows larger fluctuations around the target water level of -0.20 m NAP than the interpolated lake water level in the Markermeer. For the IJsselmeer, the 90 percentile water level shows that for 90% of the time the water level is below -15 cm NAP during summer and the 10 percentile water level shows that for 10% of the time the water level is below -22 cm NAP. Furthermore, in the Markermeer for 90% of the time the water level is below -17 cm NAP during summer and for 10% of the time the water level is below -22 cm NAP. What can be concluded from the figures is that it was impossible to keep the water level exactly at -0.20 m NAP. The water levels were already somewhat fluctuating around the target water level and therefore flexible water level management was involved in which the water level can fluctuate inside a bandwidth.

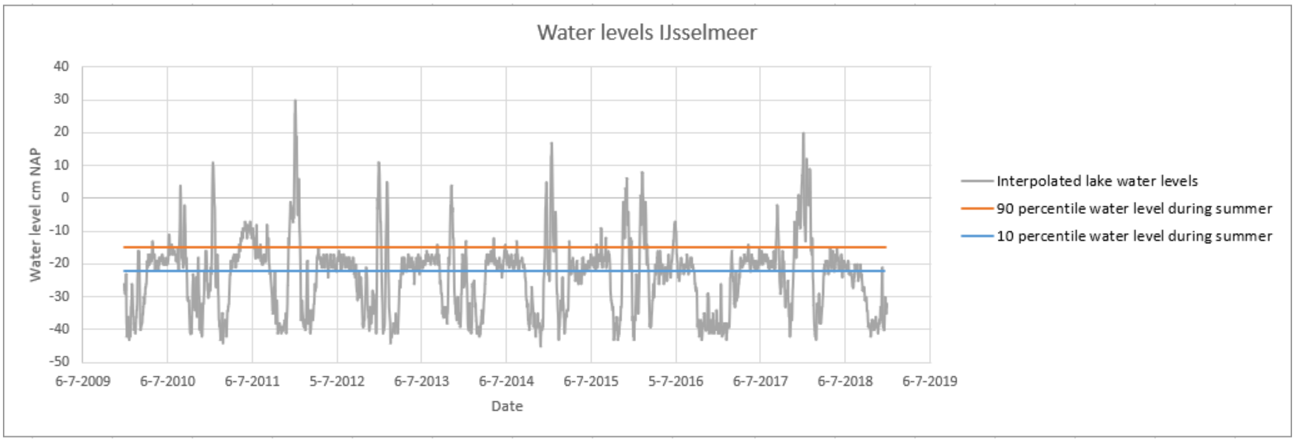


Figure 3.1: Interpolated lake water levels in the IJsselmeer from 2010 until 2019 in cm NAP.

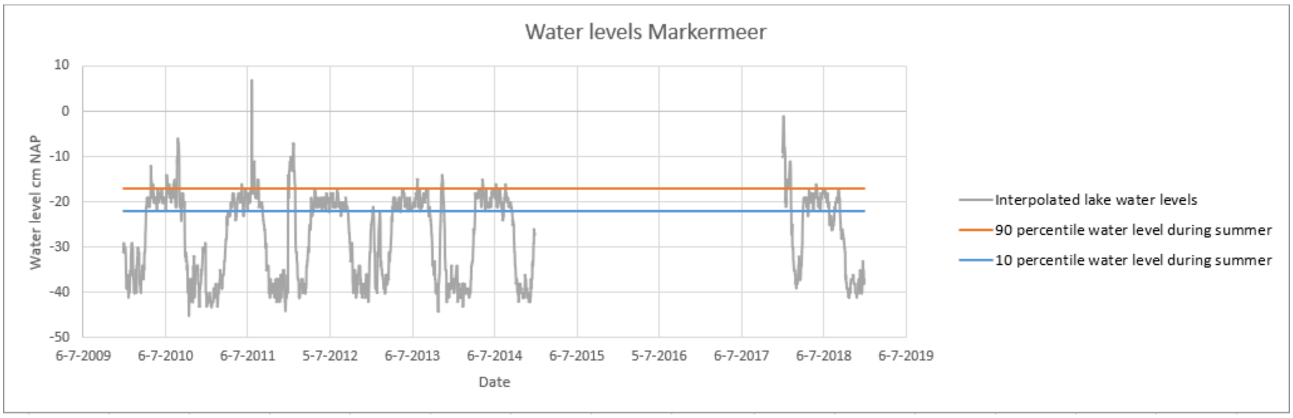


Figure 3.2: Interpolated lake water levels in the Markermeer from 2010 until 2019 in cm NAP.

3.2 Lake water level contributions during a storm

Halfway February 2020, storm Ciara travelled through western Europe. Heavy precipitation events with strong winds were the result. Data from the 10th of February until the 20th of February 2020 were gathered to show which components contribute to lake water level increase during an extreme event.

The main contributions that cause high lake water levels in the IJsselmeer and Markermeer are precipitation, rivers, sluices and inlets. *Figure 3.3* and *Figure 3.4* show the lake water level contributions during a storm in the IJsselmeer and Markermeer. In blue, ingoing fluxes are presented and in orange outgoing fluxes are visible. By subtracting outgoing fluxes from the incoming fluxes for the IJsselmeer, the lake water level will increase with 16.4 cm during a storm. This increase in lake water level is mainly determined by large discharges from the river IJssel. Furthermore, the Markermeer also has larger water fluxes going in than going out. However, in this case precipitation is the largest component that determines the increase in lake water level. By subtracting the outgoing fluxes from the incoming fluxes, an increase in lake water level of 6.1 cm in the Markermeer during a storm is reached.

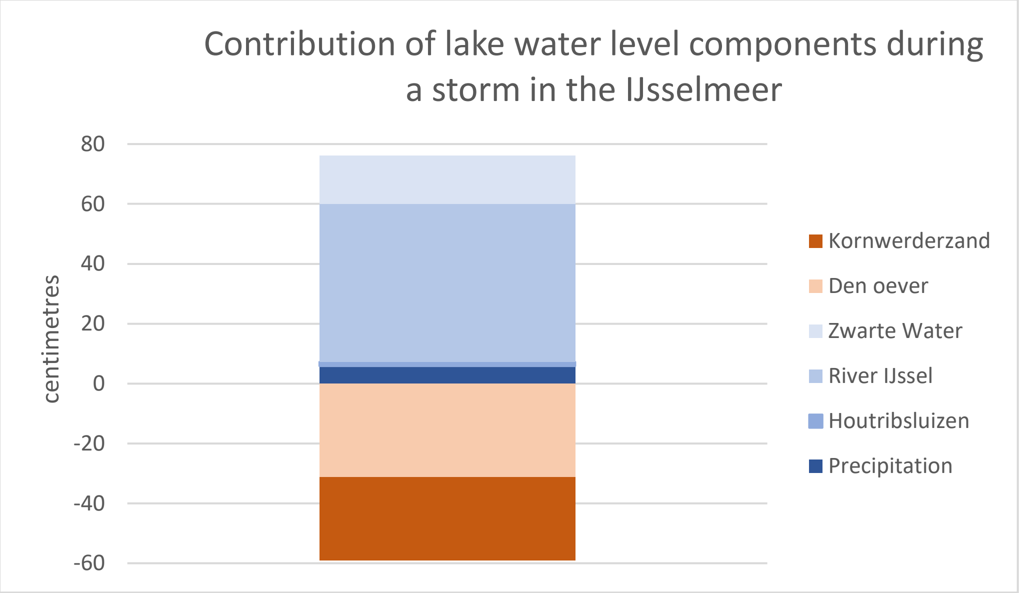


Figure 3.3: Contribution of lake water level components during an extreme weather event in the IJsselmeer.

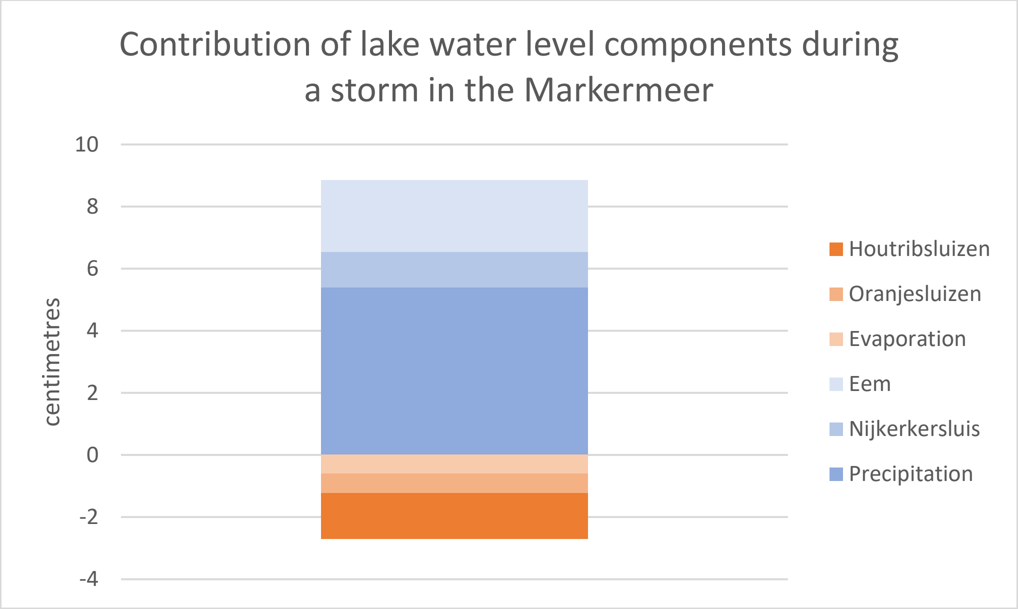


Figure 3.4: Contribution of lake water level components during an extreme weather event in the Markermeer.

3.3 Components determining high water levels

High water levels are determined by uneven distribution of water due to the wind, the wave run-up and the current lake water level. In this section, an elaboration of wind set up and wave run-up is presented.

Wind set up

Extreme winds can locally cause high water levels, because wind can skew the water surface. Strong south-westerly winds can cause a water level decrease of almost 1 meter at the leeward side and an increase in water level of more than 1.5 meters at the windward side in the IJsselmeer, as can be seen in the *Figure 3.5*.

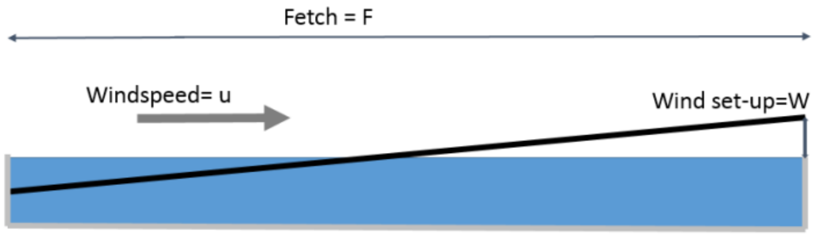


Figure 3.5: Effect of wind on water level (van Rinsum, 2015).

Wind set up can be calculated manually and by using computer programmes. Manually, the wind set up can be calculated using *Equation 3.1* (van Rinsum, 2015).

$$W = 0.5 * \kappa * \frac{u_{10}^2}{gh} * F * \cos{(\phi)} \tag{3.1}$$

In which:

W = Wind set up [m]
κ = Friction constant [-]
u_{10} = Wind velocity at 10 meters height [m/s]
g = Gravitational constant [9.81 m/s^2]
h = Water depth [m]
F = Fetch length [m]
ϕ = Angle between land and wind [°]

Friction constant kappa is an empirical factor and the Delta Commission proposed to use a value of 3.4 E-6 (Delta Commissie, 1991).

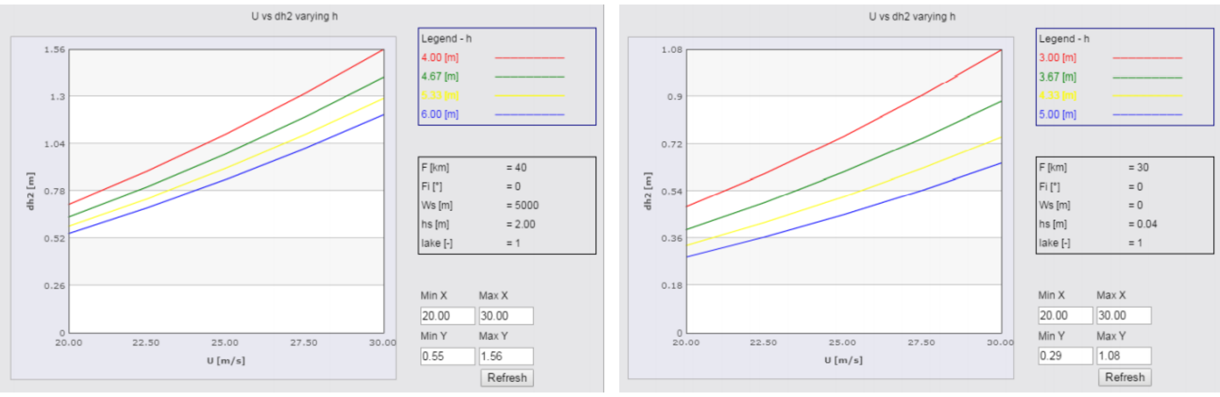
Maximum wind set up can be found at the location with the longest fetch length. The fetch length is defined as the length of the lake which is parallel to the wind direction. Wind set up is maximum when the wind acts parallel to the fetch length. If there is an angle between the wind and the fetch length, wind set up is reduced.

Wind set up can also be calculated with the computer programme “Coastal and River Engineering Support System”. For the computation, *Equation 3.1* is used. To calculate wind set up, firstly the water level increase in the deeper part is calculated and next the water level increase in the shallow part is computed. The input parameters can be seen in *Table 3.1*.

Table 3.1: Input parameters used in Coastal and River Engineering Support System.

	IJsselmeer	**Markermeer**
Fetch length	40 km	30 km
Wind speed	20 – 30 m/s	20 – 30 m/s
Length shallow part	5 km	0 km
Water depth deep part	5 m	4 m
Water depth shallow part	2 m	2 m

By implementing these values, two graphs are gained. One graph for the IJsselmeer and one graph for the Markermeer, as can be seen in *Figure 3.6*. On the horizontal axis the wind velocity can be found. The vertical axis shows wind set up. Different depths are indicated with different colours. *Figure 3.6* presents the IJsselmeer and Markermeer and is shown to get an impression about wind set up in the two lakes. In the results, the wind set up is calculated again for three case study areas in which flexible water level management is included and excluded.



F [km] = 40
Fi [°] = 0
Ws [m] = 5000
hs [m] = 2.00
lake [-] = 1

Min X 20.00 Max X 30.00
Min Y 0.55 Max Y 1.56

F [km] = 30
Fi [°] = 0
Ws [m] = 0
hs [m] = 0.04
lake [-] = 1

Min X 20.00 Max X 30.00
Min Y 0.29 Max Y 1.08

Figure 3.6: Graphs for wind set up in the IJsselmeer (left) and Markermeer (right) (Jaspers et al., 2017).

To show the impact of wind set up for different locations along the IJsselmeer, *Figure 3.7* has been designed. *Figure 3.7* shows the maximum month water levels in the IJsselmeer for the year 2020 for six measurement stations. The six measurement stations are Ramspolbrug (located on the eastern side of het Ketelmeer), Houtrib Noord (located near Parkhaven), Krabbersgat Noord (located near Enkhuizen), Den Oever binnen (located at the southwestern end of the Afsluitdijk), Kornwerderzand binnen (located at the northeaster end of the Afsluitdijk) and Lemmer (located near Lemmer). Starting with the winter period, the lines in *Figure 3.7* are further apart than during summer because during winter controlling of the system is much harder. Moreover, in the winter of 2020 storm Ciara travelled through Northern Europe, causing relatively high water levels. Because of the large wind velocities during the storm, the skewness of the water surface in the IJsselmeer is clearly visible. At the eastern side of the IJsselmeer, where Lemmer is located, the water levels are much higher than on the western side because of strong south-westerly winds. Furthermore, during summer, the lines are closer to each other, because the probability of heavy storms is smaller.

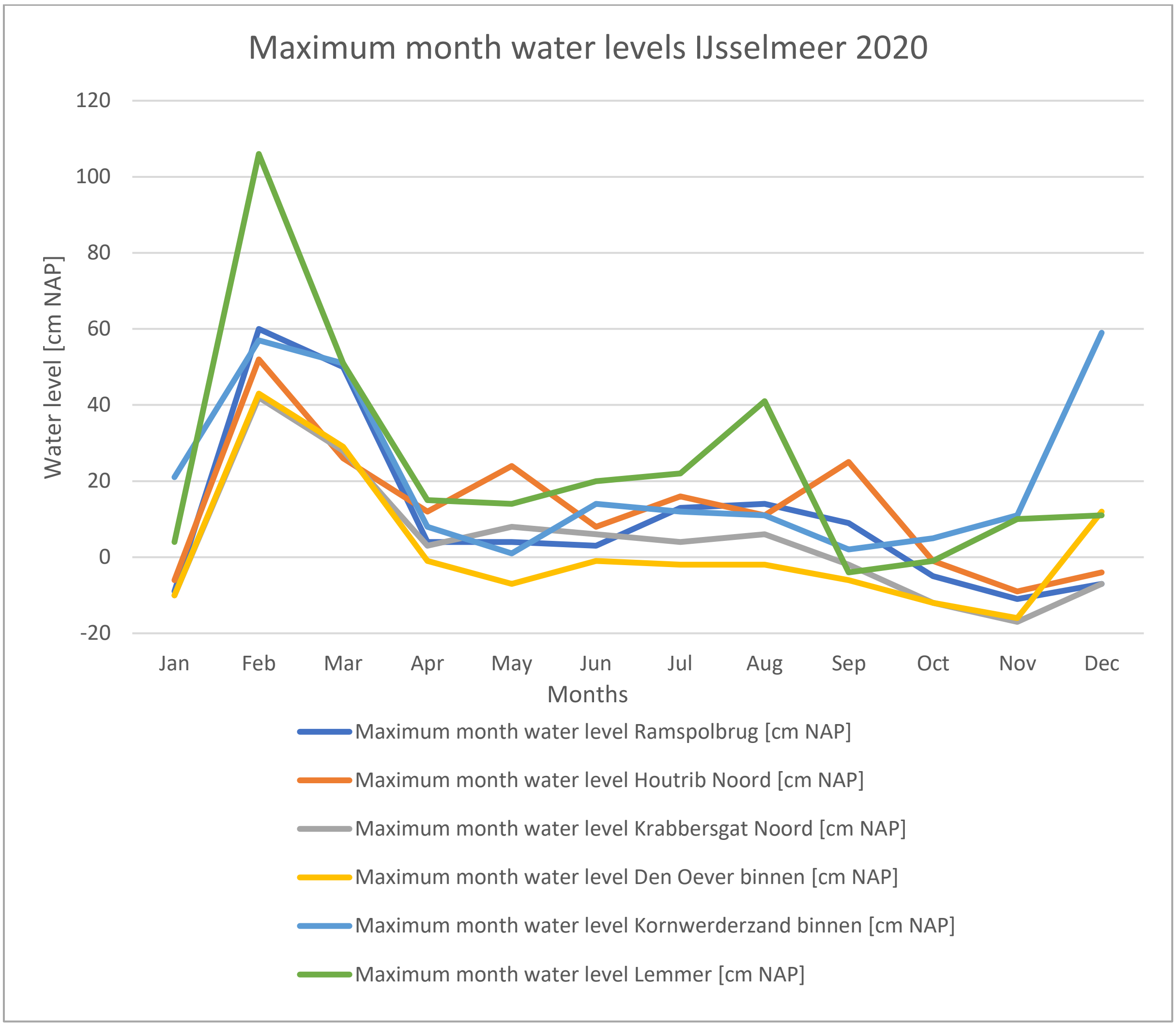


Figure 3.7: Maximum month water levels for the IJsselmeer in 2020 in cm NAP.

Wave run-up

The wave run-up height is presented by $R_{u2\%}$. $R_{u2\%}$ is the wave run-up level which is measured vertically from the still water level and is exceeded by 2% of the amount of waves. Wave run-up is mainly important for smooth slopes and embankments, but sometimes also for rough slopes. However, an exact mathematical description is impossible, because of the stochastic nature of waves. Each wave will namely give a different run-up level. Therefore, the wave run-up equation is derived empirically (van der Meer et al., 2018).

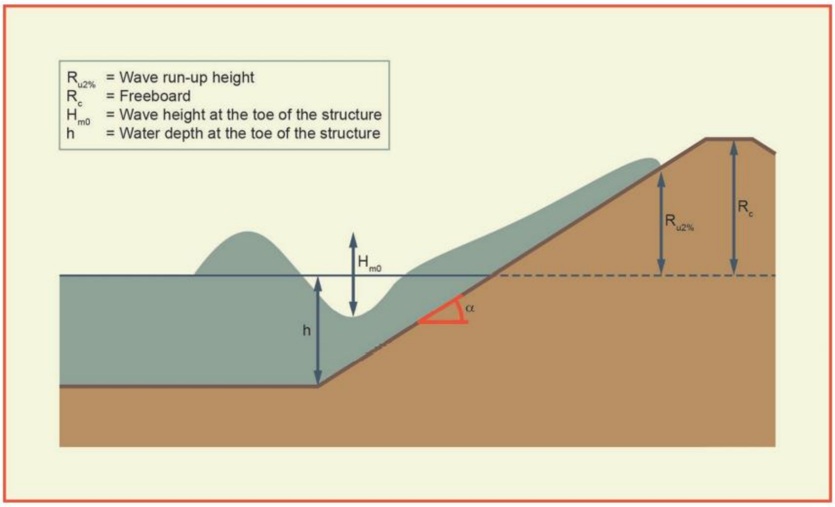


Figure 3.8: Definition of wave run-up height ($R_{u2\%}$) on a smooth slope (van der Meer et al., 2018).

The general formulae that can be applied for the 2% wave run-up height for relatively smooth slopes with shallow foreshores are given by *Equations 3.2* and *3.3*.

$$\frac{R_{u2\%}}{H_{m0}} = 1.65 * \gamma_b * \gamma_f * \gamma_\beta * \xi_{m-1.0} \tag{3.2}$$

Maximum wave run-up:

$$\frac{R_{u2\%}}{H_{m0}} = 1.0 * \gamma_f * \gamma_\beta \left(4 - \frac{1.5}{\sqrt{\gamma_b * \xi_{m-1.0}}}\right) \tag{3.3}$$

In which $R_{u2\%}$ is the wave run-up height exceeded by 2% of the incoming waves [m], H_{m0} is the wave height [m], γ_b is the influence factor for berm [-], γ_β is the influence factor for oblique wave attack [-], γ_f is the influence factor for roughness on a slope [-] and $\xi_{m-1.0}$ is the breaker parameter which is smaller than 3 for gentle slopes [-] (van der Meer et al., 2018).

For a relatively smooth slope the influence factor for roughness is around 1.0. The influence of the wave direction on wave run-up is defined by γ_β. To calculate γ_β *Equation 3.4* can be used.

$$\gamma_\beta = 1 - 0.0022(\beta) \qquad \text{for } 0° \leq \beta \leq 80° \tag{3.4}$$

β is the angle of wave attack defined at the toe of the structure. A visualisation of the angle can be seen in *Figure 3.9*.

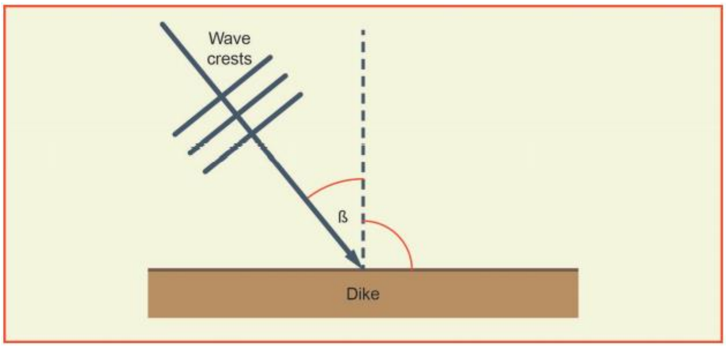


Figure 3.9: Definition of angle bèta (van der Meer et al., 2018).

Lastly, wave run-up is reduced by berm. Berm is part of the dike profile in which the slope varies between the horizontal and the steeper part of the dike. Berm is defined by the width of the berm B and by the vertical difference between the middle of berm and the water level, d_B.

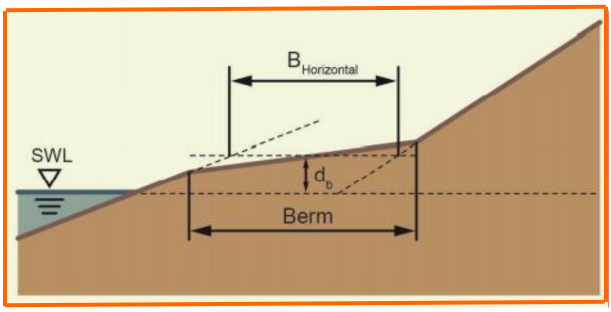


Figure 3.10: Definition of width B and height d_B of berm (van der Meer et al., 2018).

The characteristic berm length, L_{Berm}, is the horizontal length between two points on the slope, namely 1.0 H_{m0} above the middle of the berm and 1.0 H_{m0} below the middle of berm (van der Meer et al, 2018). The influence factor of berm can be calculated with *Equation 3.5*.

$$\gamma_b = 1 - r_b(1 - r_{db}) \tag{3.5}$$

r_b stands for the influence of the width of berm and will become 0 when there is no berm present. Secondly, r_{db} stands for the vertical difference between the still water level and the middle of berm and becomes 0 if the berm lies on the still water level (van der Meer et al., 2018).

$$r_b = \frac{B}{L_{Berm}} \tag{3.6}$$

$$r_{db} = 0.5 - 0.5\cos\left(\pi \frac{d_b}{R_{u2\%}}\right) \quad \textit{For a berm above still water level} \tag{3.7}$$

$$r_{db} = 0.5 - 0.5\cos\left(\pi \frac{d_b}{2 * H_{m0}}\right) \quad \textit{For a berm below still water level} \tag{3.8}$$

The reduction for wave run-up is maximum for a berm located on the still water level and decreases with increasing db. Berm located above $R_{u2\%}$ has no influence on wave run-up.

3.4 Flood risk

In this research flood risk is defined as the yearly probability of exceedance of hydraulic loads multiplied by the consequences of inundation and is expressed in euros per year. Kapalan and Garrick stated that risk is a set of scenarios, each of which has a probability and a consequence (Kapalan & Garrick, 1981). Therefore, discretization is necessary, and the discretized parts are added.

The total flood risk (*R*) is computed using *Equation 3.9*. T_1 is the largest return period and D_1 is the water damage associated to the largest return period.

$$R = \frac{1}{T_1} * D_1 + \left(\frac{1}{T_2} - \frac{1}{T_1}\right) * \frac{D_1+D_2}{2} + \left(\frac{1}{T_3} - \frac{1}{T_2}\right) * \frac{D_2+D_3}{2} + \left(\frac{1}{T_4} - \frac{1}{T_3}\right) * \frac{D_3+D_4}{2} + \left(\frac{1}{T_5} - \frac{1}{T_4}\right) * \frac{D_4+D_5}{2} \qquad (3.9)$$

In which:

T	=	Return period	[y]
D	=	Water damage	[€]
R	=	Total flood risk	[€/y]

For the probability of exceedance the return period (T) matters. The return period gives the estimated period between two flooding events of similar intensity. When the return period is 100 years, the probability of exceedance is 1/100. So the inverse of the return period is the probability. A water level with a probability of exceedance of 1/100, means that 1/100 years this water level is exceeded.

Consequences are mainly determined by the surface area that will be inundated and the water depth above inundated land. Furthermore, the function of the area is very important. Consequences will be much larger when houses and farms are flooded then when a grassland is inundated. The consequences will be reduced when water damage mitigation strategies are applied.

3.5 Waterschadeschatter

The Waterschadeschatter is a damage model for regional flooding. As explained in section 3.4, consequences have to be defined to determine flood risk. By using the Waterschadeschatter, consequences can be visualized. In the model, maps with water depth are uploaded. Because damage due to inundation is not only determined by the water depth, but also the duration of inundation, the season and the return period must be uploaded. In the Waterschadeschatter inundation depths are calculated using AHN3 (Actueel Hoogtebestand Nederland) with a resolution of 0.5 x 0.5 meters. The Waterschadeschatter uses a compound land use map with a resolution of 0.5 x 0.5 meters as well. The best characteristics of the BAG register (function of buildings), TOP10NL (roads, parks in urban areas, and waterways), BRP (location of crop fields), OSM (Open Street Map) and CBS Bodemgebruik (different kinds of land uses) are combined in this land use map.

The total water damage is the sum of direct damage and indirect damage. Direct damage arises when there is direct contact with surface water. Indirect damage is damage caused by direct damage. As an example for indirect damage a shop is flooded. The time the shop is closed for recovery costs money because nothing can be sold during these days. The model uses damage amounts for both direct and indirect damage. Per land use category three damage amounts are provided, namely the average, the maximum and the minimum. The price level of 2015 is used for the computations. In *Equation 3.10* the damage function can be found.

$$Damage\ function = direct\ damage * \gamma_{depth} * \gamma_{duration} * \gamma_{season} + indirect\ damage\ per\ day * recovery\ time \qquad (3.10)$$

Damage amounts are determined by *Landbouw Economisch Instituut* and CBS by using county wide data. For direct damage amounts of buildings it is assumed that for a maximum water depth of 0.15 meters, water damage increases linearly with water depth. In addition, the maximal inundation depth due to heavy rainfall events is 0.3 meters inside buildings. For this inundation depth, loose inventory can be reused (Waterschadeschatter, 2021). The Waterschadeschatter is primary developed for water damage and not for fluvial flooding. If fluvial flooding was included, houses cannot recover and the replacement value should be taken into account. For buildings with the functions health, education, industry, shopping and offices, direct damage amounts are based on an average building with a ground floor of 50 m^2. By dividing the estimated repair costs by the surface area of the ground floor of 50 m^2, the price per square meter can be defined (Waterschadeschatter, 2021). The duration of indirect damage of buildings corresponds to a damage amount times the duration of closure of the building. This duration is equal to the duration of inundation plus the recovery time. Indirect damage of buildings with a business function is estimated as the lost turnover minus the costs per day. Furthermore, for indirect damage of buildings with the functions education, health, industry and shopping, a water damage of €43 m^{-2} day^{-1} (low), €87 m^{-2} day^{-1} (average) and €130 m^{-2} day^{-1} (high) is estimated (Waterschadeschatter, 2021). Lastly, for buildings where people are living, indirect damage is approximated as the costs incurred to accommodate residents.

For direct damage of infrastructure, in general € 0.20 per m^2 can be used to remove sludge. This value is determined by the rent of the suction sweeper per hour divided by the number of meters that can be cleaned per hour. The indirect damage depends on the amount of cars that have to make a detour due to inaccessible roads and the length of the detour. The Waterschadeschatter only takes indirect damage into account for main roads, so not the roads in a residential area. Lastly, direct damage amounts of crops are estimated as the lost crop yield. However, indirect damages for agricultural damage are hard to determine and are compensated by extra profit made by other farmers due to increased prices.

Direct damage depends on the inundation depth, the duration of nuisance and the season, as can be seen in *Equation 3.10*. Indirect damage depends on two factors, namely the recovery time of roads and the recovery time of buildings. In Genemuiden, for T=1,000 years, associated with a water level of 2.29 m NAP, roads and some houses and farms will get inundated. Because both roads and buildings will experience water damage, Genemuiden with a return period of 1,000 years is chosen to show the impacts of direct and indirect damage. The impacts are shown in *Figures 3.11, 3.12* and *3.13* and are site specific. What can be concluded from the figures is that direct damage with a duration of nuisance of only one hour shows already a significant direct damage. This is because houses and farms will get inundated and this direct damage will stay more or less constant through time. However, a duration of nuisance of 16 hours shows an increase in direct damage. This increase in direct damage is caused by destroying meadow hay, which cannot recover after 12 hours anymore. Having a closer look to the indirect damage, the indirect damage of primary and secondary roads increases with longer recovery times. Because roads are inaccessible, cars need to make a detour. Lastly, the indirect damage of buildings increases exponentially for longer recovery times.

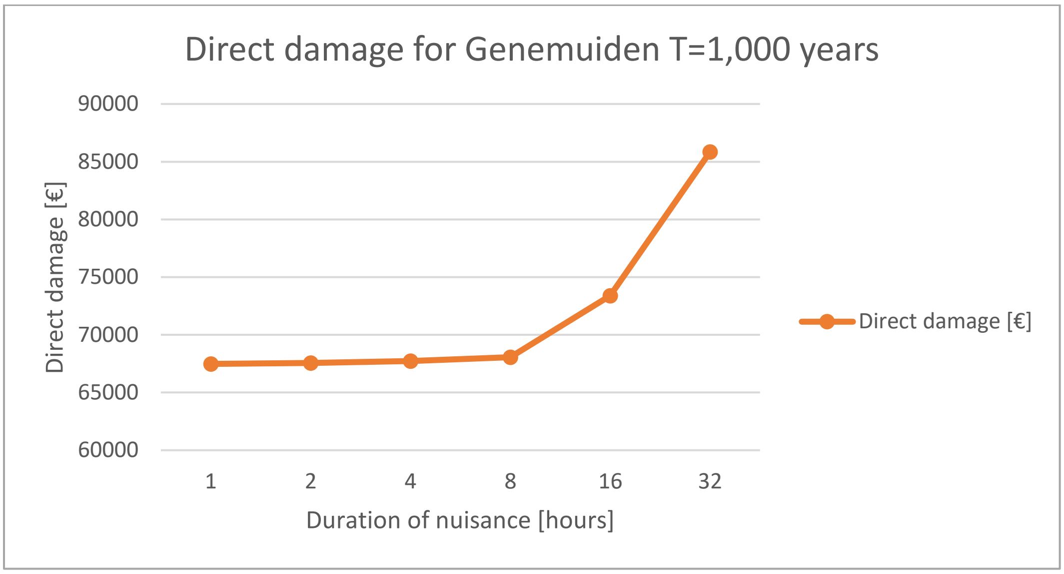


Figure 3.11: Direct damage for the area near Genemuiden. Direct damage will increase above a duration of nuisance of 12 hours. This is because meadow hay cannot recover after 12 hours anymore.

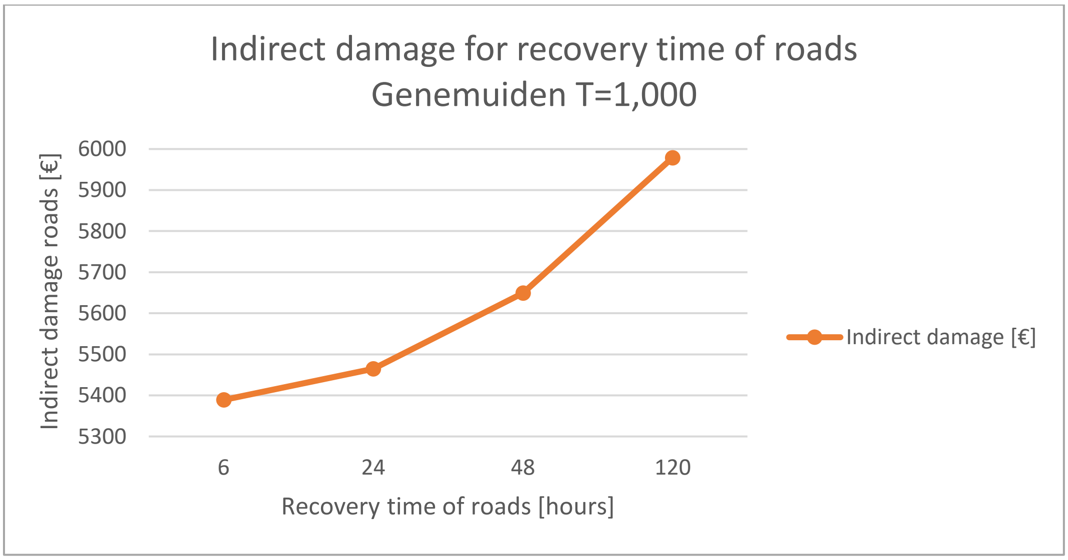


Figure 3.12: Indirect damage for recovery time of roads near Genemuiden.

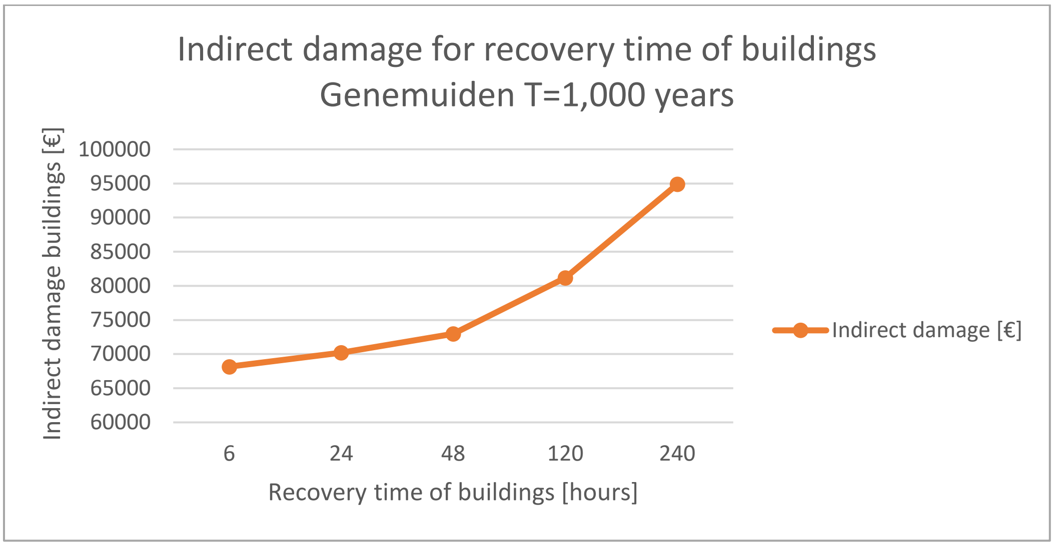


Figure 3.13: Indirect damage for recovery time of buildings in the case study area near Genemuiden. The longer the recovery time, the larger the indirect damage.

3.6 Hydra-NL

Hydra-NL is a probabilistic model. It can calculate the return period for hydraulic loads based on the water level, wind set up, fetch length, wave height, wave conditions, high water level periods and wave run-up. The calculations also take into account materials present on levees.

By using Hydra-NL components that determine high water levels in the IJsselmeer and Markermeer are included. The wind velocity, the fetch length and the angle between the land and the wind are included in the calculations and in this way wind set up is involved. Furthermore, the wave run-up height exceeded by 2% of the incoming waves is taken into account as well by the determination of the probability that a certain hydraulic load will occur.

Because both calculations for wind set up and wave run-up are taken into account, this probabilistic model is used to determine the probability that certain hydraulic loads during a flood event occur for the situation in which flexible water level management is excluded and included.

4. Materials and Methods

This chapter shows the materials and methods applied in this research. Section 4.1 presents a compact overview of the materials and methods used. Moreover, section 4.2 dives deeper into the materials and section 4.3 discusses the methodology in detail.

4.1 General strategy

In *Figure 4.1* a compact overview of the materials and methods applied in this research is shown. To carry out the GIS analysis, ArcMap version 10.8.1 is used. In ArcMap AHN3, *Legger Waterkeringen*, CBS and Topo RD are used as inputs and will be further explained in section 4.2. Information obtained from the GIS analysis is uploaded into Hydra-NL to determine the hydraulic loads for each case study area. Hydraulic loads are used in the Waterschadeschatter to determine the consequences. When the consequences are defined, the total flood risk and flood risk for each return period are computed excluding and including flexible water level management. Next, the GIS analysis is extrapolated to the whole IJsselmeer region, in which Hydra-NL is used to calculate interpolated water levels in the IJsselmeer region and the damage table from STOWA is used to determine the total water damage and flood risk. Lastly, Hydra-NL is validated by using water level data from Rijkswaterstaat and water damage mitigation strategies for the case study areas are discussed. The methodology is explained in more detail in section 4.3.

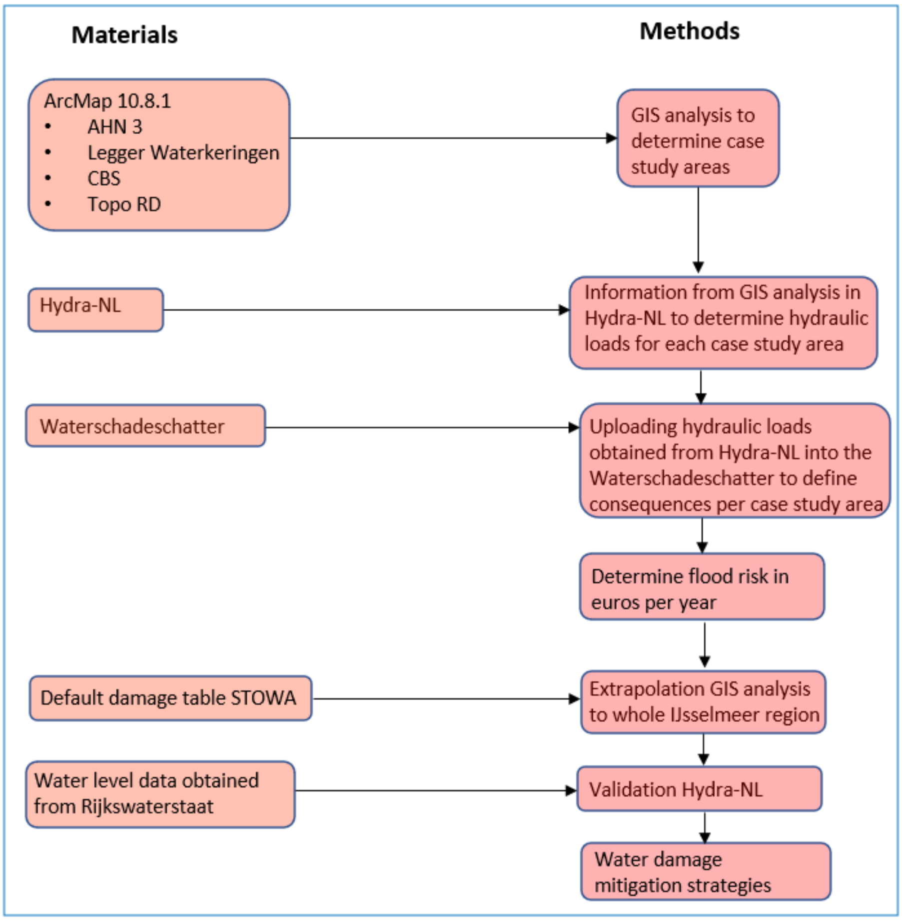


Figure 4.1: Short overview of materials and methods applied in this research.

4.2 Materials

The GIS analysis is executed using ArcMap version 10.8.1. AHN3 (Actueel Hoogtebestand Nederland) (AHN, 2021) is used as an input, as can be seen in *Table 4.1*. It is the digital elevation map of the Netherlands. Furthermore, the *legger waterkeringen* (Hoogheemraadschap Hollands Noorderkwartier (2021), Hoogheemraadschap Amstel, Gooi en Vecht (2021), Waterschap Zuiderzeeland (2021), Waterschap Vallei en Veluwe (2021), Waterschap Drents Overijsselse Delta (2021), Wetterskip Fryslan (2021)) is a formal map in which the location of levees is visualized. Lastly, CBS (CBS, 2021) is used as an input in ArcMap to show different functions of land. Four function classes are used, namely buildings and infrastructure areas, pasturelands, recreation areas and nature areas. These four function classes are representative for areas outside primary levees in the IJsselmeer region. Information derived from ArcMap is used in Hydra-NL version 2.8.2 to determine hydraulic loads. Water level data obtained from Rijkswaterstaat is used to validate Hydra-NL. Finally, the hydraulic loads are uploaded into the Waterschadeschatter to define the consequences of flexible water level management in areas outside primary levees. The default damage table is used in the Waterschadeschatter to compute water damage.

Table 4.1: Overview of tools and data used in this research.

Name	**Description**	**Source**
ArcMap 10.8.1	Programme in which geographic information is analysed	(Esri, 2021)
AHN3	Digital elevation map of the Netherlands	(AHN, 2021)
Legger Waterkeringen	Map in which the Dutch levees are visualized	(WSP, 2021)
CBS	Visualizes different land functions in the Netherlands	(CBS, 2021)
Topo RD	Community base map containing streets, roads, parks, cities, buildings and water	ArcGIS online
Waterschadeschatter	Tool to determine damage due to flooding	(Waterschadeschatter tool, 2021)
Hydra-NL 2.8.2	Probabilistic model which calculates the statistics of hydraulic loads	(Helpdesk Water, 2021)
Water level data obtained from Rijkswaterstaat	Water level data series to validate Hydra-NL	(Rijkswaterstaat Waterinfo, 2021)
Default damage table	Table used in the Waterschadeschatter to calculate water damage	(STOWA, 2021)

4.3 Methodology

In *Figure 4.1* the research strategy is presented. Firstly, a literature study is executed. Topics which are emphasized are to determine how water levels are regulated and to investigate which components influence high water levels. After analysing the whole IJsselmeer region, case study areas are chosen and are analysed using GIS. The GIS analysis for the case study areas is discussed in detail in section 4.3.1 and the methodology to verify the GIS analysis is shown in section 4.3.2. Furthermore, the methodology to choose three case study areas is presented in section 4.3.3 and characteristics of the case study areas are presented in section 4.3.4. The three case study areas are visited during a fieldtrip and observations are compared with data used in models. The field report can be found in *Appendix A*. Information gained from the GIS analysis is used in Hydra-NL to determine hydraulic loads for different return periods. Inputs in Hydra-NL are explained in section 4.3.5. Next, the hydraulic loads are uploaded into the Waterschadeschatter to determine water damage for the cases in which flexible water level management is excluded and included for the case study areas. In section 4.3.6 inputs for the Waterschadeschatter are discussed. Finally, the total flood risk for each case study area is computed. To define the total water damage and flood risk for the whole IJsselmeer region, the GIS analysis is extrapolated in section 4.3.7. Moreover, a validation of Hydra-NL is presented to check whether the water levels from Hydra-NL are matching occurred water levels. The methodology of the validation of Hydra-NL is presented in section 4.3.8. Lastly, the way in which water damage mitigation strategies for the case study areas are derived, is discussed in section 4.3.9.

4.3.1 Approach GIS analysis case studies

The GIS analysis starts with a broad view in which the whole IJsselmeer region is mapped. Buildings and infrastructure areas outside primary levees mainly consist of parking lots, harbours, buildings with a water related function and occasionally some residential areas. Next, pasturelands outside primary levees only consist of pasturelands and recreation areas outside primary levees only consist of recreation areas. Lastly, nature areas outside primary levees consist of wet and dry nature areas.

After visualizing the whole IJsselmeer region, case study areas are chosen. They are selected based on their geographical location, their function, different stakeholders and complaints, which is described in section 4.3.3. The location, elevation and boundaries of the area of investigation are presented in section 4.3.4, together with their land use. This data from GIS is needed in Hydra-NL to calculate hydraulic loads for different return periods. When the hydraulic loads are known, shape files of the case study areas are designed in GIS and are converted into a raster file. Each raster file gets the value for the hydraulic load associated to their return period. Five return periods are chosen, which are T=10, T=30, T=300, T=1,000 and T=10,000 years. The return periods are chosen in such a way that they are representative for flooding events in areas outside primary levees (Kennisportaal Klimaatadaptatie, 2021). There are three case study areas and five return periods, so 15 raster files are made with the value for the hydraulic load associated to their return period. Finally, the raster files are converted into an ascii file and are uploaded in the Waterschadeschatter to determine the consequences. This process is executed twice, once for the situation excluding flexible water level management and once for the situation in which flexible water level management is included.

Inundation maps are designed by subtracting AHN3 from the water level belonging to one return period for areas situated above NAP. For areas located below NAP the water level is subtracted from AHN3 and the absolute value is taken. To calculate the inundated area, cells representing inundation are added and multiplied by the cell size.

4.3.2 Verification GIS analysis

The GIS analysis forms the base of this research. Therefore, it is valuable to verify if the GIS analysis shows reliable results. To check the results, the locations and heights of the winter and summer levees are checked with observations made in the field. Furthermore, it is checked whether land use types are similar and whether Hydra-NL shows outcomes that match occurred water levels. These three items are checked, because they can affect the end result heavily.

4.3.3 Methodology case studies

Case studies are used to show effects of flexible water level management in areas outside primary levees. The effects are site specific and therefore three different case studies have been investigated. The case study areas are chosen based on their geographical location, their function, complaints and different stakeholders.

In this research four function classes are discussed to show per function class what the consequences of applying flexible water level management are. The function classes used are buildings and infrastructure areas, pasturelands, recreation areas and nature areas and are representative for the IJsselmeer region. Parkhaven is chosen because it is a large, familiar residential area outside primary levees with potentially a lot of damage after inundation. Moreover, Genemuiden is chosen because it is one of the largest pastureland areas. Lastly, Schellinkhout is chosen. It is a nature and recreation area and in this way the consequences for the two function classes are visualized.

Complaints about higher water levels mainly come from the chosen areas (Rijkswaterstaat, 2017). In Parkhaven, residents do already suffer from high water levels. Their gardens and terraces inundate during a storm and they are afraid that, by applying flexible water level management, more frequent flooding will occur with larger water depths. By implementing flexible water level management, the Ramspol weir will close more often. Therefore, floodplains will inundate more frequently and residents living near Genemuiden are worried about this. Lastly, complaints were received about the beach at Schellinkhout which will disappear during high water conditions.

So there are different stakeholders with different stakes living in the three case study areas. The stakeholders are residents, farmers, campsite owners, nature managers and catering owners. Their concerns are mainly about increasing water levels and the increase in flood risk. Residents are worried about their houses. Farmers complain about their land which will be inundated more frequently and campsite owners are afraid that, during high water conditions, guests need to leave. Lastly, nature managers are worried about the spring set up, because nests of birds will be destroyed by the increase of water levels.

Figure 4.2: The three case study areas which are studied in more detail.

4.3.4 Case study areas

Parkhaven

Parkhaven is a residential area outside primary levees along the IJsselmeer, located in the neighbourhood of Lelystad. It has a surface area of 5 hectare. Even before applying flexible water level management, some terraces and gardens were already flooded during storms (Jaspers et al., 2017). The terraces and gardens have an elevation between 0.4 m NAP and 0.7 m NAP and the streets are located above 1.5 m NAP, as can be seen in *Figure 4.3*. *Figure 4.4* shows water levels for Parkhaven from 1975 to 1990 together with the 90 percentile and 10 percentile water levels during summer. For 90% of the time the water level is below -8 cm NAP and for 10% of the time the water level is below -25 cm NAP.

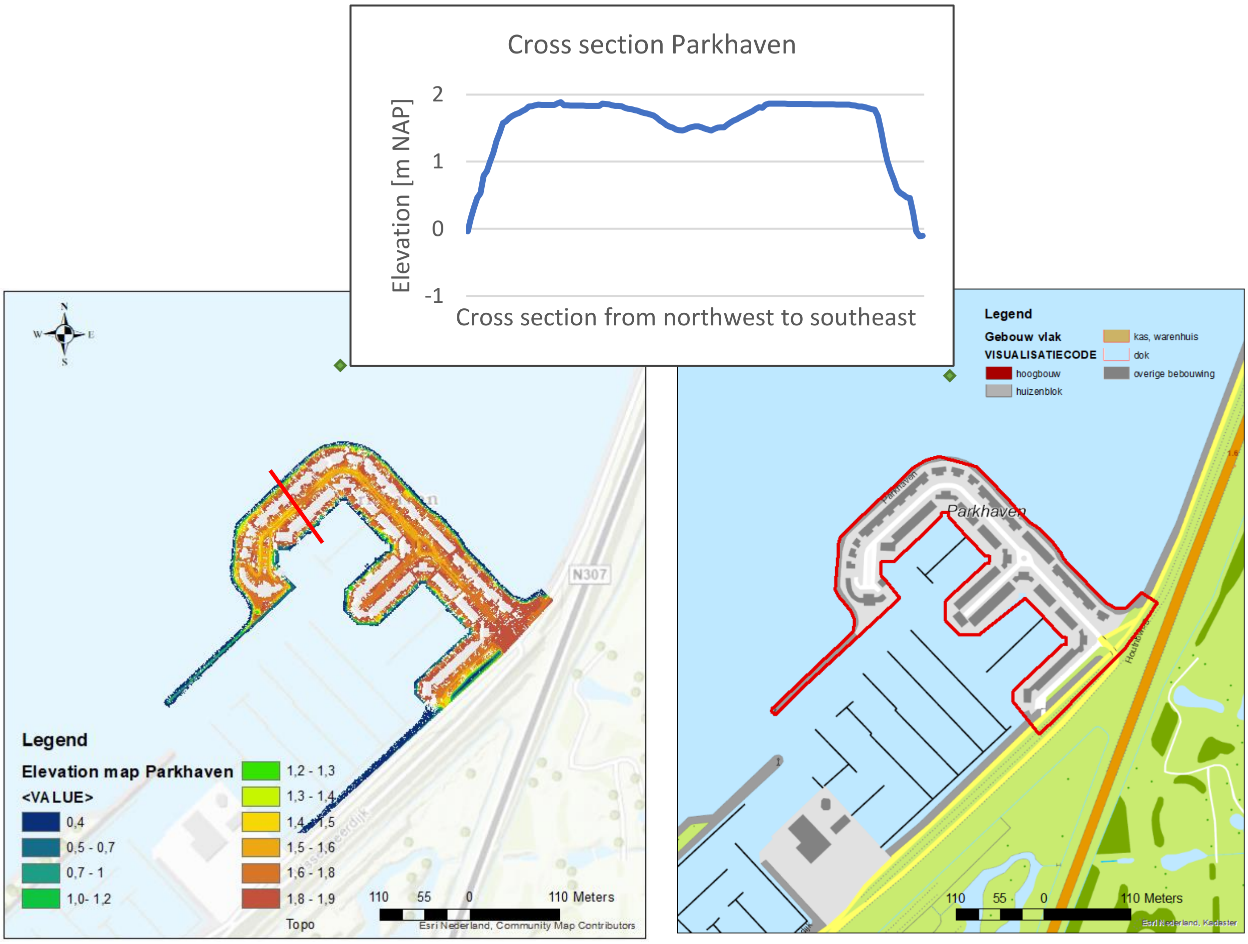


Figure 4.3: Elevation map together with cross section from northwest to southeast (left) and land use map (right) of Parkhaven. The surrounding area is located behind the winter levee and will therefore not be inundated. The green diamond shows the location in Hydra-NL.

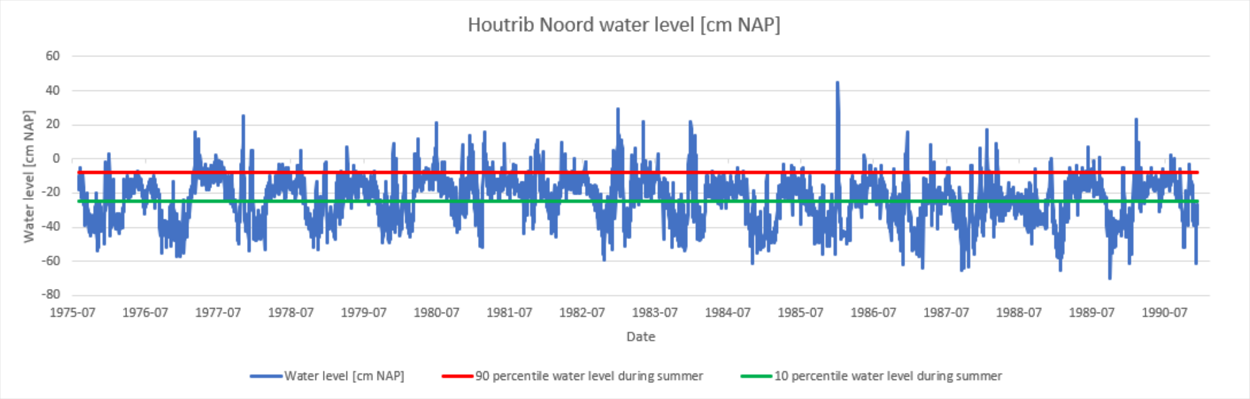


Figure 4.4: Water levels Parkhaven (1975-1990) with 90 and 10 percentiles during summer in cm NAP.

Genemuiden

The area located outside primary levees of het Zwarte Water near Genemuiden is a pastureland area. The area has an outer summer levee with an elevation of 0.7 m NAP and an inner summer levee of 1.0 m NAP and has a surface area of 150 hectare, as can be seen in *Figure 4.5*. This location is situated upstream of the Ramspol bellows weir and the weir will be closed when the water level is predicted to reach 0.5 m NAP. Possibly, the weir will close more often due to flexible water level management. Furthermore, in *Figure 4.6* water levels are presented for a period from 1933 to 1985. The 90 percentile and 10 percentile water levels during summer are calculated and for 90% of the time the water level is below 2 cm NAP and for 10% of the time the water level is below -27 cm NAP.

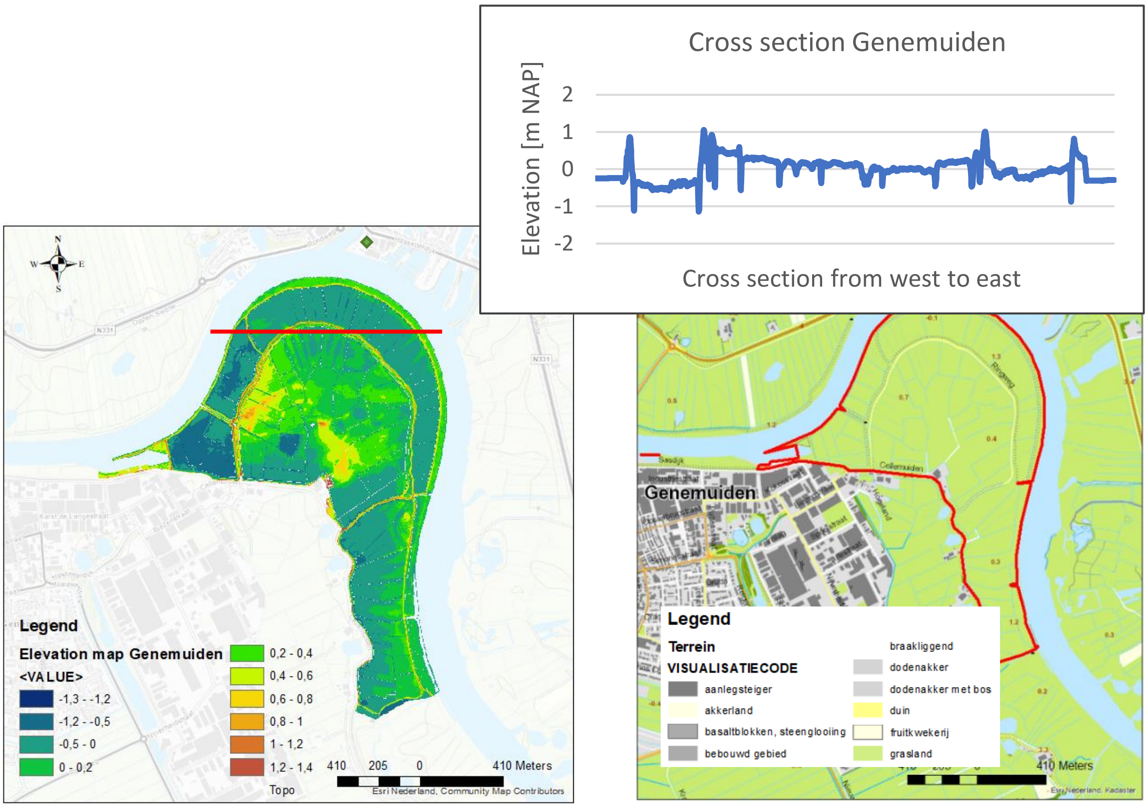


Figure 4.5: Elevation map together with cross section from west to east (left) and land use map (right) of het Zwarte Water near Genemuiden. Genemuiden city is located behind the winter levee and will therefore not be inundated. However, the region south of the defined area is not taken into account in this research, but is an area outside primary levees where inundation can take place. The green diamond shows the location in Hydra-NL.

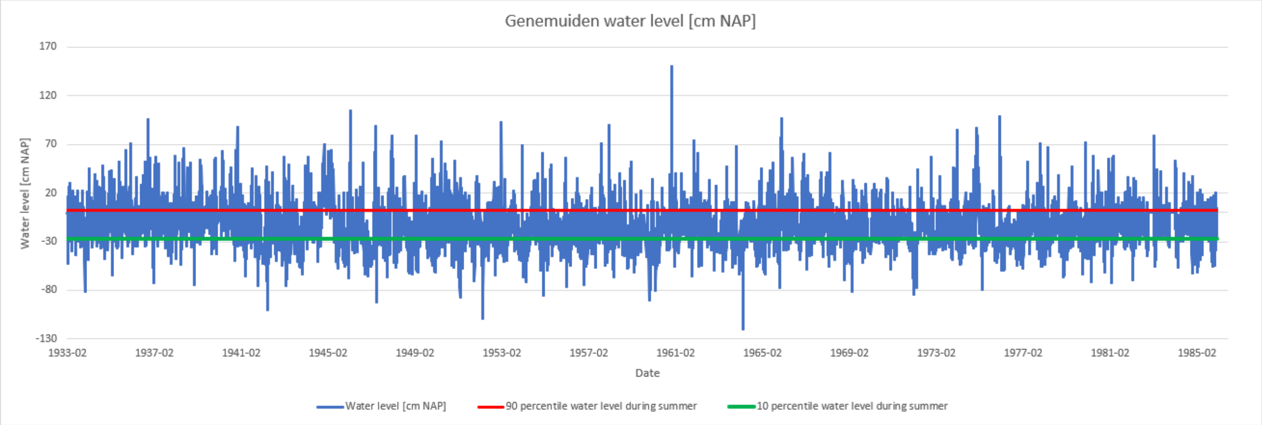


Figure 4.6: Water levels Genemuiden (1933-1985) together with 90 and 10 percentiles water level during summer in cm NAP.

Schellinkhout

The area outside primary levees near Schellinkhout is a nature and recreation area and is located along the Markermeer. The area on the left of the gully presents a meadow bird area and the area to the right of the gully forms a polder outside primary levees with its own pumping station. Most parts in the area are located below -0.5 m NAP, as can be seen in *Figure 4.7*. The summer levee has an elevation of 0.8 m NAP. However, the gully has much lower levees of 0.2 m NAP. The total surface area of Schellinkhout is 45 hectare. The 90 percentile water level during summer is -14 cm NAP and the 10 percentile water level is -25 cm NAP, as can be seen in *Figure 4.8*.

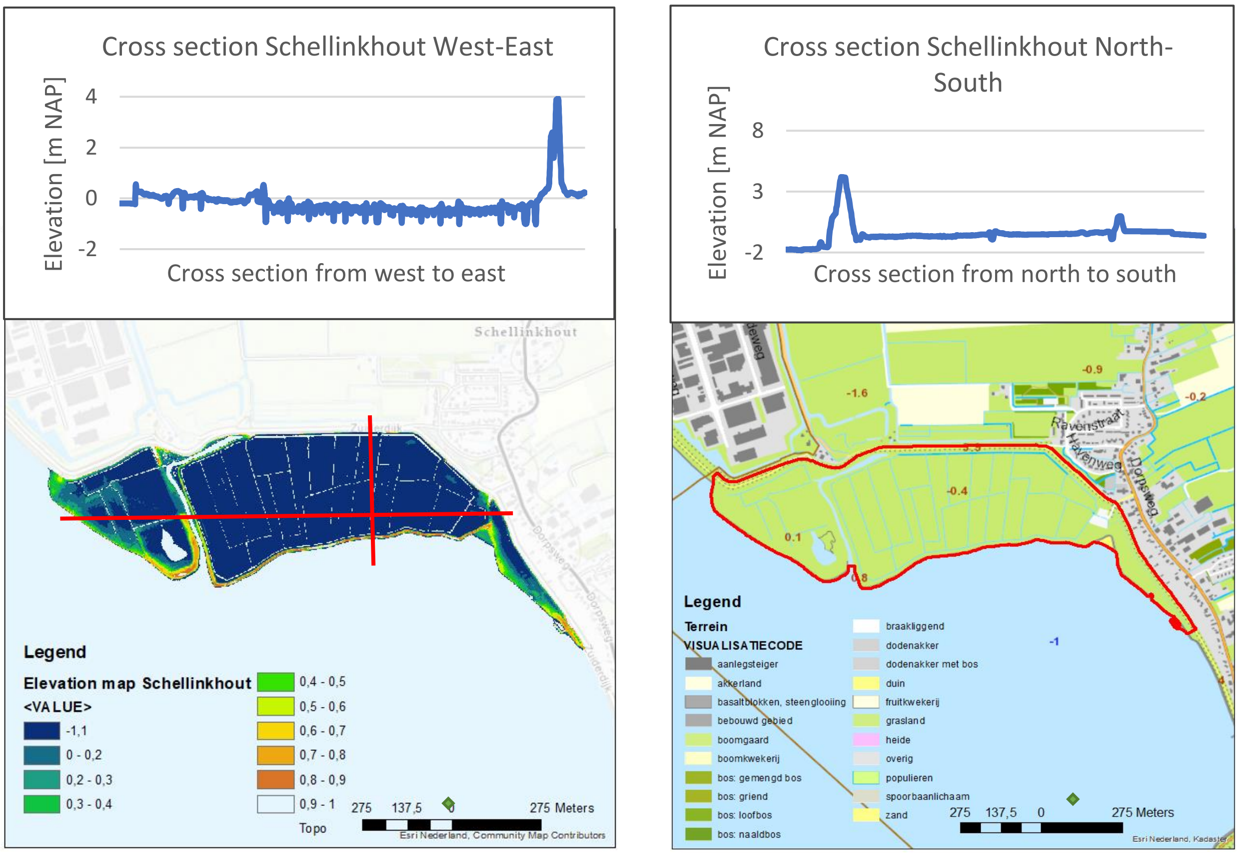


Figure 4.7: Elevation map together with two cross sections (left) and land use map (right) of Schellinkhout. The surrounding area is located behind the winter levee and will not be inundated. The green diamond shows the location in Hydra-NL.

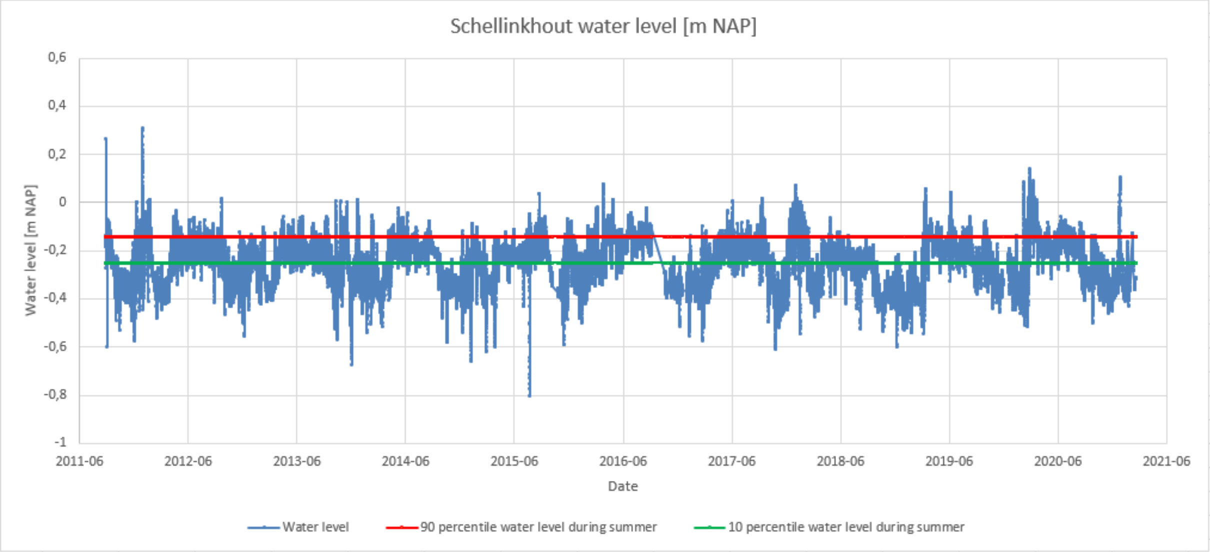


Figure 4.8: Water levels Schellinkhout (2011-2021) together with 90 and 10 percentiles water level during summer in m NAP.

4.3.5 Inputs Hydra-NL

Hydra-NL is a probabilistic model and is used to determine hydraulic loads for different return periods. The hydraulic load is calculated by adding the lake water level, the wind set up and the wave-run up. To determine wave run-up, the water level is subtracted from the hydraulic load. Wind set up can be computed by subtracting the lake water level from the water level. Probabilities together with hydraulic loads are discussed for return periods of 10, 30, 300, 1,000 and 10,000 years. The return periods are chosen such that in this range inundation is more likely to occur in areas outside primary levees.

Hydraulic loads are calculated by adding a levee profile of the case study areas in Hydra-NL. First, the points in Hydra-NL closest to the case study areas are added and are shown with green diamonds in *Figures 4.3, 4.5* and *4.7* in section 4.3.4. These points are located just outside the coast inside the lake. The distance between the point located in the water and the start of the foreland is entered in Hydra-NL. Moreover, the slope, roughness factor, orientation and height of the levee are used as an input as well. By using this information a profile is added and the hydraulic loads are calculated.

Table 4.2: Information needed in Hydra-NL to calculate hydraulic loads.

	Distance between point in Hydra-NL and foreland [m]	**Distance between foreland and levee [m]**	**Height of levee [m NAP]**	**Orientation of levee [°]**	**Slope [%]**	**Roughness factor [-]**
Parkhaven	80	300	3.4	310	1.8	1.0
Genemuiden	200	900	3.0	30	2.1	1.0
Schellinkhout	500	400	4.1	170	1.9	1.0

4.3.6 Inputs Waterschadeschatter

The Waterschadeschatter is a damage model for regional flooding. In this tool an ascii file containing the hydraulic load associated to one return period, AHN3, the duration of nuisance, the recovery time of roads and buildings and the month of occurrence are uploaded. The duration of nuisance has been estimated looking to the relation between the damage factor and the duration of inundation in the user manual from STOWA. A duration of nuisance of two days is given as a maximum in the linear graph shown in figure 4.7 in the user manual and is doubled for every larger return period. The duration of nuisance mainly affects crops when land is inundated for more than 24 hours. Furthermore, the recovery time of roads depends on the number of cars that have to make a detour and the length of the detour. The recovery time of buildings depends on the availability of contractors. Lastly, the month of occurrence is March since during this month the spring set up takes place.

4.3.7 Extrapolation GIS analysis

To compute interpolated water levels in the IJsselmeer and Markermeer for the situation in which flexible water level management is included and excluded, again Hydra-NL is used. This time, not hydraulic loads, but water levels are calculated since interpolation is very hard with hydraulic loads. Hydraulic loads are location specific and depend on the slope, orientation and roughness of the cross section. Therefore, interpolation is done with water levels. Water levels for the points in Hydra-NL located along the Markermeer, IJsselmeer, Ketelmeer and Zwarte Meer are interpolated linearly for the return periods T=10, T=30, T=300, T=1,000 and T=10,000 years. In GIS the inundated area associated to the function class for each return period is calculated. This is done using the function "Intersect" in the "Arc Toolbox".

For the case study areas, the water damage could be computed using the Waterschadeschatter. However, by analysing the whole IJsselmeer region the GIS files are too large, since the water damage tool cannot handle files larger than 200 km^2. Therefore, the default water damage table from STOWA is used, which is also used for the calculation inside the Waterschadeschatter. This time, the total water damage is calculated manually with the damage function presented in *Equation 3.10* for the situation in which flexible water level management is excluded and included. So the same procedure is used as in the Waterschadeschatter. Average direct and indirect damages are obtained from the water damage table. For buildings and infrastructure areas, the water damage table for residential areas is used, which shows an overestimation, since buildings and infrastructure areas also consists of parking lots or harbours with much lower water damages. For pasturelands, the agricultural grass and fodder table is chosen and for recreation areas the day recreational area table is used. Lastly, for nature areas, the natural grassland table is chosen. The average water depth for each return period is calculated excluding and including flexible water level management by subtracting AHN3 from the water level for areas located above NAP and for areas situated below NAP the water level is subtracted from AHN3 and the absolute value is taken. Both the duration of inundation and recovery time are based on the height of the water level.

The case study areas are extrapolated to give a first insight in potential flood risk in other areas located outside primary levees. This extrapolation is executed to show the order of magnitude of flood risk. Exact calculations are difficult, since elevations and land use in areas outside primary levees differ.

4.3.8 Validation Hydra-NL

Water level series from measurement stations close to Parkhaven, Genemuiden and Schellinkhout have been requested from Rijkswaterstaat to check whether water levels from Hydra-NL are matching occurred water levels. The nearest measurement station to Schellinkhout with a data series of 9 years is the measurement station at the pumping station in Schellinkhout. The nearest station to Genemuiden is measurement station "de Ketting" with a data series of 52 years and the closest measurement station to the residential area Parkhaven is Houtrib Noord with a data series of 15 years. The measurement locations can be seen in *Figure 4.9.*

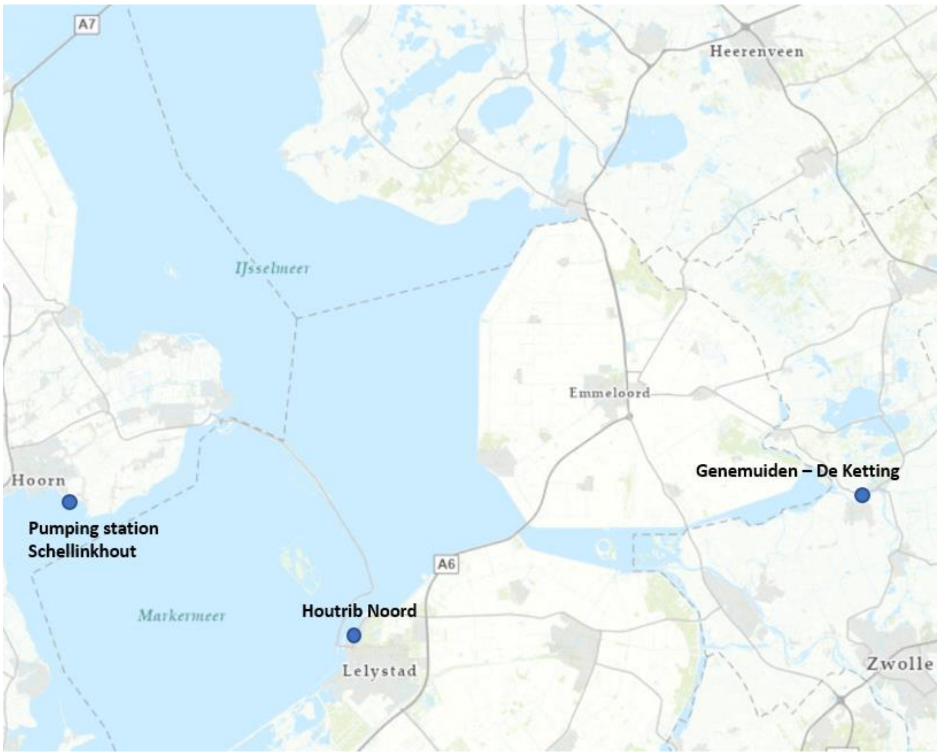


Figure 4.9: Measurement locations closest to case study areas.

4.3.9 Water damage mitigation strategies for case study areas

The search terms "water damage mitigation" and "protection against water" on the internet, in papers and articles, are used to get familiar with different water damage mitigation strategies. In the case study areas is looked for weak spots which must be reinforced, but also how residents themselves can mitigate water damage. To sharpen the mitigation strategies, a focus group discussion is held. The discussion focusses on my devised mitigation strategies and other measures which could mitigate water damage in the three case study areas. The focus group discussion was held with four experts from WSP with a background in surroundings and environment, water safety, climate adaptation and ecology. Different backgrounds are used to take different interest and perspectives into account. Two weeks before the day of the discussion, a compact document (*Appendix C*) with information needed for the discussion was sent to the participants and a meeting room was reserved. A PowerPoint presentation was made in which the questions for the focus group discussion were shown during the discussion to stay on track. Afterwards a report of the focus group discussion was created (*Appendix D*) in which the most important findings are presented.

5. Results

In this chapter, the results and a discussion of the results is presented. Section 5.1 shows characteristics of areas outside primary levees in the IJsselmeer region. Next, section 5.2 compares observations made when visiting the three case study areas with AHN3. Section 5.3 presents the results in which flexible water level management is excluded and section 5.4 shows the results in which flexible water level management is included for the three case study areas. Furthermore, the results in which flexible water level management is included and excluded are compared in section 5.5. Lastly, section 5.6 presents a sensitivity analysis, section 5.7 shows the results from the extrapolated GIS analysis for the whole IJsselmeer region and in section 5.8 Hydra-NL is validated.

5.1 Characteristics of areas outside primary levees in the IJsselmeer region

Characteristics of areas outside primary levees in the IJsselmeer region are shown in *Table 5.1* and *Figure 5.1*. This analysis is done using ArcMap and the results from ArcMap are imported in Excel. The red lines in *Figure 5.1* show elevations of the function classes of the case study areas. Schellinkhout is a nature and recreation area and represents these two function classes.

Table 5.1: Characteristics of areas outside primary levees in the IJsselmeer region.

	Areas outside primary levees in the IJsselmeer region [ha]	**Percentage [%]**	**Mean elevation [cm NAP]**	**Mean elevation function classes case study areas [cm NAP]**
Buildings and infrastructure areas	460	2.9	187	163 *(Parkhaven)*
Pasturelands	11,345	71.7	115	-11 *(Genemuiden)*
Recreation areas	1,330	8.4	122	35 *(Schellinkhout)*
Nature areas	2,684	17.0	60	-48 *(Schellinkhout)*

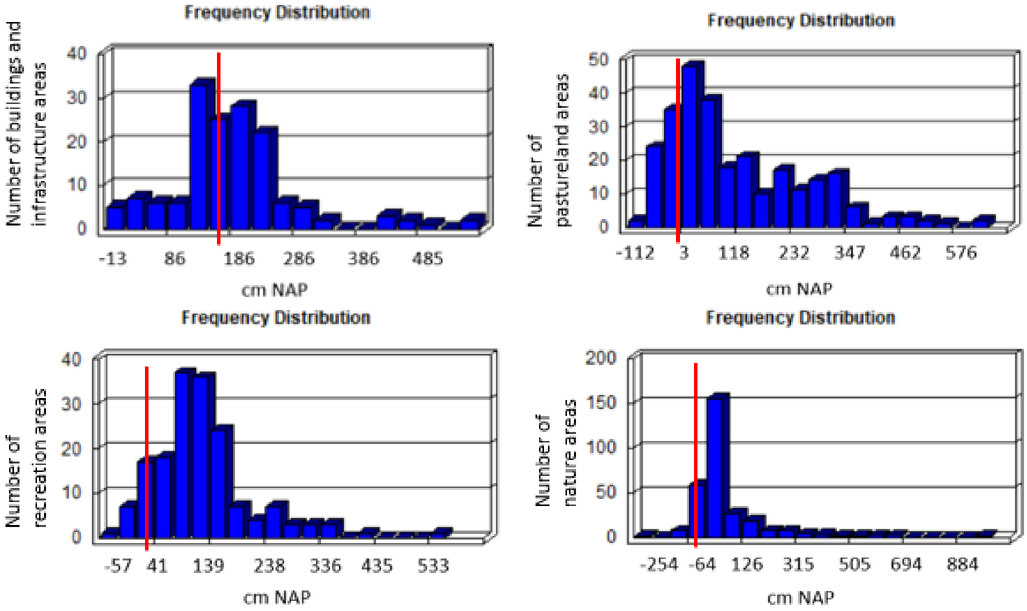


Figure 5.1: Elevation frequency distribution for each function class. The red lines show the mean elevations of the function classes of the case study areas.

5.2 Comparing observations during fieldtrip with AHN3

In general, observations made in the field are matching data from the GIS analysis. Starting with case study area Parkhaven, gardens and terraces are indeed located much lower than the houses with a difference of approximately 1 meter, which can be seen in *Figure 5.2*. When looking into AHN3, the road in Parkhaven has an elevation above 1.5 m NAP and terraces and gardens differ in elevation between 0.4 and 0.7 m NAP. The winter levee is covered with grass and is situated at the same location as stated in the *legger waterkeringen*. All dike stretches relevant for this research are uploaded into GIS.

Next, in Genemuiden there are two summer levees. Both these grassy levees are seen in the field as well as in AHN3. However, it looked like the two summer levees had the same height while being in the field, but AHN3 reveals that there is a vertical difference of approximately 0.3 meters. Furthermore, when only looking in AHN3, it looks like there is a weak spot in the southern part of the research area. A ditch namely ends at a spot which has an elevation of 0.6 m NAP. However, when making observations in the field, it was discovered that there is a valve present below the second summer levee which can be closed, as can be seen in *Figure 5.3*, and therefore the hinterland is protected.

In the research area near Schellinkhout one summer levee is present which lowers near the beach from approximately 0.8 m NAP to 0.2 m NAP which has been done on purpose for recreation. Disappearing of the summer levee can both be seen in AHN3 as well as in the field. Furthermore, the low lying gap on the southeast of the beach is clearly visible in AHN3, but the drop of around 0.1 m directly on the eastern side of the gap is not visible. What also cannot be seen from AHN3 is the fence which catches duckweed at the end of the ditch in the nature area, which can be seen in *Figure 5.4*.

In this research accuracy does not play a relevant role. For instance, looking to the case study area near Genemuiden, the outer summer levee has an elevation of 0.7 m NAP and the inner summer levee has an elevation of 1.0 m NAP. For a return period of 10 years the hydraulic load is more than 1.5 m NAP, which is further explained in sections 5.3 and 5.4. This value for the hydraulic load seems relatively high. However, this area forms the floodplains of het Zwarte Water and are designed to inundate frequently. In this case, it does not matter if the summer levees are a few centimetres lower or higher, the area will totally inundate for water levels with a return period of 10 years. The same way of reasoning holds for the other two case study areas. Therefore, accuracy is trifling in this research.

Lastly, hydraulic loads for different return periods, which are computed using Hydra-NL in sections 5.3 and 5.4, show realistic outcomes compared to elevations of winter levees. The highest hydraulic loads are smaller than the elevations of the winter levees. Therefore, the hinterland will not be inundated and only consequences for areas outside primary levees are discussed.

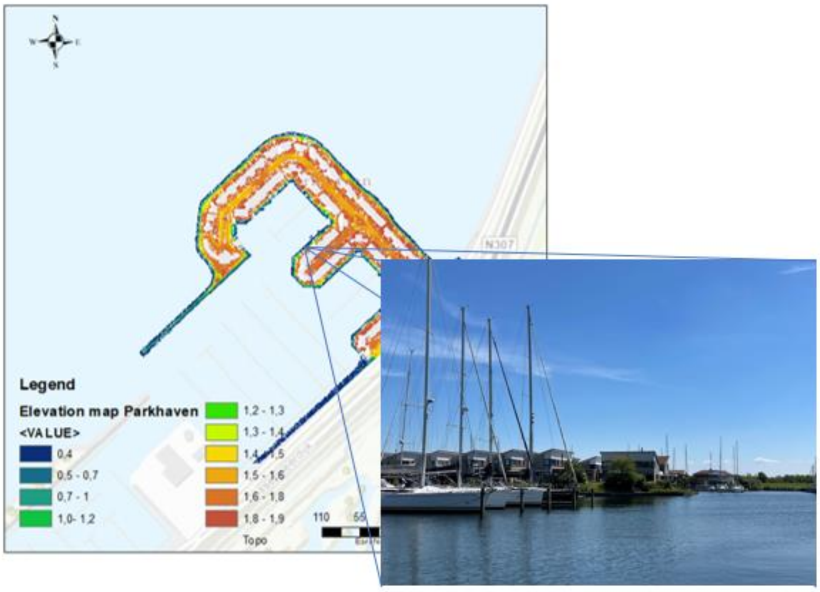


Figure 5.2: Houses and gardens in Parkhaven.

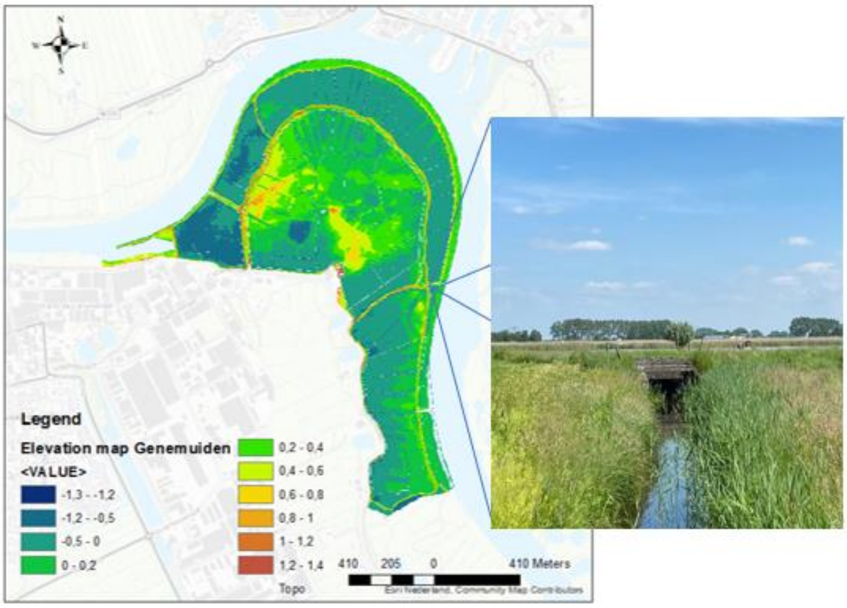


Figure 5.3: Valve in the pastureland area of Genemuiden.

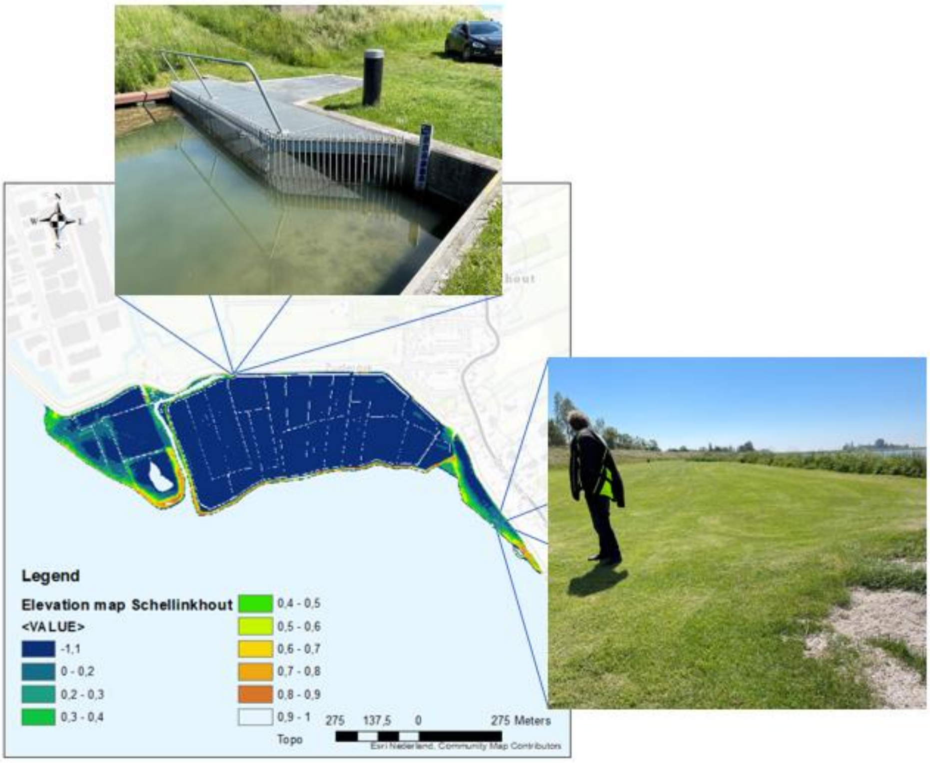


Figure 5.4: Fence which catches duckweed leading to the pumping station behind the primary levee and drop on the eastern side of the gap in Schellinkhout.

5.3 Results excluding flexible water level management

5.3.1 Calculated hydraulic loads from Hydra-NL

In this section, results from Hydra-NL excluding flexible water level management are presented for each case study area.

Parkhaven

The closest point in Hydra-NL is located 80 m from the coast of the residential area and the foreland is around 300 meters long. The orientation of the winter levee with respect to the North is about 310 degrees and the winter levee has a roughness factor of 1.0, which is the standard roughness for levees covered by grass. By adding a profile, hydraulic loads are calculated. The prevailing wind direction in Hydra-NL comes from the northwest. Because Parkhaven is located behind the Houtribdijk, wave run-up is relatively small. The decreasing lake water levels for larger return periods can be explained by looking to the local system of the protrusion in which Parkhaven is located. Negative lake water levels with respect to NAP are typical for the IJsselmeer, since during winter the water level is tried to be maintained at -0.40 m NAP.

Table 5.2: Hydraulic loads together with water level, wave run-up and wind set up for Parkhaven in which flexible water level management is not included.

Exceedance probability [/year]	Hydraulic load [m NAP]	Wave run-up [m]	Water level [m NAP]	Lake water level [m NAP]	Wind set up [m]
1/10,000	2.98	0.78	2.20	-0.17	2.37
1/1,000	1.83	0.12	1.71	-0.19	1.90
1/300	1.50	0.02	1.48	-0.13	1.61
1/30	1.12	0.01	1.11	0.18	0.93
1/10	0.94	0	0.94	0.22	0.72

Genemuiden

In Hydra-NL, the Vechtdelta is added to calculate hydraulic loads at het Zwarte Water near Genemuiden. The closest point is situated 200 meters from the foreland. The foreland itself is at the most 900 meters long and the orientation with respect to the North is about 30 degrees. The roughness factor is again 1.0 and the prevailing wind direction from Hydra-NL is west-southwest. Het Zwarte Meer is also oriented from west-southwest to east-northeast. Therefore, water levels are relatively high because of the large wind set up.

Table 5.3: Hydraulic loads together with water level, wave run-up and wind set up for Genemuiden in which flexible water level management is not included.

Exceedance probability [/year]	Hydraulic load [m NAP]	Wave run-up [m]	Water level [m NAP]	Lake water level [m NAP]	Wind set up [m]
1/10,000	2.65	0.07	2.58	0.82	1.76
1/1,000	2.29	0.02	2.27	0.55	1.72
1/300	2.21	0.09	2.12	0.40	1.72
1/30	1.76	0.01	1.75	0.01	1.74
1/10	1.53	0.01	1.52	0.10	1.42

Schellinkhout

Near Schellinkhout another point of Hydra-NL is located. This point is located 500 meters from the foreland. The foreland itself is 400 meters long and the orientation is about 170 degrees. Furthermore, this winter levee is as well covered with grass and therefore the roughness factor has a value of 1.0. By using these values together with the elevation, hydraulic loads are computed. Most of the time, the wind blows the water away from the coast and therefore wave run-up and wind set up are both relatively small.

Table 5.4: Hydraulic loads together with water level, wave run-up and wind set up for Schellinkhout in which flexible water level management is not included.

Exceedance probability [/year]	Hydraulic load [m NAP]	Wave run-up [m]	Water level [m NAP]	Lake water level [m NAP]	Wind set up [m]
1/10,000	1.21	0.19	1.02	0.79	0.23
1/1,000	0.78	0.04	0.74	0.38	0.36
1/300	0.62	0.01	0.61	0.23	0.38
1/30	0.40	0	0.4	0.02	0.38
1/10	0.29	0	0.29	-0.08	0.37

5.3.2 Consequences defined per case study area

Water damages are computed with the help of the Waterschadeschatter for the situation in which flexible water level management is excluded.

Parkhaven

In *Table 5.5* total water damage, flood risk and flood risk per hectare for the residential area Parkhaven can be found. Roads and houses are located at an elevation above 1.5 m NAP. Therefore, for exceedance probabilities of 1/10 and 1/30 years, the recovery time of roads and houses is equal to zero. The spring set up takes place in March, and therefore the probability to reach high water levels is largest in this month. When looking to flood risk, an event with an exceedance probability of 1/1,000 years has the largest flood risk, since Parkhaven will be flooded during such an event. For Parkhaven, extreme events are most important and the total flood risk is 2,500 €/year.

In *Figure 5.5*, the inundation map for Parkhaven is presented for an hydraulic load of 1.83 m NAP and an exceedance probability of 1/1,000 years. Inundation maps together with the inundated area for the remaining four hydraulic loads can be found in *Appendix B*. This appendix shows inundation maps for the situation in which flexible water level management is excluded and included. From the inundation maps can be concluded that Parkhaven will experience inundation for return periods T=1,000 years and T=10,000 years and Genemuiden and Schellinkhout will already be flooded for a return period of T=10 years.

Table 5.5: Total water damage and flood risk in Parkhaven.

Exceedance probability [/year]	Hydraulic load [m NAP]	Duration of nuisance [hours]	Recovery time of roads [days]	Recovery time of buildings [days]	Month of occurrence [month]	Total water damage [€]	Flood risk [€/y]	Flood risk per hectare [€/ha/y]
1/10,000	2.98	48	5	10	March	4,000,000	400	80
1/1,000	1.83	24	2	5	March	1700	2,000	400
1/300	1.50	12	1	0	March	600	2	0.5
1/30	1.12	6	0	0	March	150	10	2
1/10	0.94	3	0	0	March	50	5	1

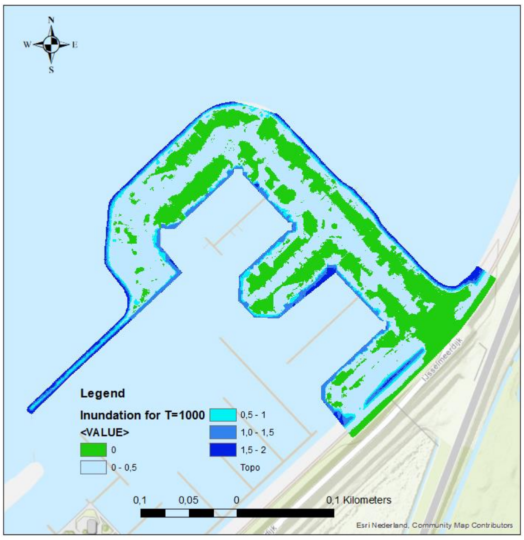


Figure 5.5: Inundation map Parkhaven for an hydraulic load of 1.83 m NAP.

Genemuiden

Table 5.6 shows total water damage, flood risk and flood risk per hectare for the area outside primary levees near Genemuiden. Some houses and farms are situated in the pasturelands. Above 2.0 m NAP, farms and houses experience damage. Therefore, the total water damage massively increases. Looking to flood risk, an event with an exceedance probability of 1/30 years has the largest flood risk, because the whole area including houses and farms will get inundated. The total flood risk for Genemuiden is 1,410 €/year. In *Figure 5.6*, the inundation map for an hydraulic load of 2.21 m NAP can be seen for which houses and farms are flooded. Inundation maps for the remaining hydraulic loads together with their inundated area, can be found in *Appendix B*.

Table 5.6: Total water damage and flood risk in the area outside primary levees near Genemuiden.

Exceedance probability [/year]	Hydraulic load [m NAP]	Duration of nuisance [hours]	Recovery time of roads [days]	Recovery time of buildings [days]	Month of occurrence [month]	Total water damage [€]	Flood risk [€/y]	Flood risk per hectare [€/ha/y]
1/10,000	2.65	48	2	5	March	104,000	10	0.1
1/1,000	2.29	24	2	2	March	90,000	90	0.5
1/300	2.21	12	1	2	March	74,000	190	1.3
1/30	1.76	6	1	0	March	400	1,100	7.4
1/10	1.53	3	1	0	March	100	20	0.1

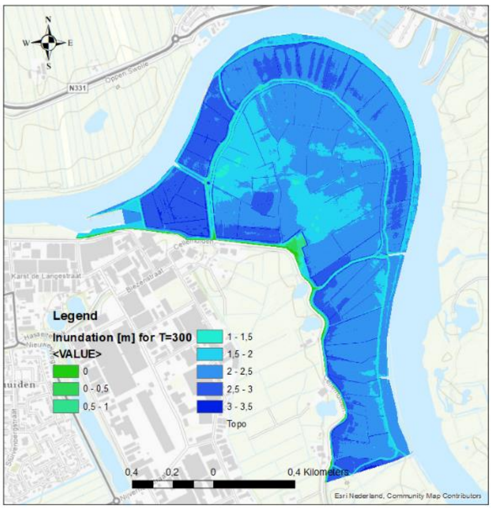


Figure 5.6: Inundation map of Genemuiden for an hydraulic load of 2.21 m NAP.

Schellinkhout

The total water damage, flood risk and flood risk per hectare for the nature and recreation area near Schellinkhout stays relatively low. This is mainly due to the fact that there are no houses or farms present. Only one road is present, which leads to the parking lot. Most damage is caused by destroying meadow hay for a duration of nuisance longer than 12 hours. The inundation map for an hydraulic load of 0.29 m NAP with an exceedance probability of 1/10 years can be seen in *Figure 5.7*. The remaining inundation maps are shown in *Appendix B*. Lastly, smaller and frequent events do have the largest flood risk in Schellinkhout, since the area will already be flooded for an hydraulic load with a return period of 10 years and the total flood risk excluding flexible water level management is 19 €/year.

Table 5.7: Total water damage and flood risk in the nature and recreation area near Schellinkhout.

Exceedance probability [/year]	Hydraulic load [m NAP]	Duration of nuisance [hours]	Recovery time of roads [days]	Recovery time of buildings [days]	Month of occurrence [month]	Total water damage [€]	Flood risk [€/y]	Flood risk per hectare [€/ha/y]
1/10,000	1.21	48	2	0	March	4,900	0.5	0.01
1/1,000	0.78	24	1	0	March	3,300	3.7	0.08
1/300	0.62	12	1	0	March	280	4.2	0.09
1/30	0.40	6	1	0	March	110	6.0	0.13
1/10	0.29	3	0	0	March	40	5.0	0.11

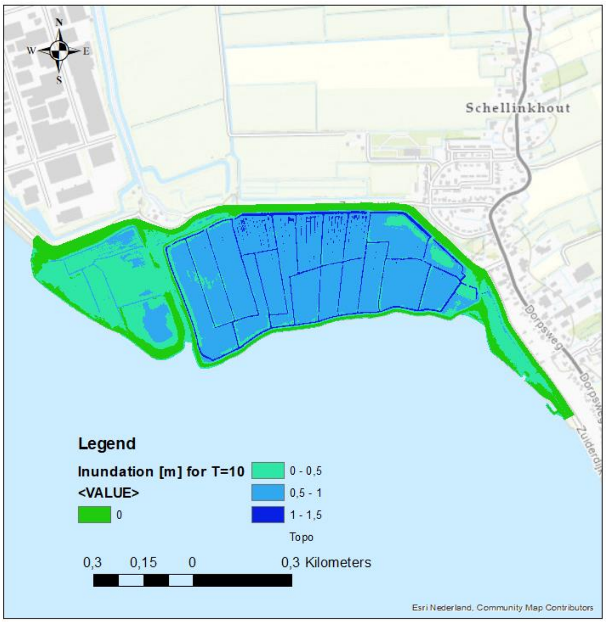


Figure 5.7: Inundation map of Schellinkhout for an hydraulic load of 0.29 m NAP.

5.4 Results including flexible water level management

5.4.1 Calculated hydraulic loads from Hydra-NL

In this section, computed hydraulic loads from Hydra-NL, in which the current water level decree is taken into account, are presented for the three case study areas. The only difference in the input in Hydra-NL, compared to the situation excluding flexible water level management, is that a climate scenario is added in which the lake water level is increased with 10 centimetres. This increase of 10 centimetres water level is applied to show the impact of flexible water level management for which the upper boundary of the bandwidth is reached. This will result in an overestimation, since for most of the time the water level will stay inside the bandwidth between the lower and upper boundary.

Parkhaven

The prevailing wind direction in Hydra-NL comes from the northwest. Negative lake water levels with respect to NAP are typical for the IJsselmeer during a heavy storm with low lake water levels and high wind velocities.

Table 5.8: Hydraulic loads for Parkhaven in which flexible water level management is included.

Exceedance probability [/year]	Hydraulic load [m NAP]	Wave run-up [m]	Water level [m NAP]	Lake water level [m NAP]	Wind set up [m]
1/10,000	3.18	0.90	2.28	-0.09	2.37
1/1,000	1.99	0.20	1.79	-0.08	1.87
1/300	1.62	0.03	1.59	-0.07	1.66
1/30	1.21	0.01	1.20	0.26	0.94
1/10	1.03	0.00	1.03	0.31	0.72

Genemuiden

Westerly winds are the prevailing wind direction. Therefore, wind pushes the water into het Ketelmeer and het Zwarte Meer and, as a result, wind set up is relatively large.

Table 5.9: Hydraulic loads for Genemuiden in which flexible water level management is included.

Exceedance probability [/year]	Hydraulic load [m NAP]	Wave run-up [m]	Water level [m NAP]	Lake water level [m NAP]	Wind set up [m]
1/10,000	2.72	0.27	2.45	0.79	1.66
1/1,000	2.35	0.04	2.31	0.59	1.72
1/300	2.17	0.02	2.15	0.52	1.63
1/30	1.82	0.00	1.82	0.40	1.42
1/10	1.59	0.00	1.59	0.27	1.32

Schellinkhout

Most of the time, wind comes from the west-southwest. As a consequence, wind blows the water away from the coast of Schellinkhout and therefore both wave run-up and wind set up are relatively small.

Table 5.10: Hydraulic loads for Schellinkhout in which flexible water level management is included.

Exceedance probability [/year]	Hydraulic load [m NAP]	Wave run-up [m]	Water level [m NAP]	Lake water level [m NAP]	Wind set up [m]
1/10,000	1.38	0.27	1.11	0.84	0.27
1/1,000	0.94	0.11	0.83	0.57	0.26
1/300	0.74	0.03	0.71	0.47	0.24
1/30	0.49	0.00	0.49	0.12	0.37
1/10	0.39	0.00	0.39	-0.01	0.40

5.4.2 Consequences defined per case study area

Water damages arising by applying flexible water level management are computed with the help of the Waterschadeschatter. Finally, the total water damage in euros is obtained.

Parkhaven

In *Table 5.11* total water damage, flood risk and flood risk per hectare for the residential area Parkhaven, by applying flexible water level management, can be found. What strikes is the fact that for an event with an exceedance probability of 1/1,000 years the total water damage is much larger than for the case in which flexible water level management is excluded. Therefore, flood risk has increased for an event with an exceedance probability of 1/300 years. The total flood risk for Parkhaven including flexible water level management is 2,700 €/year, an increase of 8% with respect to the case in which flexible water level management was not applied. In *Figure 5.8,* the inundation map for Parkhaven is presented for an hydraulic load of 1.99 m NAP associated to an exceedance probability of 1/1,000 years. For this water level, streets and houses experience inundation of about 0.5 meters.

Table 5.11: Total water damage and flood risk in Parkhaven in which flexible water level management is taken into account.

Exceedance probability [/year]	Hydraulic load [m NAP]	Duration of nuisance [hours]	Recovery time of roads [days]	Recovery time of buildings [days]	Month of occurrence [month]	Total water damage [€]	Flood risk [€/y]	Flood risk per hectare [€/ha/y]
1/10,000	3.18	48	5	10	March	4,000,000	400	80
1/1,000	1.99	24	2	5	March	235,000	2,000	400
1/300	1.62	12	1	1	March	650	300	50
1/30	1.21	6	0	0	March	155	10	2
1/10	1.03	3	0	0	March	50	5	1

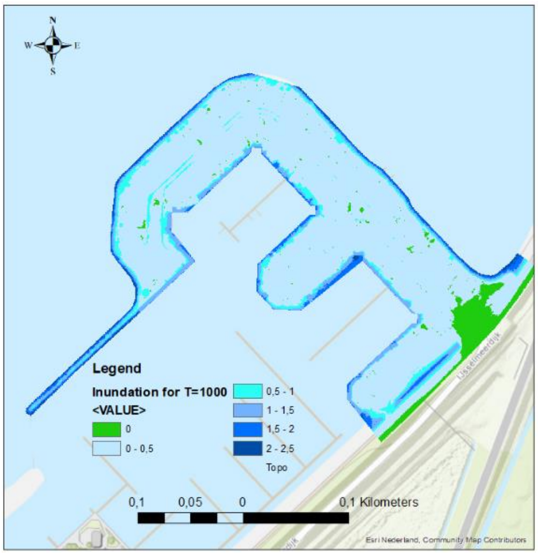


Figure 5.8: Inundation map of Parkhaven for an hydraulic load of 1.99 m NAP.

Genemuiden

Table 5.12 shows total water damage, flood risk and flood risk per hectare for the pasturelands near Genemuiden for which flexible water level management is included. In *Figure 5.9,* the inundation map for an hydraulic load of 2.17 m NAP can be seen. The value for the hydraulic load is smaller than when the former water level decree was active. This has to do with smaller wind set up and wave run-up. Also for the case in which flexible water level management is included, flood risk for an event with an exceedance probability of 1/30 years is most important and the total flood risk for Genemuiden has slightly changed to 1,430 €/year.

Table 5.12: Total water damage and flood risk in the area outside primary levees near Genemuiden in which flexible water level management is taken into account.

Exceedance probability [/year]	Hydraulic load [m NAP]	Duration of nuisance [hours]	Recovery time of roads [days]	Recovery time of buildings [days]	Month of occurrence [month]	Total water damage [€]	Flood risk [€/y]	Flood risk per hectare [€/ha/y]
1/10,000	2.72	48	2	5	March	105,000	11	0.1
1/1,000	2.35	24	2	2	March	90,000	100	0.6
1/300	2.17	12	1	2	March	76,000	200	1.5
1/30	1.82	6	1	0	March	400	1,100	7.5
1/10	1.59	3	1	0	March	100	20	0.1

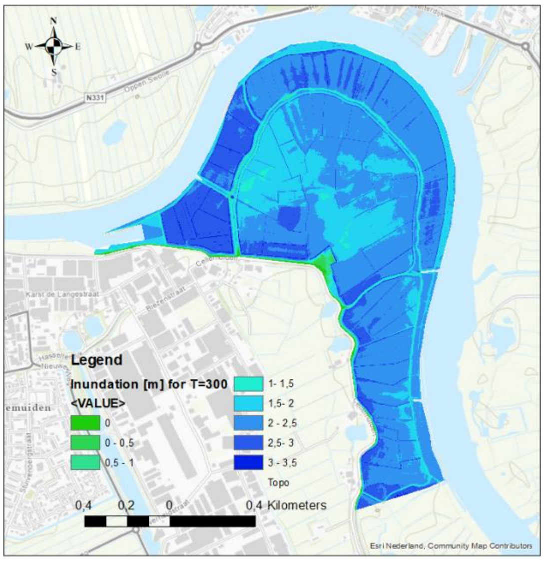


Figure 5.9: Inundation map of Genemuiden for an hydraulic load of 2.17 m NAP.

Schellinkhout

The total water damage, flood risk and flood risk per hectare for the nature and recreation area near Schellinkhout can be seen in *Table 5.13* and stays relatively low because there is almost no economic value to protect. The inundation map for an hydraulic load of 0.39 m NAP, associated to an exceedance probability of 1/10 years, can be seen in *Figure 5.10*. Again, smaller and frequent events do have the largest flood risk in Schellinkhout and the total flood risk is 20 €/year.

Table 5.13: Total water damage and flood risk in case study area Schellinkhout in which flexible water level management is taken into account.

Exceedance probability [/year]	**Hydraulic load [m NAP]**	**Duration of nuisance [hours]**	**Recovery time of roads [days]**	**Recovery time of buildings [days]**	**Month of occurrence [month]**	**Total water damage [€]**	**Flood risk [€/y]**	**Flood risk per hectare [€/ha/y]**
1/10,000	1.38	48	2	0	March	4,900	0.5	0.01
1/1,000	0.94	24	2	0	March	3,400	3.8	0.08
1/300	0.74	12	1	0	March	300	4.3	0.10
1/30	0.49	6	1	0	March	120	6.2	0.14
1/10	0.39	3	0	0	March	45	5.5	0.12

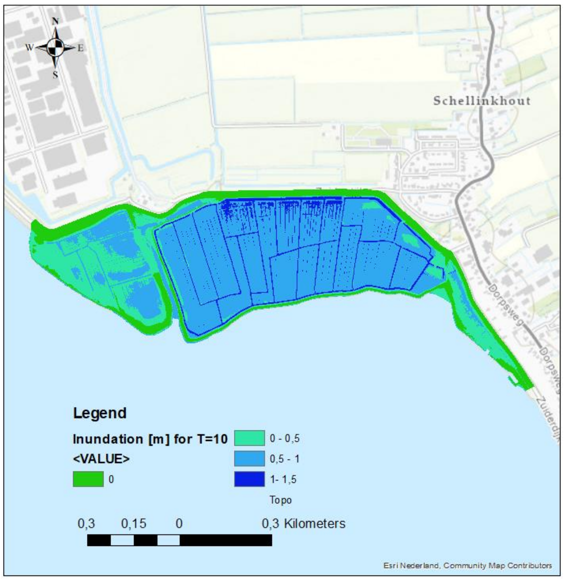


Figure 5.10: Inundation map of Schellinkhout for an hydraulic load of 0.39 m NAP.

5.5 Comparing results including and excluding flexible water level management

Starting by comparing components that make up the hydraulic load of Parkhaven for the current water level decree with the former water level decree, the wave run-up and lake water level are higher when flexible water level management is included. However, wind set up stays more or less constant. Finally, the total hydraulic loads are higher when flexible water level management is applied. In *Figure 5.11,* hydraulic components can be compared for the case in which flexible water level management is included and excluded for case study area Parkhaven.

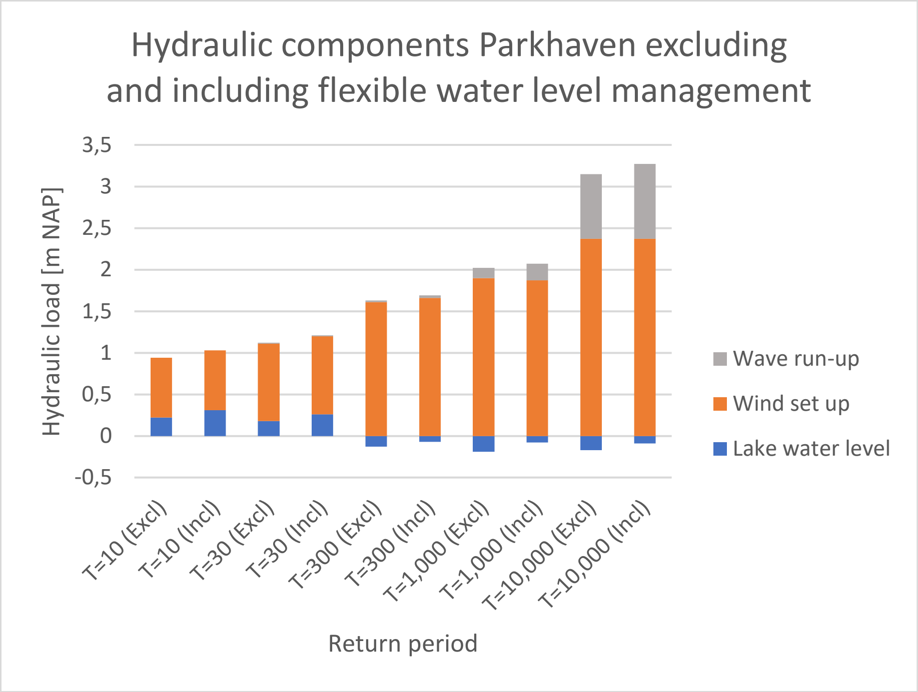


Figure 5.11: Hydraulic components Parkhaven excluding and including flexible water level management.

For Genemuiden, hydraulic loads for the situation in which flexible water level management is applied are higher, as can be seen in *Figure 5.12*. There is only one exception. The return period of 300 years shows a smaller hydraulic load. This has to do with the smaller wind set up and wave run-up compared to the case in which flexible water level management is excluded. If lake water level increases, the wave height decreases and thus wave run-up drops. However, it is a combination of factors which determines the rise or decrease of hydraulic components. Furthermore, in general lake water level and wave run-up are larger when flexible water level management is applied. Wind set up is smaller which seems logical, since in *Equation 3.1* to calculate wind set up, water depth is located in the denominator and for a larger water depth, wind set up becomes smaller.

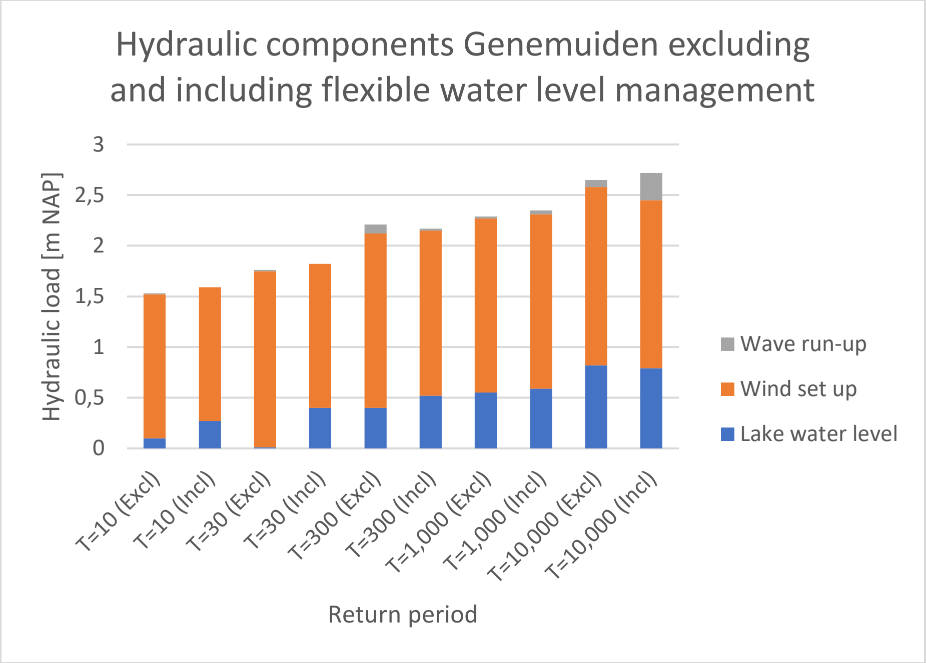


Figure 5.12: Hydraulic components Genemuiden excluding and including flexible water level management.

Lake water level and wave run-up are larger when flexible water level management is applied for case study area Schellinkhout. Again, wind set up is smaller, because of the larger water depth which arises by applying flexible water level management. The smaller wind set up does not balance the components which become larger and therefore hydraulic loads are larger when flexible water level management is applied, which can be seen in *Figure 5.13.*

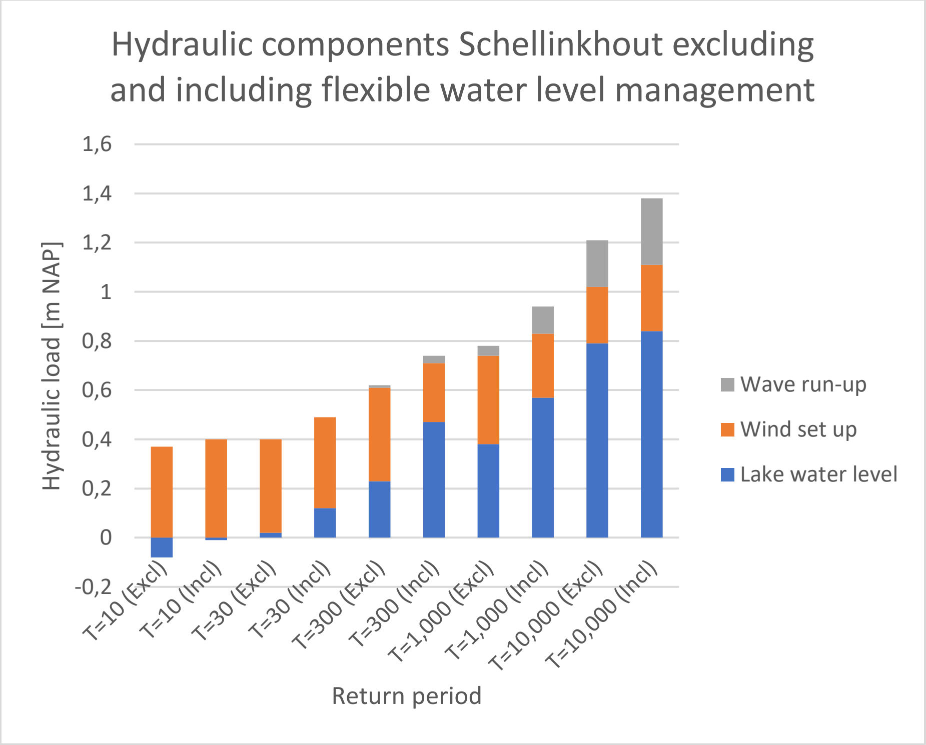


Figure 5.13: Hydraulic components Schellinkhout excluding and including flexible water level management.

In *Figure 5.14*, the flood risk per hectare for the selected return periods for the three case study areas excluding and including flexible water level management is plotted on a logarithmic scale. From the figure can be concluded that Parkhaven has the largest total flood risk per hectare and increases with 10% when flexible water level management is included. Furthermore, the total flood risk per hectare for Genemuiden is much lower than for Parkhaven and the total flood risk per hectare barely changes when flexible water level management is applied. Lastly, Schellinkhout has the lowest total flood risk per hectare and smaller and frequent events contribute most to the total flood risk. For both Genemuiden and Schellinkhout the total flood risk per hectare increases with less than 3% by applying flexible water level management.

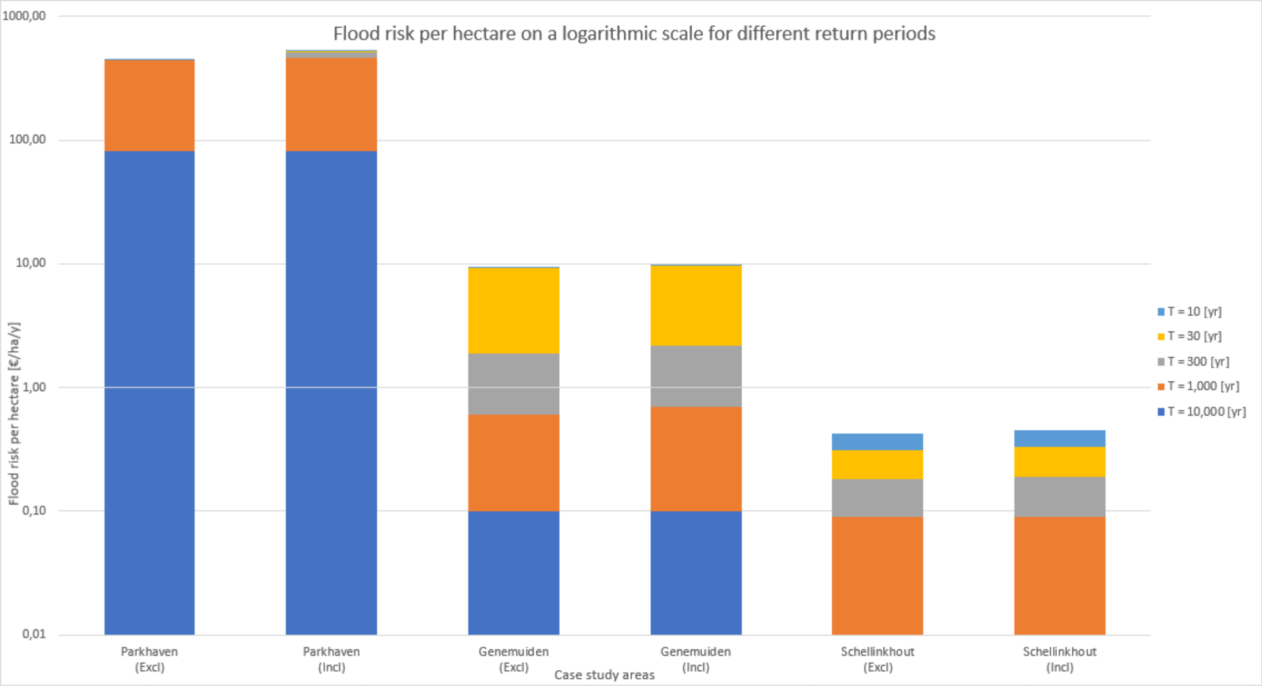


Figure 5.14: Flood risk per hectare for different return periods for Parkhaven, Genemuiden and Schellinkhout excluding and including flexible water level management on a logarithmic scale.

5.6 Sensitivity analysis

Since Hydra-NL is such a black box, a sensitivity analysis is carried out to get insight in the system behaviour and important parameters. Performing a sensitivity analysis is based on changing one input in the model and observing the changes in the behaviour of the model (Dikov, 2020). The following steps are executed in the sensitivity analysis for wind set up and wave run-up (Dikov, 2020):

1. Define the basis of the model.
2. Compute the output variable for a new input variable while leaving other input values unchanged.
3. Calculate sensitivity by dividing the %-change in the output variable over the %-change in the input variable.

Wind set up

Wind set up is calculated using *Equation 3.1*: $W = 0.5 * \kappa * \frac{u_{10}^2}{gh} * F * \cos(\phi)$.

Only the wind velocity at 10 meters height, the water depth, the fetch length and the angle between the land and the wind can be changed. The higher the computed sensitivity, the more sensitive the output is to changes in the input. In *Table 5.14* can be seen that wind velocity has the highest sensitivity and the angle between the land and the wind the lowest sensitivity.

Table 5.14: Sensitivity analysis for wind set up.

	Base case	Changing wind velocity	Changing water depth	Changing fetch length	Changing angle
Wind velocity [m/s]	10	*20*	10	10	10
Water depth [m]	3	3	*4*	3	3
Fetch length [m]	10,000	10,000	10,000	*30,000*	10,000
Angle [°]	30	30	30	30	*60*
Result of calculation	0.05	0.2	0.04	0.15	0.03
Sensitivity		3	0.6	1	0.4

Wave run-up

The maximum wave run-up can be computed with *Equation 3.3*:

$$R_{u2\%} = \left(1.0 * \gamma_f * \gamma_\beta \left(4 - \frac{1.5}{\sqrt{\gamma_b * \xi_{m-1.0}}}\right)\right) * H_{m0}$$

The influence factor for roughness (γ_f), the influence factor for oblique wave attack (γ_β), the influence factor for berm (γ_b), the breaker parameter ($\xi_{m-1.0}$) and the wave height (H_{m0}) are changed one by one to determine their sensitivity. The chosen base case values, are the numbers gained from the *Manual on wave overtopping (van der Meer et al., 2018)*. The influence factor for roughness, together with the wave height, do have the highest sensitivity. The influence factor for berm has the lowest sensitivity, which can be seen in the *Table 5.15*.

Table 5.15: Sensitivity analysis for wave run-up.

	Base case	**Changing γ_f**	**Changing γ_β**	**Changing γ_b**	**Changing $\xi_{m-1.0}$**	**Changing H_{m0}**
γ_f [-]	0.40	*0.5*	0.4	0.40	0.4	0.4
γ_β [-]	0.86	0.86	*0.9*	0.86	0.86	0.86
γ_b [-]	0.65	0.65	0.65	*0.7*	0.65	0.65
$\xi_{m-1.0}$ [-]	1.8	1.8	1.8	1.8	*2.5*	1.8
H_{m0} [m]	0.4	0.4	0.4	0.4	0.4	*0.8*
Result calculation	0.36	0.45	0.37	0.36	0.39	0.72
Sensitivity		1	0.6	0.13	0.21	1

5.7 Extrapolation GIS analysis to whole IJsselmeer region

Water levels for the points in Hydra-NL are interpolated for the return periods T=10, T=30, T=300, T=1,000 and T=10,000 years and their associated inundated areas for the case in which flexible water level management is excluded, *Table 5.16*, and included, *Table 5.17*, are derived. In *Figure 5.15*, two maps can be found. One map visualizes the inundated land for interpolated water levels excluding flexible water level management and one map envisions the inundated area for interpolated water levels including flexible water level management for the return periods mentioned at the beginning of this section. From the maps can be concluded that the total inundated area excluding and including flexible water level management hardly differs. However, looking to inundated buildings and infrastructure areas for an exceedance probability of 10,000 years, the inundated area increases with 30% when flexible water level management is included. Because buildings and infrastructure areas cover less than 3% of all areas outside primary levees in the IJsselmeer region, the total inundated area including and excluding flexible water level management looks very similar.

Table 5.16: Inundated areas excluding flexible water level management for the IJsselmeer region.

Return period [years]	Interpolated water level [m NAP]	Inundated area [ha]	Inundated buildings and infrastructure areas [ha]	Inundated pasturelands [ha]	Inundated recreation areas [ha]	Inundated nature areas [ha]
10,000	1.71	13,743	143	10,443	1,006	2,151
1,000	1.37	12,972	59	10,029	809	2,104
300	1.20	12,623	44	9,800	704	2,075
30	0.91	11,830	27	9,283	498	2,022
10	0.76	11,297	18	8,905	392	1,982

Table 5.17: Inundated areas including flexible water level management for the IJsselmeer region.

Return period [years]	Interpolated water level [m NAP]	Inundated area [ha]	Inundated buildings and infrastructure areas [ha]	Inundated pasturelands [ha]	Inundated recreation areas [ha]	Inundated nature areas [ha]
10,000	1.86	14,004	194	10,590	1,054	2,166
1,000	1.51	13,311	95	10,186	898	2,132
300	1.33	12,926	54	9,991	784	2,097
30	1.03	12,878	33	9,504	592	2,049
10	0.86	11,695	24	9,196	464	2,011

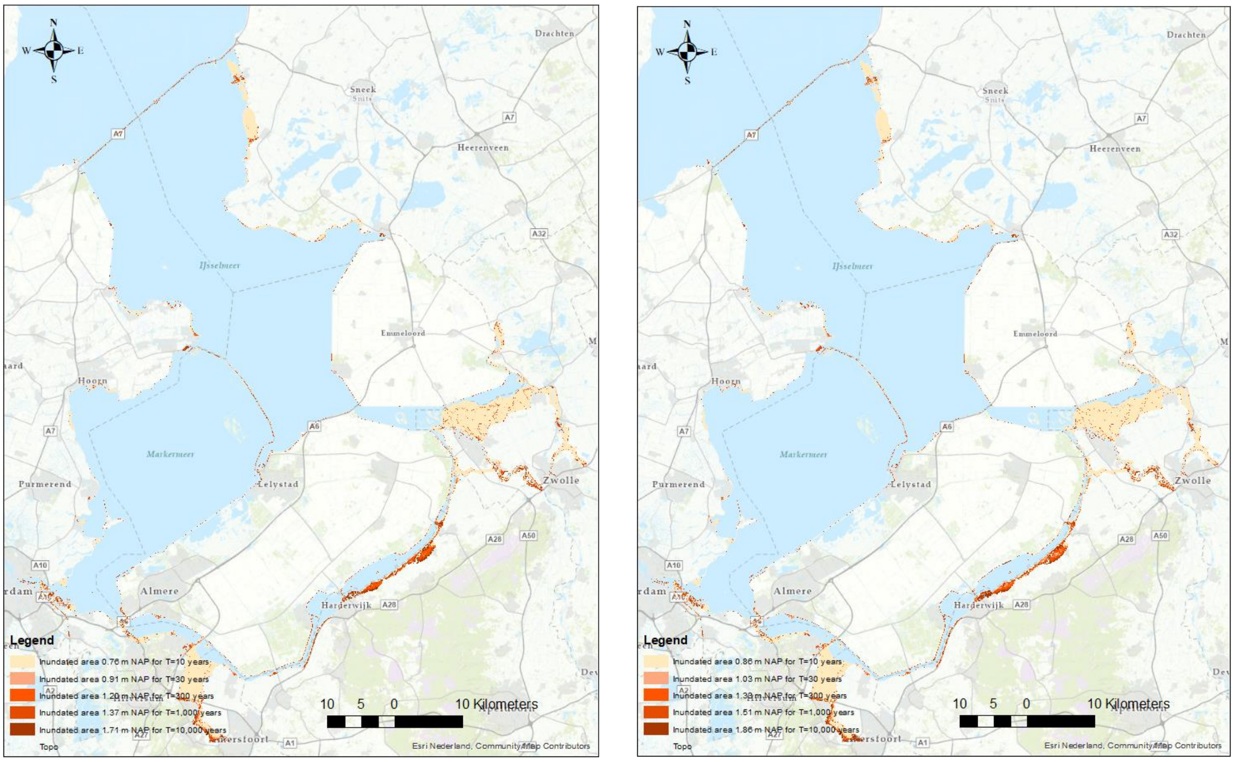


Figure 5.15: Inundated land excluding (left) and including (right) flexible water level management for five return periods.

The default water damage table from STOWA is used to calculate water damage and flood risk in the whole IJsselmeer region for the case in which flexible water level management is excluded and included. Total water damage is calculated using the damage function presented in *Equation 3.10.* In *Table 5.18,* water damage for each function class is presented together with total water damage and flood risk in the IJsselmeer region for the case in which flexible water level management is excluded. *Table 5.19* shows water damages and flood risks for the scenario in which flexible water level management is included. From the tables can be concluded that water damage in buildings and infrastructure areas, and then especially water damage from residential areas, contributes most to flood risk. Furthermore, the highest flood risk can be found for smaller and frequent events. This is due to the fact that for an interpolated water level associated to a return period of 10 years, a large part of areas outside primary levees will be inundated. The total flood risk when flexible water level management is excluded is 7,854 K€/year and increases to 10,667 K€/year when flexible water level management is included, an increase of almost 3 million euros per year.

Table 5.18: Total water damage, flood risk and water damage for each function class when flexible water level management is excluded.

Return period [years]	Interpolated water level [m NAP]	Average inundation depth [m]	Total water damage [K€]	Flood risk [K€/y]	Water damage buildings and infrastructure areas [K€]	Water damage pasturelands [K€]	Water damage recreation areas [K€]	Water damage nature areas [K€]
10,000	1.71	1.37	582,897	58	562,524	15,651	1,496	3,223
1,000	1.37	1.13	209,698	356	193,706	12,398	992	2,601
300	1.20	1.01	139,199	407	125,306	10,828	772	2,292
30	0.91	0.80	71,849	3,165	61,522	8,124	432	1,769
10	0.76	0.69	44,159	3,866	35,647	6,722	293	1,496

Table 5.19: Total water damage, flood risk and water damage for each function class when flexible water level management is included.

Return period [years]	Interpolated water level [m NAP]	Average inundation depth [m]	Total water damage [K€]	Flood risk [K€/y]	Water damage buildings and infrastructure areas [K€]	Water damage pasturelands [K€]	Water damage recreation areas [K€]	Water damage nature areas [K€]
10,000	1.86	1.48	843,340	84	820,993	17,146	1,694	3,507
1,000	1.51	1.23	354,997	539	337,652	13,706	1,072	2,565
300	1.33	1.10	182,442	627	166,959	12,023	936	2,523
30	1.03	0.89	95,062	4,162	83,245	9,253	572	1,995
10	0.86	0.77	62,563	5,254	52,734	7,746	388	1,694

5.8 Validation Hydra-NL

Water damage and flood risk are based on outcomes from Hydra-NL. Water level series from measurement stations close to Parkhaven, Genemuiden and Schellinkhout have been requested from Rijkswaterstaat to check whether water levels from Hydra-NL are matching occurred water levels. In *Figures 5.16, 5.17* and *5.18* the data series available for each location are shown together with the exceedance probability of 1/10 years excluding and including flexible water level management obtained from Hydra-NL. Comparing occurred water levels with water levels from Hydra-NL, occurred water levels are lower than water levels computed in Hydra-NL for the three case study areas. Furthermore, discrepancy between water levels calculated in Hydra-NL and occurred water levels probably has to do with calibration of Hydra-NL. Only main, important hydraulic structures are used for calibration and certainly not the three case study areas. Another reason that occurred water levels are not matching the results from Hydra-NL, is that Hydra-NL has to deal with model uncertainties and statistical uncertainties (M. Duits (Hydra-NL expert), email, September 2nd 2021). Lastly, with respect to hydraulic loads, different choices have been made for the determination of the storm surge duration in the lakes, which also could induce deviating water levels (M. Duits (Hydra-NL expert), email, September 2nd 2021).

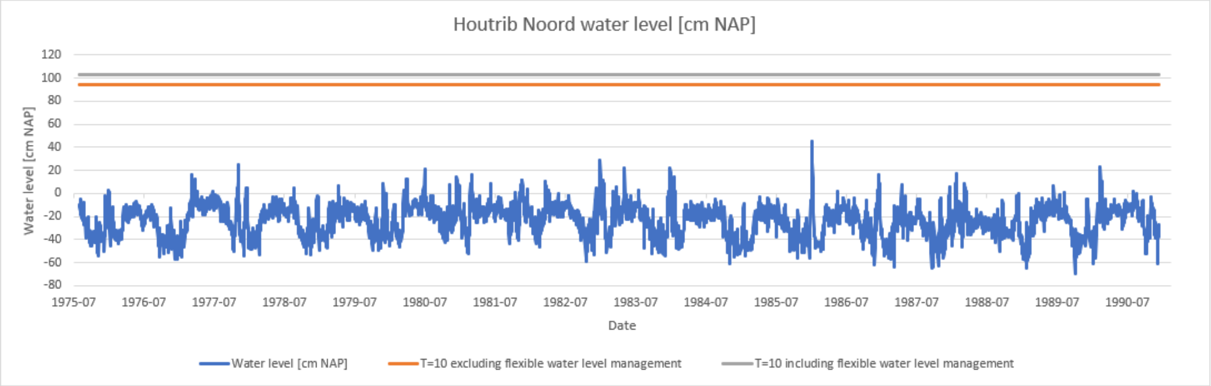


Figure 5.16: Water level data of measurement station Houtrib Noord from 1975 until 1990 in cm NAP. An exceedance probability of 1/10 years excluding flexible water level management has a water level of 0.94 m NAP and an exceedance probability of 1/10 years including flexible water level management has a water level of 1.03 m NAP.

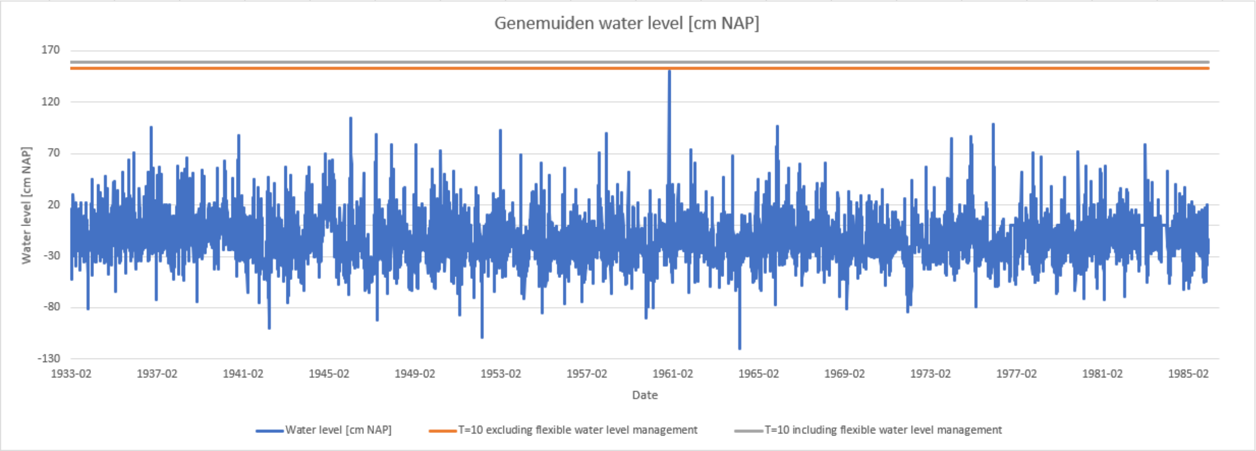


Figure 5.17: Water level data of measurement station de Genemuiden – De Ketting from 1933 until 1985 in cm NAP. An exceedance probability of 1/10 years excluding flexible water level management has a water level of 1.53 m NAP and an exceedance probability of 1/10 years including flexible water level management has a water level of 1.59 m NAP.

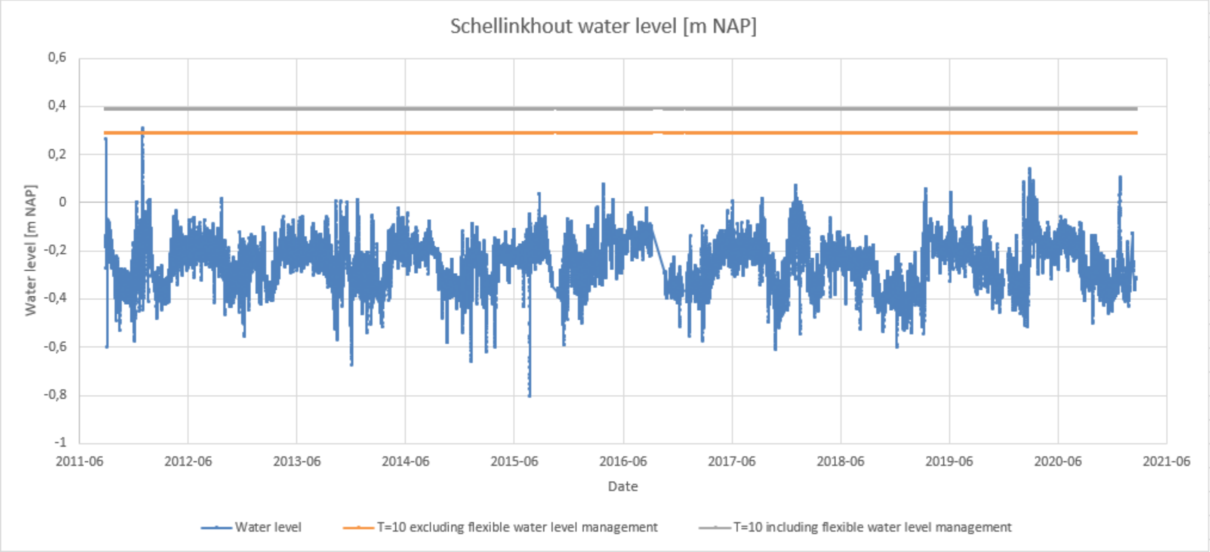


Figure 5.18: Water level data of pumping station Schellinkhout from 2011 until 2020 in m NAP. An exceedance probability of 1/10 years excluding flexible water level management has a water level of 0.29 m NAP and an exceedance probability of 1/10 years including flexible water level management has a water level of 0.39 m NAP.

In section 4.3.4, water levels before applying flexible water level management for the case study areas are presented together with the 90 and 10 percentiles water level during summer. Starting with Parkhaven, for 90% of the time the water level is below -8 cm NAP and for 10% of the time the water level is below -25 cm NAP. Comparing this result with water levels obtained from Hydra-NL associated to a return period of 10 years, again it can be concluded that there is a large deviation between water levels computed in Hydra-NL and occurred water levels. Also for Genemuiden and Schellinkhout there is a large difference between the 90 and 10 percentiles water level during summer and the water levels calculated in Hydra-NL, which makes the results obtained from Hydra-NL less reliable.

6. Water damage mitigation strategies

In this chapter, water damage mitigation strategies for the case study areas, resulting from the focus group discussion, are presented. These mitigation strategies are made up using water levels computed in Hydra-NL, which are higher than occurred water levels. Section 6.1 shows the effect of using pumps in the Afsluitdijk. Next, in section 6.2, water damage mitigation strategies before flexible water level management was implemented are discussed and in section 6.3 water damage mitigation strategies by applying flexible water level management are provided. Moreover, in section 6.4, water damage mitigation strategies are presented for the scenario in which the target water level is elevated with 20 cm. Lastly, in section 6.5, two mitigation strategies are discussed on national scale.

6.1 Pump capacity versus extreme discharge IJssel

Before applying structural measures, the ratio between extreme discharges from the river IJssel and the pump capacity of new pumps in the Afsluitdijk, which should be ready in 2022, is discussed. An extreme discharge of 1,500 m^3/s in the IJssel (Rijkswaterstaat waterinfo, 2021), which has a return period of 30 years calculated in Hydra-NL, leads to an increase of 11.8 cm/day by taking a surface area of 1,100 km^2 for the IJsselmeer. The total pump capacity, without water release under the influence of gravity, is 235 m^3/s (Deltaprogramma IJsselmeergebied, 2018) which leads to a water level decrease of 1.8 cm/day. Water release under the influence of gravity depends on the sea level and is not always possible. Therefore, water release under the influence of gravity is not taken into account in the calculation. So, during extreme discharges from the IJssel and a full pump capacity, the water level in the IJsselmeer increases with 10 cm/day. When the lower boundary of the bandwidth during winter of -0.40 m NAP is maintained, peak discharges with a duration of 5 days will increase the water level to 0.1 m NAP. Most areas outside primary levees are located above 0.1 m NAP. However, by also taking into account wind set up and wave run-up, inundation cannot be excluded. When extreme discharges from the IJssel are encountered during the spring set up, inundation is inevitable. However, peaks in discharge are forecasted days in advance and the spring set up will be delayed when high discharges are expected. The water level cannot drop below -0.40 m NAP to create extra water storage, because stability problems may arise for shores and levees. To conclude, extreme discharges from the IJssel cannot be pumped away and, even with the arrival of pumps in the Afsluitdijk, there are not enough steering wheels yet to control water levels in the IJsselmeer.

6.2 Water damage mitigation strategies before applying flexible water level management

In 2009, the concept of multi-layered water safety was introduced in “het Nationaal Waterplan” to create a water safety policy for inundation from the main water system. The multi-layered water safety consists of three layers. The first layer is prevention of inundation, the second layer focusses on a sustainable spatial planning and the third layer aims for a better preparation when high water levels are expected. These three layers are discussed when working out mitigation strategies.
At the time of construction it was decided to build the houses in Parkhaven at a higher elevation (spatial planning). Houses and roads in Parkhaven are located above 1.5 m NAP for which the probability of exceedance is 1/1,000 years. Pasturelands outside primary levees near Genemuiden are part of the floodplains and are allowed to inundate. However, farmers and some residents do live here. Therefore, two summer levees were build, which belong to the first layer in the multi-layered water safety. In addition, because this area consists of pasturelands and almost no agriculture, the second layer is taken into account as well. Lastly, one summer levee was built in the area outside

primary levees near Schellinkhout to prevent the area against water damage. This is a first layer water damage mitigation strategy. The area has a low economic value and therefore inundation is not a big deal looking to the second layer of the multi-layered water safety.

6.3 Water damage mitigation strategies by applying flexible water level management

Houses in Parkhaven are located at an elevation above 1.5 m NAP. It was a conscious decision to build the residential area outside primary flood defences and was designed way before even was thought about applying flexible water level management. The probability that houses will get inundated is changed to 1/300 years which follows from this research. If such events take place, water damage can be mitigated by reinforcing the current bank protection by elevating the maximum height and by making the bank protection less steep to reduce wave run-up, which belongs to the first layer. Looking to the second layer of the multi-layered water safety, below streets an infiltration system can be installed to deal with wave overtopping. The incoming water from the waves can infiltrate into the pipe system which can be pumped away. However, when the water level rises above the residential area, the infiltration system is no longer useful. Lastly, looking to the third layer of the multi-layered water safety, people, cars and other valuable properties can be moved to higher areas when high water conditions are expected.

For the area outside primary levees near Genemuiden the flood risk does not change significantly by applying flexible water level management but hydraulic loads do increase. Because both hydraulic loads are increasing and more extreme weather events will be encountered in the future, different water damage mitigation strategies are presented. To mitigate water damage in the first layer, the inner summer levee can be heightened and widened, but still it must be taken into account that this area is allowed to inundate and therefore the levee should not be elevated infinitely. An elevation of the inner summer levee of 1.82 m NAP, which can mitigate water damage for water levels with return periods up to 30 years, is appropriate to use. A water damage mitigation strategy of the second layer of the multi-layered water safety, is to use a different kind of farming. Lastly, a water damage mitigation strategy in the third layer is to move cattle to higher areas, and when the water depth becomes even larger, also residents and farmers must be evacuated. Therefore, evacuation plans need to be designed.

Also for Schellinkhout the flood risk is not changing significantly by applying flexible water level management, but hydraulic loads do increase. Therefore, different water damage mitigation strategies are presented. The economic value to protect in the area outside primary levees near Schellinkhout is relatively low. However, when the area is inundated for a couple of hours, meadow hay can be destroyed. To mitigate water damage in the first layer, embankments can be raised. Especially the quays near the fence and the small inlet on the eastern side of the area. Since a large part of the area is a nature area, a different type of nature which can resist wet conditions can be chosen in the spatial planning. Lastly for the third layer, when high water conditions are expected, the area can be closed for visitors which does not happen at the moment. Before implementing water damage mitigation strategies, it must be investigated if the costs to mitigate water damage weight against the actual water damage, since water damage in this area is limited.

6.4 Water damage mitigation strategies by elevating target water level with 20 centimetres

Rijkswaterstaat investigates possibilities to retain more fresh water than the 400 million m^3 of fresh water, which is gained by applying flexible water level management, to cope with climate change. When the target water level is elevated with 20 centimetres, a fresh water buffer of 600 million m^3 can be created. However, this scenario is not worked out in detail yet and it is uncertain if and when this scenario will be implemented.
When the target water level is elevated with 20 centimetres, hydraulic loads are larger than when flexible water level management is applied, as can be seen in *Tables 6.1, 6.2* and *6.3*. For Parkhaven, the total flood risk is almost tripled compared to the case in which flexible water level management is applied. Therefore, more structural mitigation strategies must be considered. Because Parkhaven will totally be flooded for events with return periods larger than 300 years, only reinforcing the current bank protection and making it less steep might not be enough anymore. To also mitigate water damage for larger return periods, building a levee surrounding Parkhaven should be considered in the first layer. Because larger water depths will be encountered for smaller return periods, evacuation plans need to be worked out in the third layer of the multi-layered water safety. For Genemuiden and Schellinkhout, the flood risk does not change significantly but water levels do increase. Therefore the same type of water damage mitigation strategies, as presented in section 6.3, can be used to cope with increasing water levels. *Figure 6.1* shows a map in which the water damage mitigation strategies are summarized for the three scenarios.

Table 6.1: Hydraulic loads and flood risks excluding and including flexible water level management, and when the target water level is elevated with 20 centimetres for Parkhaven.

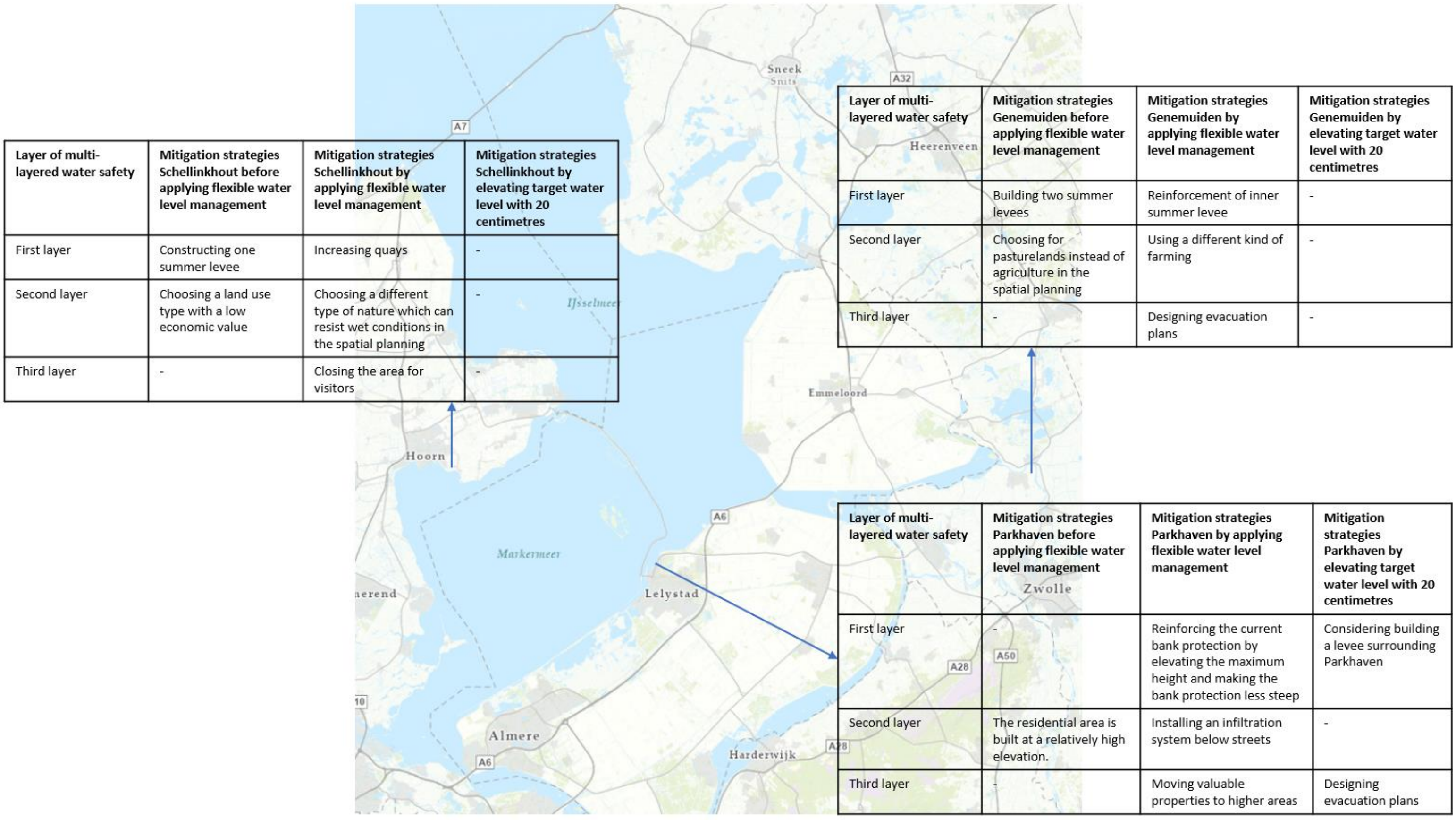
Exceedance probability [/year]	**Hydraulic load excl. flexible water level management [m NAP]**	**Hydraulic load incl. flexible water level management [m NAP]**	**Hydraulic load by elevating target water level with 20 cm [m NAP]**	**Flood risk excl. flexible water level management [€/y]**	**Flood risk incl. flexible water level management [€/y]**	**Flood risk by elevating target water level with 20 cm [€/y]**
1/10,000	2.98	3.18	3.38	400	400	400
1/1,000	1.83	1.99	2.18	2,000	2,000	3,200
1/300	1.50	1.62	1.76	2	300	3,800
1/30	1.12	1.21	1.30	10	10	20
1/10	0.94	1.03	1.12	5	5	10

Table 6.2: Hydraulic loads and flood risks excluding and including flexible water level management, and when the target water level is elevated with 20 centimetres for Genemuiden.

Exceedance probability [/year]	Hydraulic load excl. flexible water level management [m NAP]	Hydraulic load incl. flexible water level management [m NAP]	Hydraulic load by elevating target water level with 20 cm [m NAP]	Flood risk excl. flexible water level management [€/y]	Flood risk incl. flexible water level management [€/y]	Flood risk by elevating target water level with 20 cm [€/y]
1/10,000	2.65	2.72	2.80	10	11	12
1/1,000	2.29	2.35	2.41	90	100	105
1/300	2.21	2.17	2.23	190	200	210
1/30	1.76	1.82	1.87	1,100	1,100	1,100
1/10	1.53	1.59	1.67	20	20	20

Table 6.3: Hydraulic loads and flood risks excluding and including flexible water level management, and when the target water level is elevated with 20 centimetres for Schellinkhout.

Exceedance probability [/year]	Hydraulic load excl. flexible water level management [m NAP]	Hydraulic load incl. flexible water level management [m NAP]	Hydraulic load by elevating target water level with 20 cm [m NAP]	Flood risk excl. flexible water level management [€/y]	Flood risk incl. flexible water level management [€/y]	Flood risk by elevating target water level with 20 cm [€/y]
1/10,000	1.21	1.38	1.54	0.5	0.5	0.5
1/1,000	0.78	0.94	1.07	3.7	3.8	3.8
1/300	0.62	0.74	0.87	4.2	4.3	4.3
1/30	0.40	0.49	0.59	6.0	6.2	6.5
1/10	0.29	0.39	0.49	5.0	5.5	5.8



Layer of multi-layered water safety	Mitigation strategies Schellinkhout before applying flexible water level management	Mitigation strategies Schellinkhout by applying flexible water level management	Mitigation strategies Schellinkhout by elevating target water level with 20 centimetres
First layer	Constructing one summer levee	Increasing quays	-
Second layer	Choosing a land use type with a low economic value	Choosing a different type of nature which can resist wet conditions in the spatial planning	-
Third layer	-	Closing the area for visitors	-

Layer of multi-layered water safety	Mitigation strategies Genemuiden before applying flexible water level management	Mitigation strategies Genemuiden by applying flexible water level management	Mitigation strategies Genemuiden by elevating target water level with 20 centimetres
First layer	Building two summer levees	Reinforcement of inner summer levee	-
Second layer	Choosing for pasturelands instead of agriculture in the spatial planning	Using a different kind of farming	-
Third layer	-	Designing evacuation plans	-

Layer of multi-layered water safety	Mitigation strategies Parkhaven before applying flexible water level management	Mitigation strategies Parkhaven by applying flexible water level management	Mitigation strategies Parkhaven by elevating target water level with 20 centimetres
First layer	-	Reinforcing the current bank protection by elevating the maximum height and making the bank protection less steep	Considering building a levee surrounding Parkhaven
Second layer	The residential area is built at a relatively high elevation.	Installing an infiltration system below streets	-
Third layer	-	Moving valuable properties to higher areas	Designing evacuation plans

Figure 6.1: Map with summarized water damage mitigation strategies for the three scenarios.

6.5 Water damage mitigation strategies on national scale

At the beginning of 2022, pumping stations in the Afsluitdijk should be ready to use. The pumps are necessary to guarantee a sufficient water drainage into the Waddenzee until at least 2050 (Deltaprogramma IJsselmeergebied, 2018). In this way it is easier to control water levels in the IJsselmeer region.

Another water damage mitigation strategy is the room for the river project. The key of the room for the river project is to make space for the river in places where the economic value to protect is limited and at locations where more space is needed. In this way, peaks in water discharge from the river IJssel can be flattened and will have a positive effect on controlling water levels in the IJsselmeer.

7. Discussion

In this chapter the meaning of the results is presented. Section 7.1 presents uncertainties in the modelling approach and section 7.2 describes alternative methods. In addition, section 7.3 discusses external effects affecting flood risk, and section 7.4 discusses water damage after mitigation strategies are implemented qualitatively. Lastly, section 7.5 discusses international flood risk management for different lakes around the world.

7.1 Uncertainties Hydra-NL, Waterschadeschatter and GIS extrapolation

Water levels computed in Hydra-NL are higher than occurred water levels, which makes the results obtained from Hydra-NL less reliable. Therefore, Hydra-NL must be calibrated more locally before any further calculations are carried out. The Delta Commission proposed to use a value for the friction constant kappa of 3.4 E-6 (Delta Commissie, 1991), which is applied in many computations and computer programmes. However, it is more likely that the friction constant is location dependent. By using measurements, insights can be gained in variations of the value of the friction constant kappa. Therefore, for further research it is recommended to calibrate the friction constant kappa with measurements to gain more realistic results from Hydra-NL.

The same results in Hydra-NL are achieved by computing just one location or hundred locations. Therefore, Hydra-NL is applicable for both smaller scale calculations as well as computations on larger scales. However, for the extrapolated GIS analysis, to compute water damage in the whole IJsselmeer region, interpolated water levels are calculated instead of hydraulic loads. This is a simplification, which means that the simulated and actual water levels will be further apart. By taking water levels instead of hydraulic loads, only the wave run-up is not included in the return period budget and therefore it is expected that water levels are overrated, which is counterintuitive. This is due to the fact that for water level calculations the return period is spread only over the water level and for hydraulic loads the return period is spread over the water level and wave run-up. Since for the case study areas hydraulic loads are calculated and for the whole IJsselmeer region water levels are computed, smaller scale calculations in this research show better results than larger scale computations. To also calculate hydraulic loads for the whole IJsselmeer region, the difficulty is found that about 120 levee profiles must be added to finally determine interpolated hydraulic loads.

Water damage is computed in the Waterschadeschatter tool which includes many factors like water depth, duration of nuisance and recovery time of roads and buildings. Also in the Waterschadeschatter uncertainties arise. Firstly, the duration of nuisance of high water levels is used as input for the calculation. The duration of nuisance is just an estimation and can therefore deviate a couple of hours from the actual duration. In addition, the duration of nuisance mainly affects crops when land is inundated for more than 24 hours. Secondly, the recovery time of roads depends on the number of cars that must make a detour when roads are inaccessible and the recovery time of buildings mostly depends on the availability of contractors. In this research, the largest uncertainty can be found for the recovery time of buildings.
AHN3 is used in maps uploaded in the Waterschadeschatter, which has a horizontal resolution of 0.5 by 0.5 meters and is therefore quite accurate. The vertical systematic and stochastic error do both have a maximum deviation of 5 centimetres (AHN, 2021). Furthermore, the IJsselmeer and Markermeer do exist less than 50 years, so events with larger return periods have not occurred yet and therefore it is difficult to predict if water damage for larger return periods shows realistic results.

The Waterschadeschatter takes many effects into account, but does not look at ecological damage, like breeding birds living next to the lake. Breeding birds will suffer by implementing flexible water level management. These birds built their nests next to the lake. According to the research of (Van Riet, 2020) most breeding birds lay their eggs between 5 and 15 cm NAP. Because high water levels will occur more frequently, nests of birds will be destroyed more often. Therefore, it is recommended to also consider ecological damage when computing total water damage.

Due to time issues not every area located outside primary levees could be investigated in detail and therefore the three case study areas are extrapolated to other areas outside primary levees in the IJsselmeer region. To extrapolate the case study areas to other areas located outside primary levees, three uncertainties are encountered. Firstly, the elevation of the case study areas differs from other areas outside primary levees, as can be seen in *Figure 5.1*. Secondly, the function classes are quite generic. A buildings and infrastructure area can consist of a parking lot, a harbour or a residential area, as explained in section 2.1. Therefore, water damage and flood risk in buildings and infrastructure areas can vary a lot and water damage mitigation strategies might be too drastic for other buildings and infrastructure areas outside primary levees. To gain more accurate results, the function of the area must be studied carefully. The third uncertainty lies in terrain features. If for instance, there is a summer levee present, the area outside primary levees can resist higher water levels before inundation occurs.

Function classes of the case study areas are more or less matching the function classes in the IJsselmeer region. However, case study area Parkhaven shows an overestimation regarding water damage compared to other buildings and infrastructure areas. Parkhaven is an area with a residential function, whereas other buildings and infrastructure areas outside primary levees are mainly harbours, parking lots or buildings with a water related function with much lower water damages. Function classes of case study areas Genemuiden and Schellinkhout are matching the function classes appearing in the IJsselmeer region and therefore extrapolation gives better approximations.

7.2 Alternative methods

In this research AHN3 is used, but AHN4 was released during this research. The only difference between AHN4 and AHN3 is that AHN4 has a point density of 10-14 points per square meter, while AHN3 has a point density of 6-10 points per square meter. So, by using AHN4, the accuracy will increase (AHN, 2021). However, in this research the accuracy is trifling, since water levels for a return period of 10 years are already larger than the height of most levees. So water levels do have a larger sensitivity than the AHN in this study.

The scenario of elevating the target water level with 20 cm is described in section 2.4. In this case, both the target water level and bandwidth do increase. However, it might be better to only enlarge the bandwidth and not the target water level. By doing so, too high water levels are prevented and advantages of the extra fresh water buffer remain.

The Waterschadeschatter is used to compute water damage in areas outside primary levees. Another application in which water damage can be calculated after inundation is the *Schade en Slachtoffer Module*. However, this tool does not work for small scale calculations which is needed for the case study areas. Moreover, the *Schade en Slachtoffer Module* also accounts for victims after water damage when water depth increases to 4.0 metres (Van der Vaarst (Master student TU Delft), Skype meeting, October 13 2021). Since water depth does not rise above 4.0 meters in this research, this function does not add any value. Lastly, the *Schade en Slachtoffer Module* is less user-friendly, since maps with flow rates and ascent rates, resulting from SOBEK calculations, must be uploaded.

Therefore, it is recommended to use the Waterschadeschatter for further research about flexible water level management.

7.3 External effects

Subsidence is not taken into account in this research, because of the large difference in order of magnitude. Water levels are namely presented in metres and subsidence is often expressed in millimetres per year. Comparing the subsidence rate in areas outside primary levees (Van Riet, 2021) to sea level rise, the rate of subsidence is 0.5 times smaller or even smaller than the rate of sea level rise of 3.6 mm/year (The Royal Society, 2020).

The changing climate induces higher peak wind speeds which largely determines wind set up, as shown in section 5.6, and therefore water levels can be raised locally. Climate change also induces larger peak discharges in the Dutch rivers. Discharge from the river IJssel depends on discharges from the river Rhine for which peak discharge will increase between 3% and 19% until 2050 (Linde et al., 2011). Since 85.1% of incoming fluxes in the IJsselmeer region is determined by the discharge from the IJssel, as is mentioned in section 2.1, the change of pattern in discharge together with larger wind set up will increase flood risk in areas outside primary levees in the IJsselmeer region.

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 releasing water under the influence of gravity will become harder due to sea level rise. They will guarantee that target water levels can be maintained at least until 2050 (Ter Maat & van Meurs, 2010).

7.4 Water damage after implementing mitigation strategies

Water damage mitigation strategies were discussed during a focus group discussion with 4 experts from WSP with a background in surroundings and environment, water safety, climate adaptation and ecology. These different backgrounds highlight the most important perspectives, but the fields of spatial development, hydrology and meteorology are also very relevant.

After implementing water damage mitigation strategies for Parkhaven by applying flexible water level management, reinforcing the current bank protection could only significantly mitigate water damage when the maximum height is increased to 2.0 m NAP, so half a meter higher than where houses and streets are located. This is due to the fact that the largest flood risk for Parkhaven has an exceedance probability of 1/1,000 years, associated to a water level of 1.99 m NAP. By reinforcing the bank protection, water damage can be mitigated with around 2,000 €/year. An investment is only socially profitable when the cash value of future benefits is larger than the costs (Rijkswaterstaat, 2021). Taking an interest rate of 2%, the cash value is about €100,000. Increasing the bank protection costs about 20 euros per m^3 (Van der Meer, 2019) and Parkhaven has a periphery of 950 meters. Assuming only increasing the bank protection with half a meter, the costs are about €10,000 which is much lower than the cash value. Next, looking to the scenario for which the target water level is elevated with 20 centimetres, designing a levee of 2.20 m NAP surrounding Parkhaven could mitigate water damage with approximately 7,000 €/year associated to a cash value of €350,000. Constructing this levee is only profitable when the building costs are lower than €350,000.

For the area outside primary levees near Genemuiden, only reinforcement of the inner summer levee to 1.82 m NAP over a length of approximately 5 km by applying flexible water level management will mitigate water damage significantly with 1,100 €/year, and will only be economically profitable if reinforcement of the inner summer levee costs less than €55,000. When the target water level is elevated with 20 cm, the same type of mitigation strategies can be used.

For the area near Schellinkhout, water damage stays relatively low. By applying flexible water level management, a quay can be installed which will result in a water damage mitigation of 6.20 €/year. Saving 6.20 €/year is way too little to build a quay and therefore it is recommended to leave the area as it is without mitigation strategies. Also for the case in which the target water level is elevated with 20 cm, it is recommended to accept that the area will inundate once in a while.

Comparing flood risk including flexible water level management to flood risk for which the target water level is elevated with 20 centimetres for Parkhaven, the total flood risk is almost tripled. Due to this large increase in flood risk for Parkhaven, this scenario needs to be reconsidered. If this scenario is still implemented, it is recommended to construct a levee of at least 2.18 m NAP surrounding Parkhaven.

It is questioned whether extra water damage mitigation strategies are necessary for Genemuiden and Schellinkhout. For these two areas outside primary levees the total flood risk barely changes by applying flexible water level management and elevating the target water level with 20 cm, because of the relatively low economic value of both areas. However, for both areas water levels do increase. On local scale, individual flood risk increases due to more frequent flooding because higher water levels are expected. On larger scales, other interests outweigh extra flood risk. Therefore, constructing water damage mitigation strategies is a political consideration.

7.5 International flood risk management in lakes

In the IJsselmeer region, flood risk increases by applying flexible water level management. To mitigate water damage in areas outside primary levees, summer levees and elevated areas are constructed. However, in other lakes around the world, the problem of flooding is handled differently. For example in the Great Lakes, water levels have always fluctuated with almost two meters between summer and winter, but climate change is throwing past patterns out of whack with higher peaks and lower lows (Macfarlane, 2019). Instead of constructing levees and quays, as is done in the IJsselmeer region, around the Great Lakes the focus is to abandon the lake region on the long term (years to decades) (Macfarlane, 2019). However, on short term (months), primary drivers of rise and fall of water levels are precipitation, snow melt and evaporation and on very short time scales, in the region of days, strong winds together with heavy precipitation can raise water levels locally. Seawalls, bulkheads and revetments are constructed as a short term solution. However, according to Macfarlane (2019), water needs space and residents need to move, rather than trying to prevent inundation. In this way, wetlands and natural shorelines can be restored and will provide benefits for water quantity as they can serve as a water retention area. On the long term, staying in place will cost more than moving back now (Macfarlane, 2019).

Another lake with rising water levels is Lake Victoria in Africa. Radar altimetry data indicated that water levels in Lake Victoria have reached 1,137 meters above mean sea level in May 2021 (Voiland, 2021), which is the highest measured water level in decades. Hundreds of thousands of people had to be displaced and the flood disrupted drinking water, transportation and power systems.
Lake Victoria's water levels are highly sensitive to large rainfall events which will be more extreme due to climate change (Voiland, 2021). Resource managers are working to get grip on the water levels. To reduce water damage on the short term, existing protection works are repaired and improved. On the long term, hydroelectric power dams will be opened. In addition, replacing

impervious surfaces, like buildings and roads, to natural ecosystems will help controlling water levels in Lake Victoria (Voiland, 2021).

Water levels in reservoirs are controlled, just as water levels in the IJsselmeer region. To compare the Dutch lakes with a reservoir, the Ulley reservoir in Rotherham in the UK is chosen because of its gentle slope. Provided a reservoir is properly maintained, the likelihood of failing and causing inundation is very low (Patterson et al., 2018). In 2007, at the Ulley Reservoir, extreme rainfall caused an increased risk of flooding which led to evacuation of residents living close to the reservoir. Since heavier precipitation events will be encountered more often, reservoir flood maps are designed. These maps show whether your property is located in an area possibly affected by inundation (Patterson et al., 2018). Furthermore, emergency plans are put in place to be better prepared for reservoir flooding events.

Comparing flood risk management strategies in the Great Lakes with flood risk management strategies in the IJsselmeer region, the largest difference is that on the long term residents should abandon the Great Lake region, whereas in the Netherlands it is about preventing inundation. Water levels in the Great Lakes are uncontrollable and water levels in the IJsselmeer region are controllable. Since water levels in the IJsselmeer region can be well controlled for the coming decades, already thinking about just letting 15,600 hectare inundate is not necessary at the moment. However, on much longer time scales with even larger extremes, it might be the best option to accept that areas outside primary levees inundate once in a while, since most areas are economically speaking low in value. Comparing flood risk management strategies in Lake Victoria with strategies applied in the IJsselmeer region, on short time scales the strategies are quite similar. However, on longer time scales, hydroelectric power dams will be used to reduce high lake water levels. Since the Netherlands is a flat country, using hydroelectric power dams is not an option. Lastly, water levels in reservoirs are controlled, just like water levels in the IJsselmeer region. In the UK, reservoir flood maps are designed to show whether a surrounding area has a risk of flooding. In the Netherlands, flood maps are designed by waterboards, but are not used at all. It is recommended to start using these maps to set up evacuation plans.

8. Conclusion

This research investigates effects of flexible water level management on flood risk in areas outside primary levees in the IJsselmeer region. Information from the GIS analysis is used in Hydra-NL to determine hydraulic loads associated to their probability of exceedance. The hydraulic loads are used in the Waterschadeschatter to finally determine water damage and flood risk.

The research question is answered in this chapter and reads:

What are the effects of flexible water level management regarding flood risk of areas outside primary levees around the IJsselmeer and Markermeer?

Water levels calculated in Hydra-NL are higher than occurred water levels. Interpolated water levels for the whole IJsselmeer region show even larger deviations than computed water levels in Hydra-NL for the case study areas. Using interpolated water levels from Hydra-NL, it can be concluded that the total inundated area excluding and including flexible water level management hardly differs. However, in buildings and infrastructure areas, the increase in inundated area is more significant. Furthermore, looking to total water damage in the whole IJsselmeer region, about 90% of the total water damage comes from water damage in buildings and infrastructure areas and then especially from residential areas. The largest flood risk for the whole IJsselmeer region was found for smaller and frequent events, because for events with smaller return periods large parts of areas outside primary levees will be inundated. By applying flexible water level management, the total water damage in the IJsselmeer region for an event with an exceedance probability of 10 years increases from 44 million euros to 62 million euros, and flood risk increases from 4 million euros per year to 5 million euros per year, which is calculated using *Equation 3.9*.

Extrapolation of case study areas Parkhaven, Genemuiden and Schellinkhout to other areas outside primary levees in the IJsselmeer region cannot be done that easily, because every area located outside primary levees is different and different thresholds of flooding are encountered. However, the function classes of the case study areas are more or less matching the function classes of other areas outside primary levees in the IJsselmeer region. Still, Parkhaven shows an overestimation regarding water damage compared to other buildings and infrastructure areas outside primary levees. Parkhaven has a residential function, whereas other buildings and infrastructure areas are mostly harbours or parking lots with much lower water damages, which makes extrapolation difficult. The function classes of Genemuiden and Schellinkhout are approximating the function classes appearing in the IJsselmeer region and therefore extrapolation gives more reliable results. By applying flexible water level management, the total flood risk for Parkhaven increases with 8%, from 2,500 €/year to 2,700 €/year. For Genemuiden and Schellinkhout the total flood risk barely changes. Rijkswaterstaat investigates whether it is possible to raise the target water level with 20 cm, compared to the water level decree from 1992 during the spring set up, to store even more fresh water into the IJsselmeer region. The total flood risk for Parkhaven by elevating the target water level with 20 cm increases with 175%, from 2,700 €/year to 7,500 €/year, compared to the scenario in which flexible water level management is applied. For Genemuiden and Schellinkhout again the total flood risk barely changes. It can be assumed that the total flood risk in other buildings and infrastructure areas increases, but this increase will be smaller, since Parkhaven shows an overestimation regarding flood risk. Furthermore, in other pasturelands, recreation areas and nature areas outside primary levees total flood risk hardly changes since the function classes of Genemuiden and Schellinkhout can be extrapolated.

Most computations show overestimations. Water levels obtained from Hydra-NL are higher than occurred water levels, the upper boundary of -0.10 m NAP is used for calculations of flexible water level management and the case study areas have relatively low elevations compared to their function class. Furthermore, flood risk only significantly increases in residential areas for small exceedance probabilities. Since less than 3% of areas outside primary levees consist of buildings and infrastructure areas and less than 10% of buildings and infrastructure areas consist of residential areas, the flood risk is reduced. Because both most calculations show overestimations and there are just a few residential areas, most areas located outside primary levees in the IJsselmeer region will hardly suffer from applying flexible water level management.

9. Recommendations

This chapter presents suggestions for further research. In section 9.1, calibration of friction constant kappa is discussed. Next, section 9.2 recommends to calculate interpolated hydraulic loads for the IJsselmeer region and section 9.3 dives deeper into the uncertainties of the Waterschadeschatter. Lastly, section 9.4 recommends to distinguish land use categories which have similar characteristics and damage in case of flooding and section 9.5 considers whether it is possible to construct more areas outside primary levees in the IJsselmeer region.

9.1 Calibrate friction constant kappa in Hydra-NL

Water levels calculated in Hydra-NL are larger than occurred water levels. Therefore, more information should be gathered about underlying processes of Hydra-NL. It is valuable to understand which equations and boundary conditions are used, but also which assumptions are made. In this research, the friction constant kappa, used in the wind set up equation, affects water levels calculated in Hydra-NL. By taking a lower value for kappa, the wind set up decreases and therefore water levels calculated in Hydra-NL will decrease and will be closer to occurred water levels. Hence, for further research it is recommended to calibrate friction constant kappa in Hydra-NL with measurements to get rid of the systematic deviation.

9.2 Computing interpolated hydraulic loads for IJsselmeer region

In this research, hydraulic loads are computed for the case study areas and interpolated water levels are derived for the whole IJsselmeer region. However, if was found that calculating hydraulic loads leads to more accurate results. To calculate hydraulic loads, levee profiles must be added from the Hydra-NL database. First, the distance between the closest point in Hydra-NL to a certain location and the start of the foreland must be entered. Furthermore, the slope, roughness factor, orientation and height of the levee are used as input as well. To also obtain accurate results for water levels in the whole IJsselmeer region, it is recommended to add levee profiles for every location around the IJsselmeer and Markermeer in Hydra-NL to finally calculate interpolated hydraulic loads.

9.3 Accuracy of uncertainties in Waterschadeschatter

To get a better sense of accuracy of uncertainties in the Waterschadeschatter, I recommend to compute the minimal, mean and maximum damage amounts. For instance, the minimal, mean and maximum damage amounts for growing different crops are further apart than the minimum, mean and maximum damage amounts for infrastructure, as can be seen in the user manual from STOWA (Waterschadeschatter, 2021).

9.4 Distinguishing land use categories

This research indicates that buildings and infrastructure area Parkhaven shows an overestimation regarding water damage and flood risk compared to other buildings and infrastructure areas. In addition, water damage mitigation strategies presented for Parkhaven are more drastic than needed in other buildings and infrastructure areas, which are mostly harbours and parking lots. To get more realistic results for water damage and flood risk in other buildings and infrastructure areas outside primary levees in the IJsselmeer region, the land use category buildings and infrastructure areas must be split up in categories which have similar characteristics and damage in case of flooding. It is recommended to use at least the land use categories harbours, parking lots, buildings with a water related function and residential areas. The use of other important categories must be discussed in further research. However, already using the four above mentioned land use categories will result in more realistic approximations for water damage and flood risk in areas outside primary levees in the IJsselmeer region.

9.5 Constructing more areas outside primary levees?

This research shows that more than 97% of areas outside primary levees will hardly suffer from applying flexible water level management in the IJsselmeer region. Water levels can be controlled quite well and water damage stays below 10 €/ha/year for most areas. Since land is scarce in the urban agglomeration in the Netherlands, should it be considered to construct more areas outside primary levees and to use them more intensively? In 2022, pumps in the Afsluitdijk should be ready to use which makes the flood risks even smaller, since water levels can be controlled even better by then. The IJsselmeer and Markermeer do have a total water surface area of 2,000 km^2 and a fresh water volume of approximately 1.1 E10 m^3. Constructing more areas outside primary levees in shallow parts near the shore, will reduce the fresh water buffer, but this reduction is negligibly small compared to the volume of the fresh water buffer. Building houses in areas outside primary levees helps to combat house famine, more food can be produced which is needed because the Dutch population increases (CBS, 2020) and there is more space for nature areas. Consideration of constructing more areas outside primary levees should be done on national scale, but it would be interesting to dive deeper into this opportunity.

References

Algemeen Hoogtebestand Nederland. (2021). https://www.ahn.nl/

Bezuyen, K., Stive, M., Vaes, G., Vrijling, J., & Zitman, T. (2012). *Inleiding Waterbouwkunde; Lecture notes CT2320.*

Bieman, J., Kieftenburg, A. (2015). *Handreiking voor het afleiden van ontwerpwaterstanden en golfcondities*. Deltares.

Boderie, P.M.A., Bonte, B., Essink, O. (2012). *Effect peilvariaties of zoutbelasting Markermeer en IJsselmeer.*

CBS. (2020). *Bevolkingsgroei*. https://www.cbs.nl/nl-nl/visualisaties/dashboard-bevolking/bevolkingsgroei/groei

CBS. (2021). https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/natuur-en-milieu/bestand-bodemgebruik

Deltaprogramma IJsselmeergebied. (2018). *Deltanieuws*. https://magazines.deltaprogramma.nl/deltanieuws/2018/02/IJsselmeergebied

Dikov, D. (2020). *Introduction to sensitivity analysis.*

Esri. (2021). *Resources for ArcMap*. https://desktop.arcgis.com/en/arcmap

Helpdesk Water. (2021). *Download Hydra-NL.* https://www.helpdeskwater.nl/onderwerpen/applicaties-modellen/applicaties-per/omgevings/omgevings/hydra-nl/. Rijksoverheid.

Hoogheemraadschap Hollands Noorderkwartier. (2021). https://www.hhnk.nl/legger-regionale-waterkeringen

Jaspers, C.J., Vrij Peerdeman, M., Kollen, J., van Duin, C.F. (2017). *Milieueffectrapportage; Peilbesluit IJsselmeergebied*. Reference number: SWNL-0186383.

Jonkman, S.N., Jorissen, R.E., Schweckendiek, T., van den Bos, J.P. (2021). *Flood defences; Lecture Notes CIE5314.*

Kapalan, S. and Garrick, B. (1981). *On the quantitative definition of risk.*

Kennisportaal Klimaatadaptatie. (2021). *Overstromingskans.* https://klimaatadaptatienederland.nl/stresstest/bijsluiter/overstroming/basisinformatie/plaatsgebonden-overstromingskans/

Kollen, J. (2016). *Ontwerp-Peilbesluit IJsselmeergebied*. Reference number: SWNL-0186380.

Linde, A.H., Bubeek, 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.

Macfarlane, D. (2019). *Great Lakes flooding: The warning signs that homes must be moved.* The conversation.

Patterson, D., Hutchinson, J., Maughan, J., Turnbull, D. (2018). *What are the risks of reservoir flooding?*

Rijkswaterstaat, Ministerie van Infrastructuur en Milieu. (2015). *Peilbesluit IJsselmeergebied, Notitie reikwijdte en detailniveau.*

Rijkswaterstaat, Ministerie van Infrastructuur en Milieu. (2016). *Waterbeheer in Noord-Nederland*.

Rijkswaterstaat, Ministerie van Infrastructuur en Milieu. (2017). *Nota van antwoord, behorende bij Peilbesluit IJsselmeer.*

Rijkswaterstaat, Ministerie van Infrastructuur en Milieu. (2018). *Peilbesluit IJsselmeergebied.*

Rijkswaterstaat, Ministerie van Infrastructuur en Waterstaat. (2021). *Discontovoet.* Steunpunt Economische Expertise.

Rijkswaterstaat Waterinfo. (2021). https://waterinfo.rws.nl/

Schoemaker, M., Zijlstra, R., van der Meer, J., Doorslaer, K. (2019). *The influence of a berm and a wave wall at dikes on overtopping by oblique and breaking waves.*

Slim Water Management. (2021). *Nieuwe zoetwater strategie*. Optimaal operationeel waterbeheer voor Nederland.

STOWA. (2021). Standaard schadetabel. https://www.waterschadeschatter.nl/damage/

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

The Royal Society. (2020). *How fast is sea level rising?*

Van der Meer, J.W., Allsop., N.W.H., Bruce, T., De Rouck, J. Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P., Zanuttigh, B. (2018). *Manual on wave overtopping of sea defences and related structures*.

Van Riet, J. (2020). *Nestelen van broedvogels in buitendijkse gebieden*.

Van Riet, J. (2021). *Bodemdalingsanalyse van focusgebieden in het IJsselmeergebied*.

Van Rinsum, G.P. (2015). *Accuracy wind set up formula for irregularly shaped lakes with a strong varying water depth.*

Voiland, A. (2021). *Lake Victoria's rising water levels*. Earth observatory.

Waterschadeschatter. (2021). *Gebruikershandleiding definitief.*

Waterschadeschatter tool. (2021). *STOWA*. https://www.waterschadeschatter.nl/damage/

Waterschap Amstel Gooi en Vecht. (2021). https://www.agv.nl/onze-taken/legger/

Waterschap Overijsselse Delta. (2021). https://www.wdodelta.nl/keur-en-legger

Waterschap Vallei en Veluwe. (2021). https://www.vallei-veluwe.nl/wat-doet-waterschap/voldoende-water/regels-rondom-water/

Waterschap Zuiderzeeland. (2021). https://www.zuiderzeeland.nl/legger

Wetterskip Fryslân. (2021). *Leggerkaart*. https://www.wetterskipfryslan.nl/kaarten/leggerkaart

WSP. (2020). *Factsheet water balance.*

WSP. (2021). *Legger Waterkeringen*. Internal drive.

Appendices

Appendix A – Fieldtrip

Fieldtrip along the IJsselmeer and Markermeer
On Tuesday the 8th of June 2021 a fieldtrip was made to the three case study areas and two other relevant locations in relation to my research. The fieldtrip was made together with a trainee from Rijkswaterstaat, three employees form Rijkswaterstaat working on flexible water level management and my two supervisors from WSP and we gathered near strandbad Edam. In March 2021, complaints were received about high water levels by Rijkswaterstaat from this area outside primary levees, so it is an excellent location to start the day. After visiting strandbad Edam, we travelled to one of my case study areas Schellinkhout. After walking around and observations were made, the trip continued to residential area Parkhaven. Bizarre to see such a residential area with one flat and many more family houses located outside primary levees. Next, on our way to Genemuiden we made a quick stop near Ramspol Bridge. After visiting the case study area of het Zwarte Water near Genemuiden, we went to a sunny terrace in Genemuiden to end the fantastic day together.

Strandbad Edam
In March 2021, the beach at strandbad Edam suffered from high water level conditions when a water level of 0.2 m NAP was reached. Next to the beach, a camping, restaurant and harbour are located. However, they are situated at higher elevations than the beach itself. The probability of inundation at this location is relatively small, since often south-westerly winds are encountered and the Markermeer is easier to control than the IJsselmeer. However, during a storm with winds coming from the east, water levels can rise quickly. So the probability of inundation is small, but the economic damage is much larger. The 8th of June was a very sunny day with almost no wind and the water level was exactly -0.20 m NAP.


Figure A.1: Area of strandbad Edam.

Schellinkhout

Schellinkhout has a nature and recreation area located outside primary levees. The first thing I noticed, was a summer levee of 0.8 m NAP at the recreation site, presented in *Figure A.2*. This summer levee can also be seen in AHN3. Walking to the southeast, a low lying gap is present with an elevation of 0.1 m NAP, as can be seen in *Figure A.3*. There is just a small difference in elevation between the water and the grassland. During high water conditions, water can easily flow along the coast to the parking lot. Going to the west, a nature area is present in which a gully leads to a fence which catches duckweed, as is depicted in *Figure A.4*. Near the fence another low lying spot is located. However, the probability of inundation is still small, since often the wind is coming from the southwest. The consequences of inundation are small as well, since there is almost no economic value to protect.

Figure A.2: Summer levee near Schellinkhout beach.

Figure A.3: Small vertical difference between water and beach.

Figure A.4: Fence which catches duckweed in the nature area of Schellinkhout.

<u>Parkhaven</u>

Parkhaven is a residential area built in 1998. Terraces and gardens are located approximately at 0.5 m NAP and streets and houses do have an elevation above 1.5 m NAP. By applying flexible water level management the probability that gardens and terraces will be inundated is once in 10 years and the probability that streets will be flooded is once in 300 years. Wind set up is the most important factor determining high water levels. Residents from Parkhaven are aware that they are living in an area outside primary levees and aware of flexible water level management. They actively opposed RWS and went to court. So the tensions between the residents of Parkhaven and RWS ran high. Because of north-westerly winds and the funnel in which Parkhaven is located, water levels can rise quickly. Due to higher water levels in the Waddenzee during north-westerly winds, no water can be released under the influence of gravity. In addition, large discharges from the river IJssel increase the water level in the IJsselmeer as well. High water levels in Parkhaven can last for more than 2 days.

Figure A.5: Sailing yachts, houses and gardens in Parkhaven.

Ramspol bellows weir

Ramspol weir is an inflatable dam in between het Ketelmeer and het Zwarte Meer. This weir has been constructed to protect the area along het Zwarte Meer and het Zwarte Water against high water levels in the IJsselmeer. It is the biggest bellows weir in the world. The Ramspol weir will be closed when the water level rises above 0.5 m NAP by north-westerly winds. In this way, no more water can flow into het Zwarte Meer.

Figure A.6: Ramspol bellows weir.

Genemuiden

The area near Genemuiden along het Zwarte Water is a pastureland area. Cows, sheep and horses can be found here. There are two summer levees present in front of the winter levee. During a storm, the Ramspol weir will be closed and backwater effects may arise. Therefore, the pasturelands might be inundated. Stakeholders in this region are mostly farmers. They are informed a few days in advance of high water conditions.

There is one ditch going into the area and, at the end of the ditch, a small weir is present to regulate the water level. However, just behind the ditch, the second summer levee has become weaker, and when the water level rises above 0.7 m NAP, the whole area will be flooded.

Figure A.7: Area located outside primary levees along het Zwarte Water near Genemuiden.

Appendix B – Inundation maps

Parkhaven

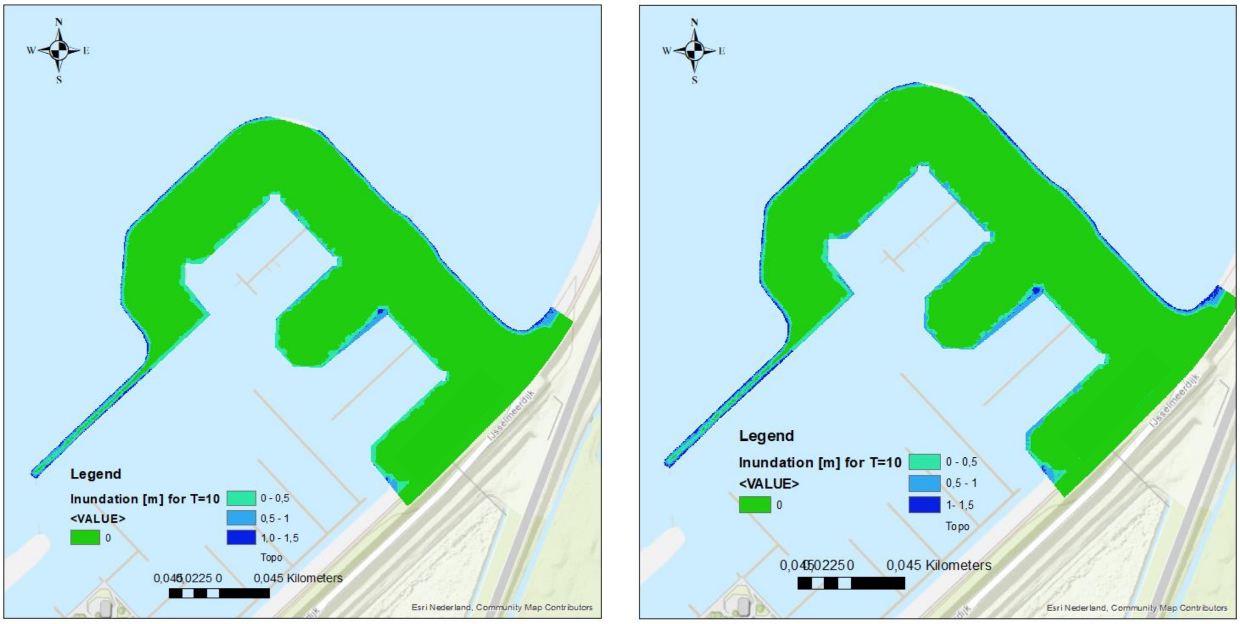


Figure B.1: Inundation maps Parkhaven for T=10 years for a situation excluding (left) and including (right) flexible water level management.

Figure B.2: Inundation maps Parkhaven for T=30 years for a situation excluding (left) and including (right) flexible water level management.

Figure B.3: Inundation maps Parkhaven for T=300 years for a situation excluding (left) and including (right) flexible water level management.

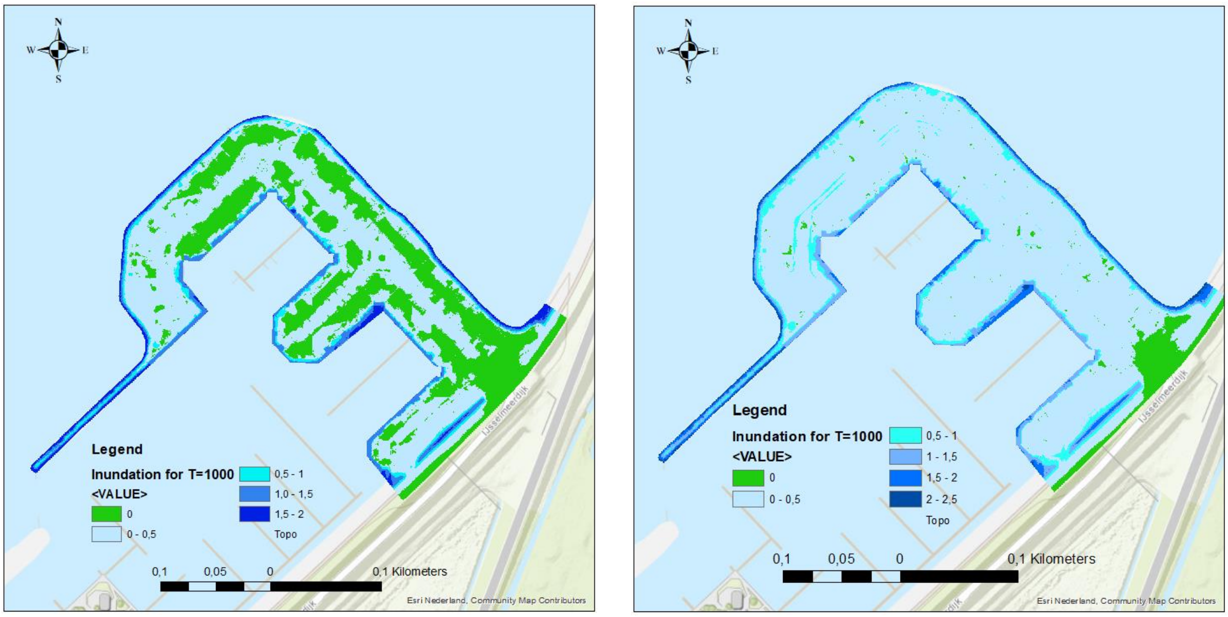


Figure B.4: Inundation maps Parkhaven for T=1,000 years for a situation excluding (left) and including (right) flexible water level management.

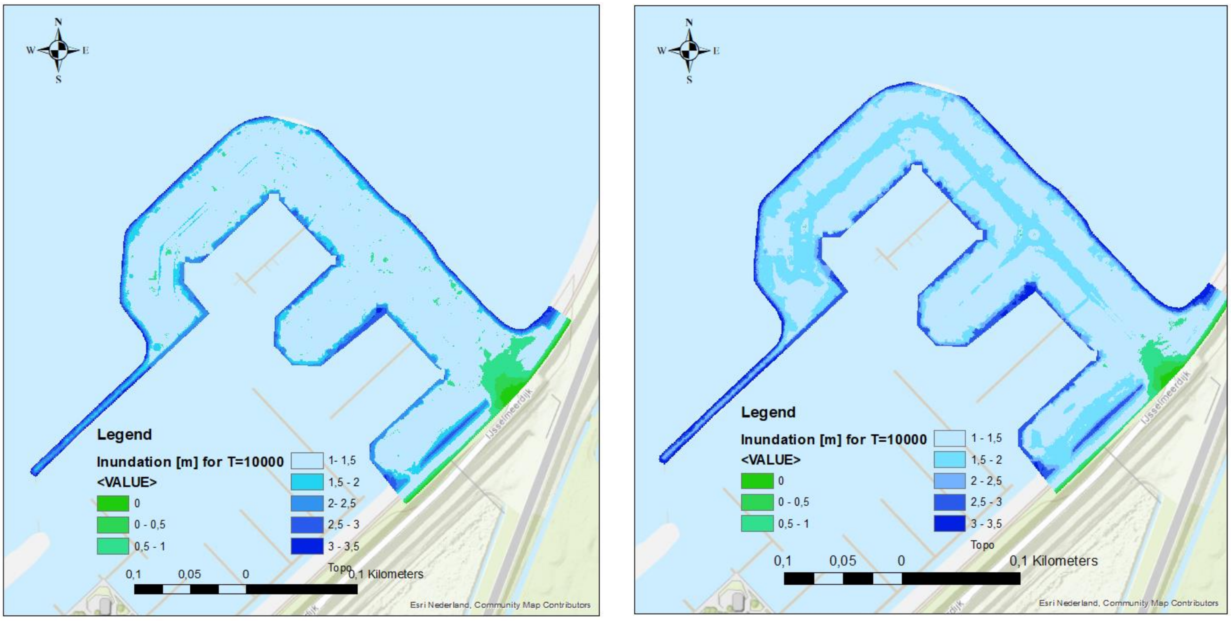


Figure B.5: Inundation maps Parkhaven for T=10,000 years for a situation excluding (left) and including (right) flexible water level management.

Table B.1: Inundated areas Parkhaven including and excluding flexible water level management.

Exceedance probability [/year]	Inundated area excluding flexible water level management [km^2]	Inundated area including flexible water level management [km^2]
1/10,000	0.050	0.051
1/1,000	0.033	0.048
1/300	0.008	0.017
1/30	0.007	0.008
1/10	0.006	0.007

Genemuiden

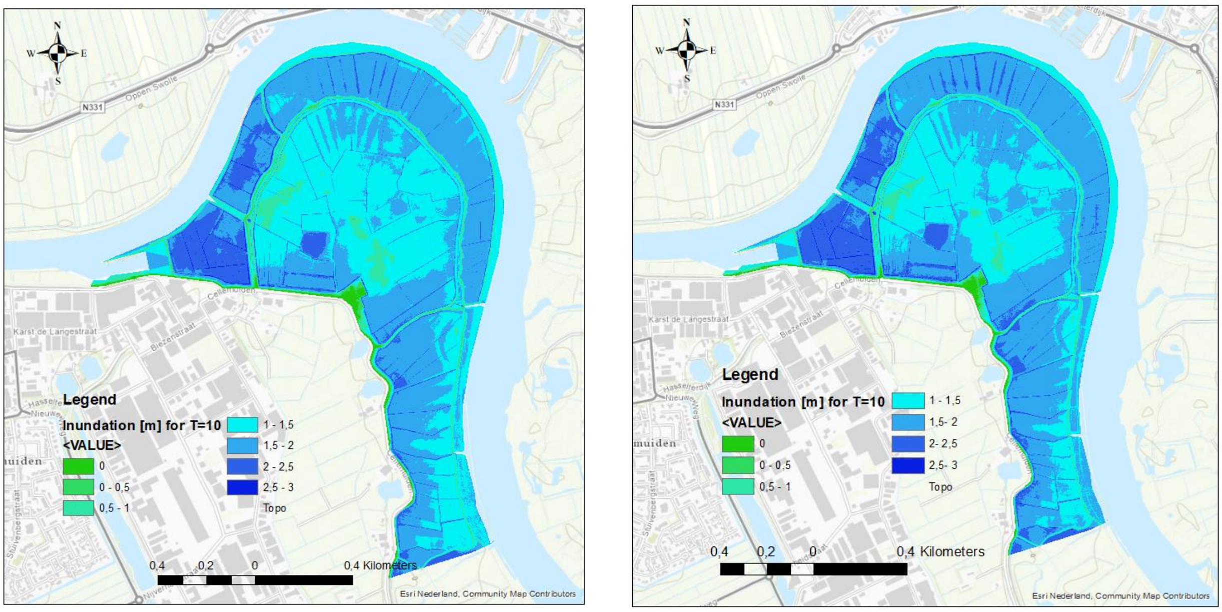


Figure B.6: Inundation maps Genemuiden for T=10 years for a situation excluding (left) and including (right) flexible water level management.

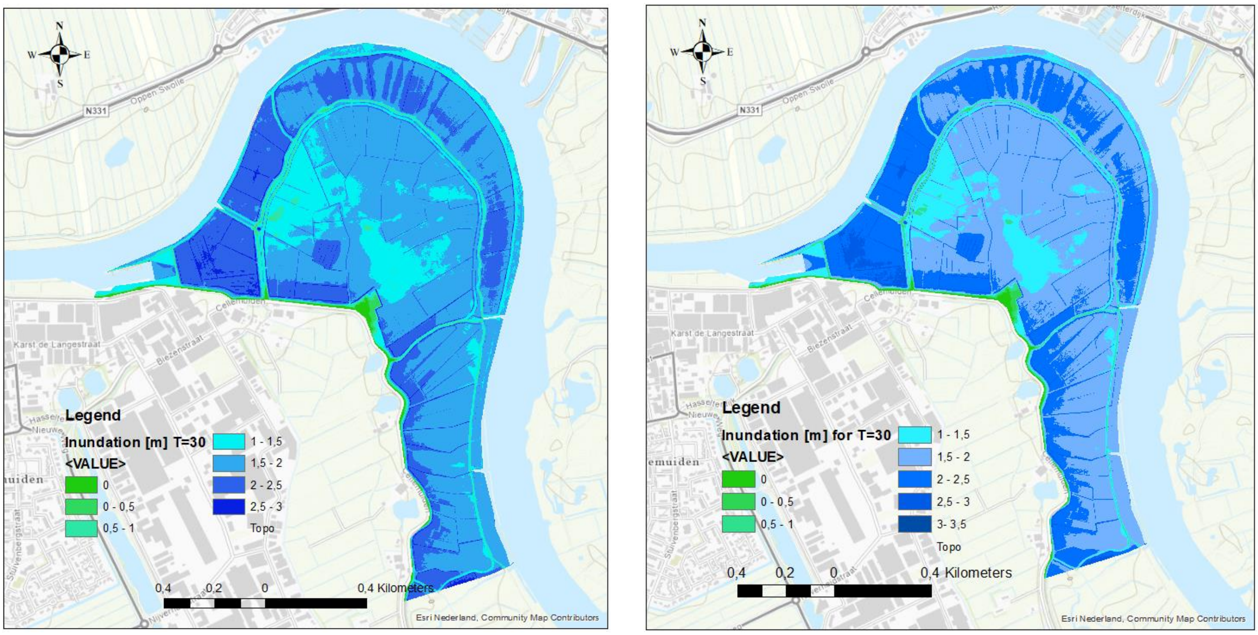


Figure B.7: Inundation maps Genemuiden for T=30 years for a situation excluding (left) and including (right) flexible water level management.

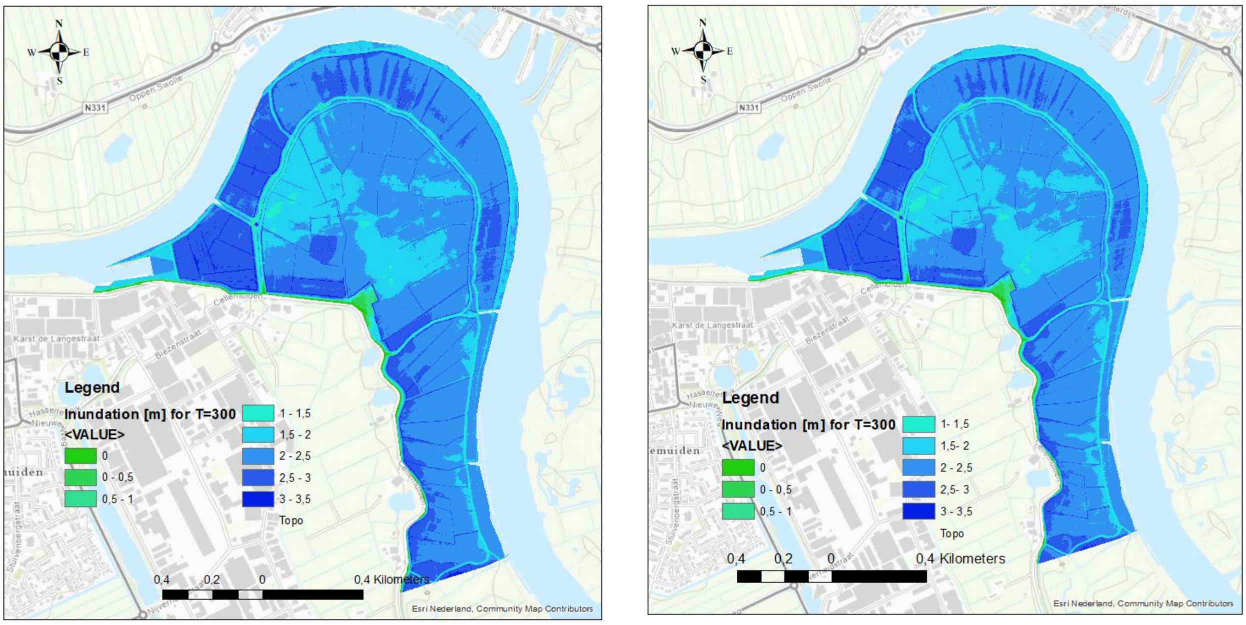


Figure B.8: Inundation maps Genemuiden for T=300 years for a situation excluding (left) and including (right) flexible water level management.

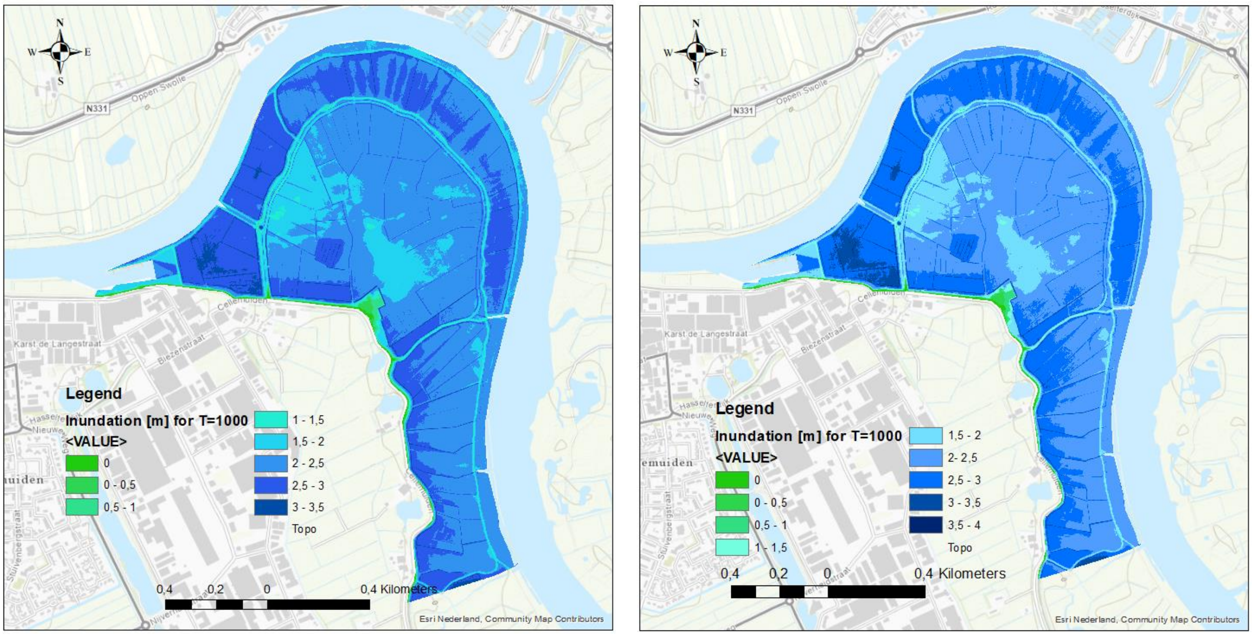


Figure B.9: Inundation maps Genemuiden for T=1,000 years for a situation excluding (left) and including (right) flexible water level management.

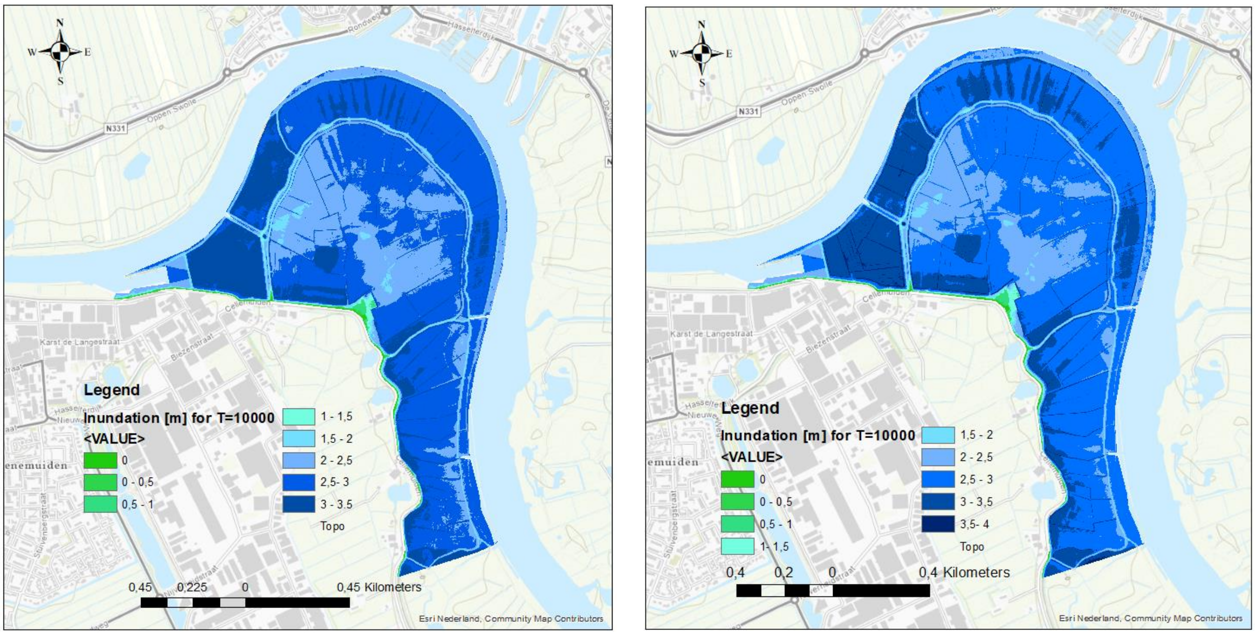


Figure B.10: Inundation maps Genemuiden for T=10,000 years for a situation excluding (left) and including (right) flexible water level management.

Table B.2: Inundated areas Genemuiden including and excluding flexible water level management.

Exceedance probability [/year]	Inundated area excluding flexible water level management [km^2]	Inundated area including flexible water level management [km^2]
1/10,000	1.506	1.506
1/1,000	1.503	1.504
1/300	1.502	1.502
1/30	1.497	1.498
1/10	1.493	1.494

Schellinkhout

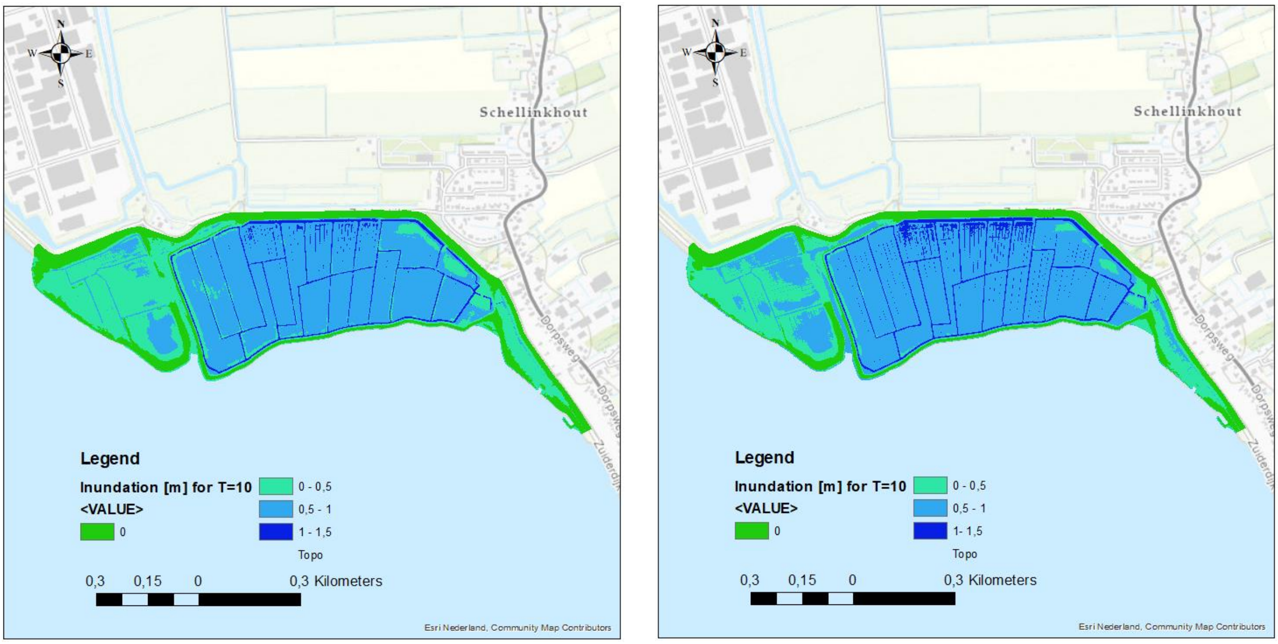


Figure B.11: Inundation maps Schellinkhout for T=10 years for a situation excluding (left) and including (right) flexible water level management.

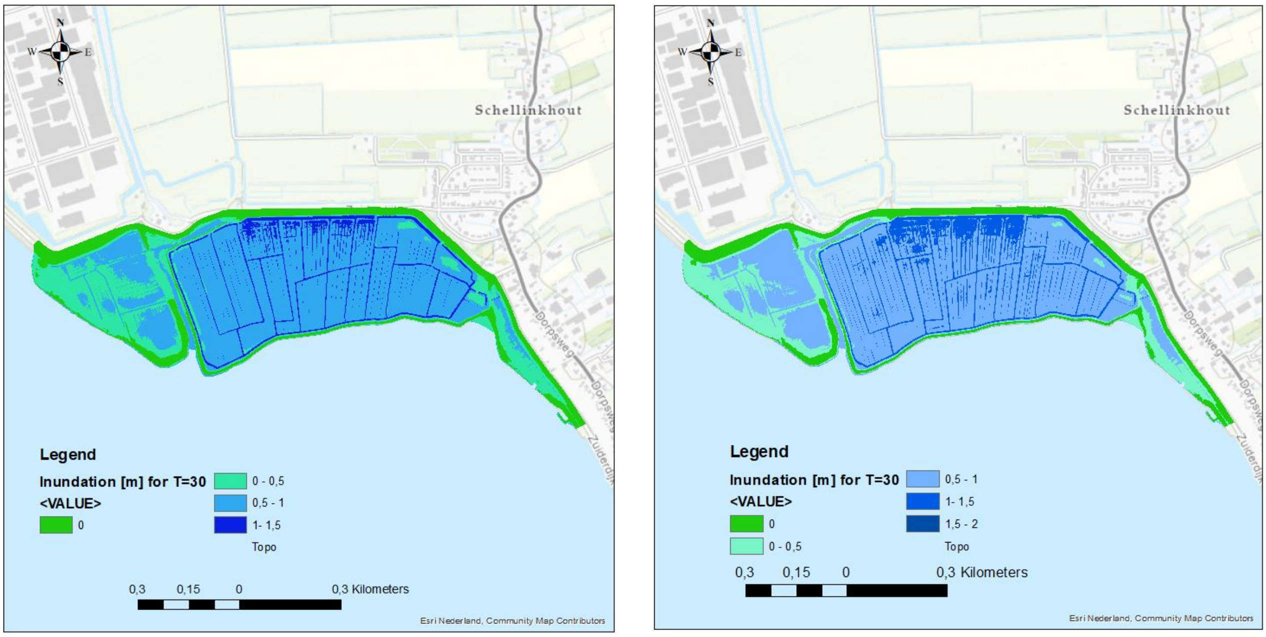


Figure B.12: Inundation maps Schellinkhout for T=30 years for a situation excluding (left) and including (right) flexible water level management.

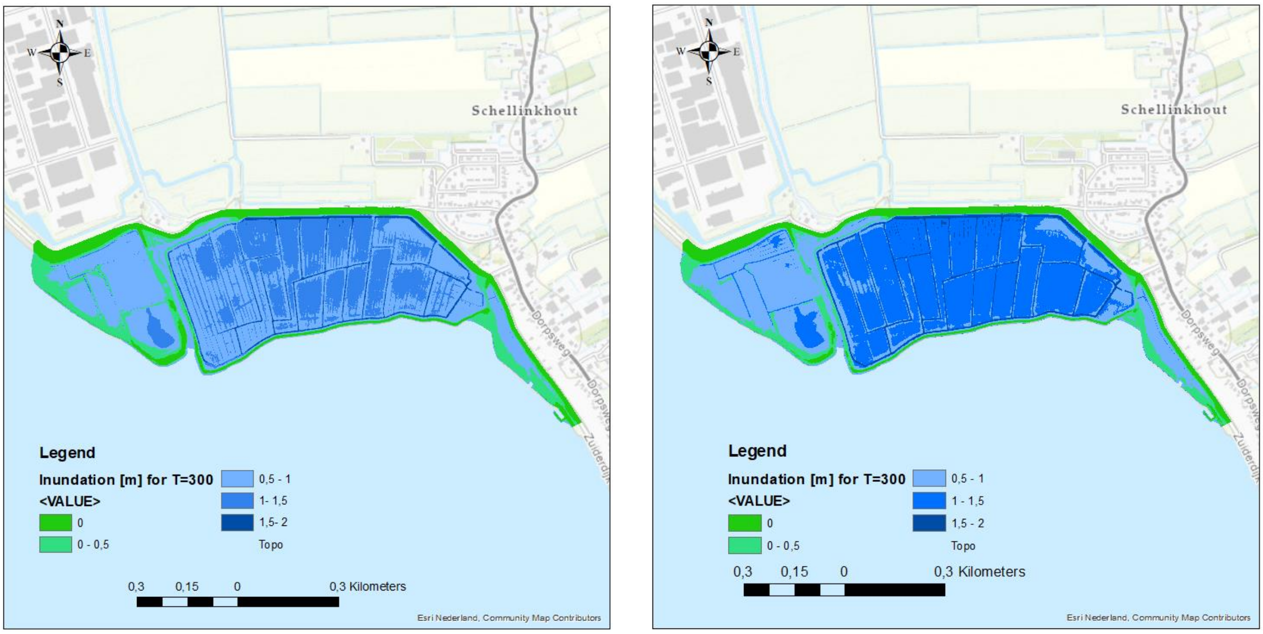


Figure B.13: Inundation maps Schellinkhout for T=300 years for a situation excluding (left) and including (right) flexible water level management.

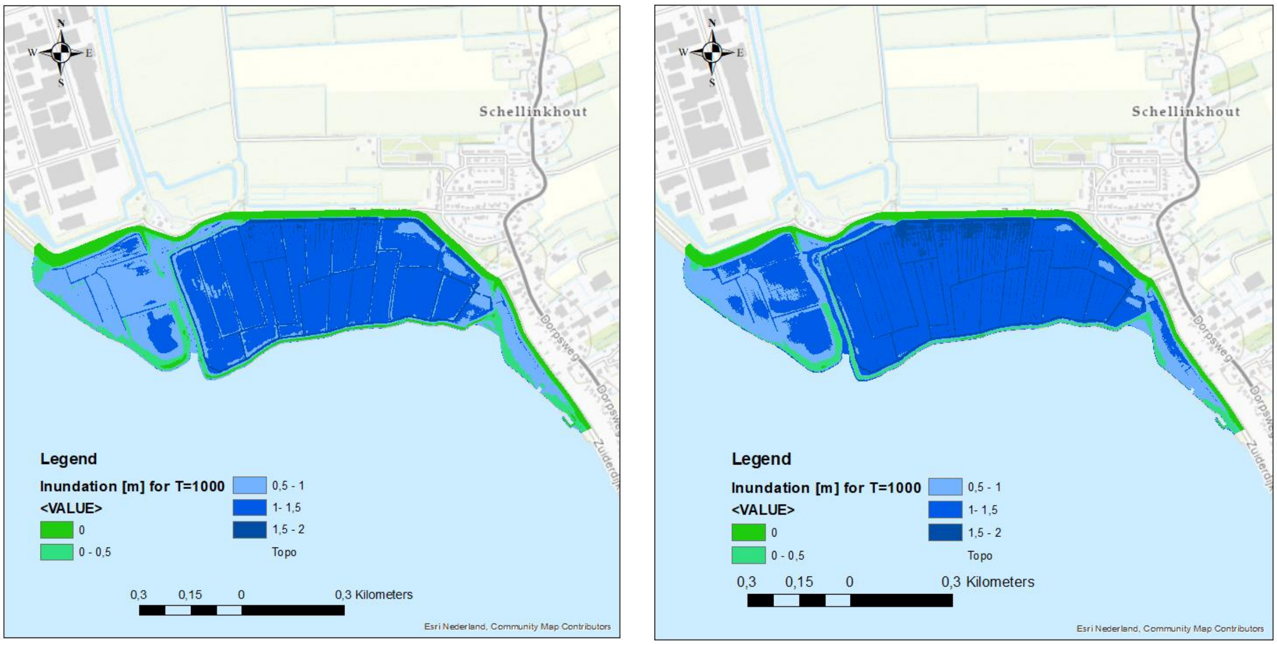


Figure B.14: Inundation maps Schellinkhout for T=1,000 years for a situation excluding (left) and including (right) flexible water level management.

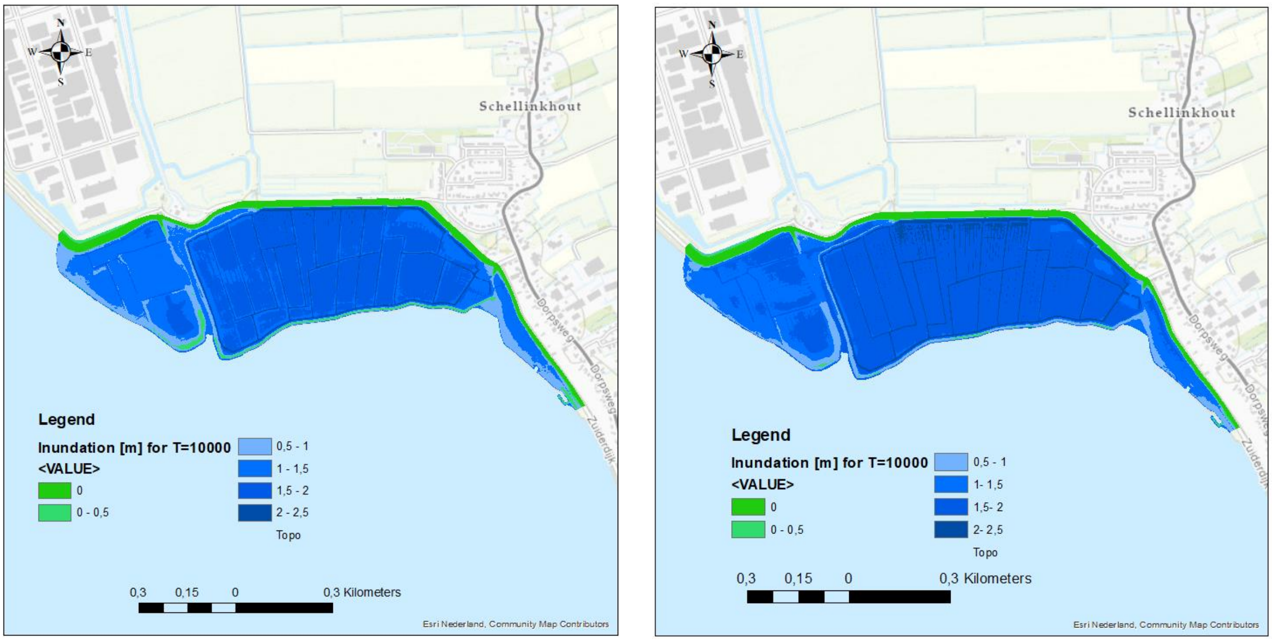


Figure B.15: Inundation maps Schellinkhout for T=10,000 years for a situation excluding (left) and including (right) flexible water level management.

Table B.3: Inundated areas Schellinkhout including and excluding flexible water level management.

Exceedance probability [/year]	Inundated area excluding flexible water level management [km^2]	Inundated area including flexible water level management [km^2]
1/10,000	0.451	0.453
1/1,000	0.441	0.448
1/300	0.433	0.439
1/30	0.418	0.425
1/10	0.401	0.417

Appendix C – Informative document focus group discussion

This informative document is presented in Dutch, since the discussion was held in Dutch and this document was offered to the focus group participants in advance.

Introductie

Het klimaat verandert en de zomers worden steeds droger. Hierdoor neemt de vraag naar zoet water toe. Om op de waterbehoefte in te spelen, past Rijkswaterstaat sinds 2019 in het IJsselmeer en Markermeer flexibel peilbeheer toe. Flexibel peilbeheer houdt in dat de waterstand in de zomerperiode kan fluctueren tussen -0,30 m NAP en -0,10 m NAP, in plaats van de waterstand op -0,20 m NAP te houden. In de winter kan, met het toepassen van het flexibel peilbeheer, een bandbreedte worden aangehouden van tussen de -0,40 m NAP en -0,05 m NAP, in plaats van de waterstand te houden op -0,40 m NAP. Zo heeft de waterbeheerder meer ruimte om te sturen op weersomstandigheden en de vraag naar zoetwater.

Probleemstelling

Bij het toepassen van flexibel peilbeheer neemt het overstromingsrisico in buitendijkse gebieden toe. Om waterschade te beperken in buitendijkse gebieden, is gekeken naar maatregelen om waterschade te verminderen. Dit is gedaan voor drie case study gebieden; Parkhaven, Genemuiden en Schellinkhout.

Hoofddoelen

- Hoe denken jullie in het algemeen over maatregelen die waterschade beperken?
- Kunnen jullie een voorbeeld geven uit de praktijk waar maatregelen om waterschade tegen te gaan zijn genomen?
- Zijn mijn maatregelen uitvoerbaar?
- Zijn mijn maatregelen nuttig?
- Zijn mijn maatregelen ook nuttig als het streefpeil wordt verhoogd met 20 centimeter?
- Hoe kan ik mijn bedachte maatregelen sterker maken?
- Welke maatregel zal de meeste waterschade voorkomen?
- Welke andere maatregelen kunnen er worden getroffen in de drie case study gebieden?
- Hoe staan bewoners tegen het nemen van maatregelen om waterschade te beperken aan?
- Maatregelen meerlaagse veiligheid langsgaan per case study gebied.

Case study gebieden

Parkhaven

- Woonwijk
- Grenst aan het IJsselmeer
- Oppervlakte van 5 hectare
- Tuinen liggen tussen 0,4 en 0,7 m NAP
- Straten en huizen liggen boven 1,5 m NAP

Tabel C.1: Waterstanden Parkhaven met en zonder flexibel peilbeheer.

Kans van voorkomen [/jaar]	Waterstand zonder flexibel peilbeheer [m NAP]	Waterstand met flexibel peilbeheer [m NAP]
1/10.000	2,98	3,18
1/1.000	1,83	1,99
1/300	1,50	1,62
1/30	1,12	1,21
1/10	0,94	1,03

Genemuiden

- Gebied met weilanden en een aantal boerderijen en huizen
- Grenst aan het Zwarte Water
- Oppervlakte van 150 hectare
- Buitenste zomerdijk hoogte 0,7 m NAP
- Binnenste zomerdijk hoogte 1,0 m NAP
- Vormen de uiterwaarden van de IJssel

Tabel C.2: Waterstanden Genemuiden met en zonder flexibel peilbeheer.

Kans van voorkomen [/jaar]	Waterstand zonder flexibel peilbeheer [m NAP]	Waterstand met flexibel peilbeheer [m NAP]
1/10.000	2,65	2,72
1/1.000	2,29	2,35
1/300	2,21	2,17
1/30	1,76	1,82
1/10	1,53	1,59

Schellinkhout

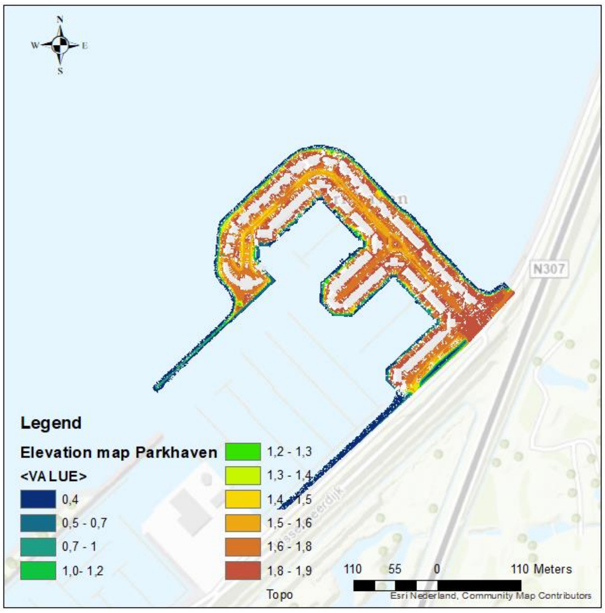
- Natuur- en recreatiegebied
- Grenst aan het Markermeer
- Oppervlakte van 45 hectare
- Grote gebieden ligger lager dan -0,5 m NAP

Tabel C.3: Waterstanden Schellinkhout met en zonder flexibel peilbeheer.

Kans van voorkomen [/jaar]	Waterstand zonder flexibel peilbeheer [m NAP]	Waterstand met flexibel peilbeheer [m NAP]
1/10.000	1,21	1,38
1/1.000	0,78	0,94
1/300	0,62	0,74
1/30	0,40	0,49
1/10	0,29	0,39

Maatregelen beperken van waterschade

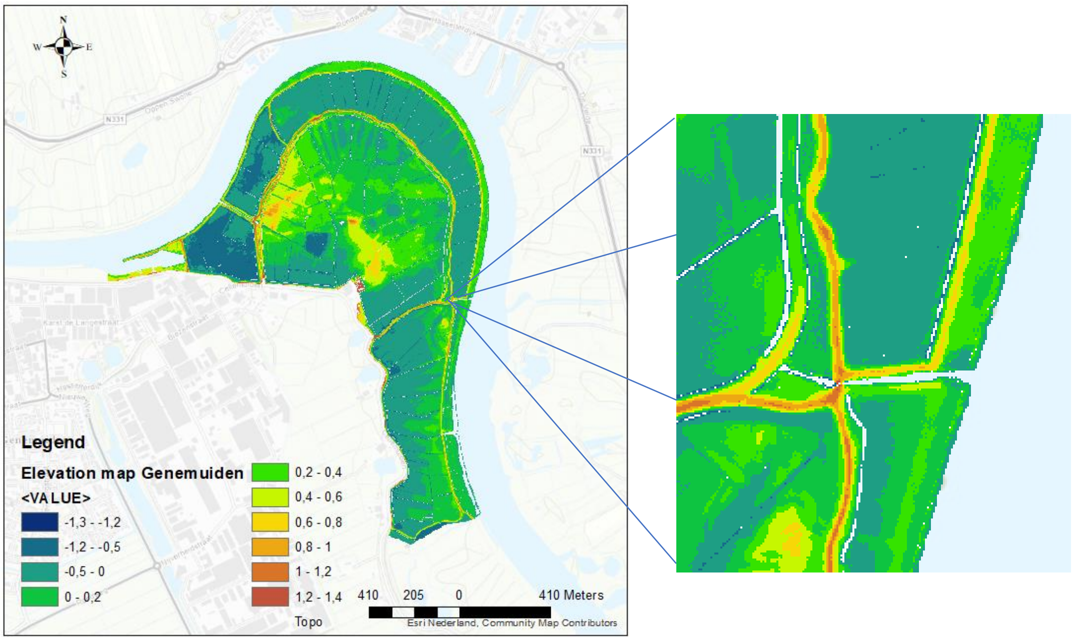
Parkhaven



Figuur C.1: Hoogtekaart Parkhaven.

1. Het gebruik van zandzakken en schotten aan de randen van Parkhaven en bij delen van huizen die niet waterbestendig zijn.
2. Waardevolle spullen, zoals auto's, kunnen naar hoger gelegen gebieden worden gebracht.

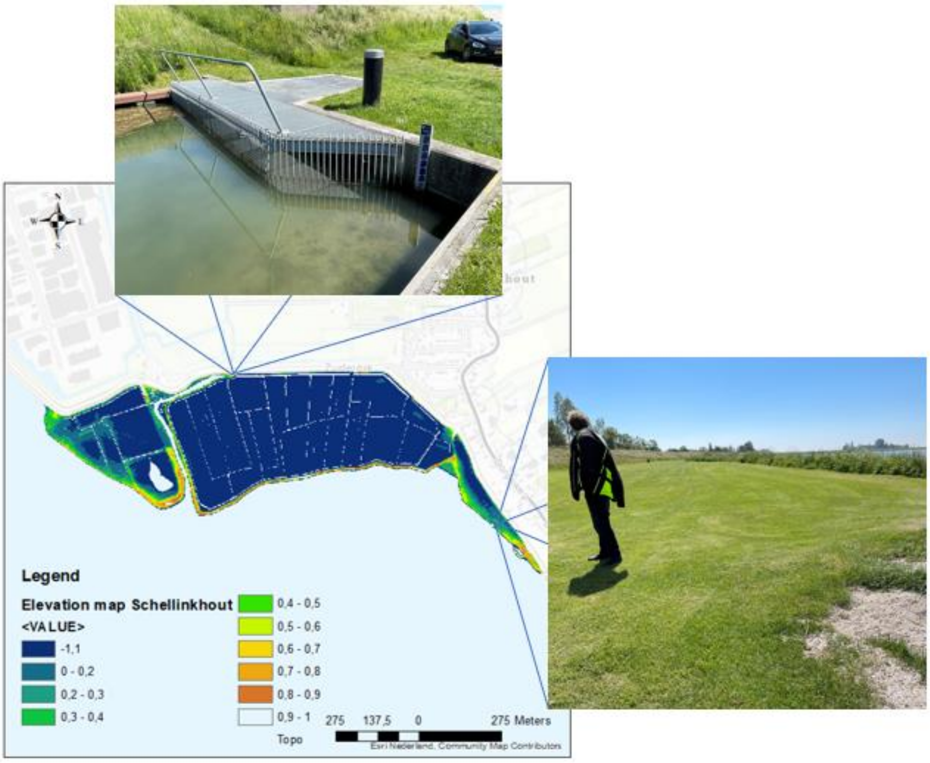
Genemuiden



Figuur C.2: Hoogtekaart Genemuiden met ingezoomd de zwakke plek in de zomerdijk.

1. Het verstevigen van de zomerdijk. Hier heeft de zomerdijk een hoogte van 0,56 m NAP, terwijl de rest van de zomerdijk op 1,0 m NAP ligt.

Schellinkhout



Figuur C.3: Hoogtekaart Schellinkhout met ingezoomd het krooshek aan de Markermeer zijde en de laaggelegen inlaat.

1. De kaden bij het krooshek ophogen. Water kan namelijk gemakkelijk via dit lage punt en de sloot naar binnen stromen.
2. Het verhogen van de laaggelegen inlaat in het oosten van Schellinkhout.

Appendix D – Report focus group discussion

An English summary can be found at the end of this section.

Bij het invoeren van flexibel peilbeheer neemt de kans op overstroming in buitendijkse gebieden toe. Met vier experts van WSP is een focus groep discussie gehouden over maatregelen die waterschade beperken in de drie case study gebieden. De experts hebben een achtergrond in klimaat, omgeving, waterveiligheid en ecologie. De discussie duurde ongeveer 1,5 uur en de volgende vragen zijn besproken:

1. *Wat vinden jullie van mijn bedachte maatregelen om waterschade tegen te gaan? Zijn ze nuttig en uitvoerbaar? Wat vinden bewoners ervan? Zijn mijn bedachte maatregelen ook nuttig als het streefpeil met 20 centimeter wordt verhoogd?*
2. *Hoe kan ik mijn bedachte maatregelen sterker maken? Welke maatregel zal de meeste waterschade voorkomen?*
3. *Welke andere maatregelen kunnen er worden getroffen in de drie case study gebieden? Kunnen jullie voorbeelden geven uit de praktijk?*
4. *Meerlaagse veiligheid langsgaan per case study gebied.*

Tijdens de discussie kwamen de volgende ideeën, suggesties en aanbevelingen naar voren:

1. Voor Parkhaven is een van mijn bedachte maatregelen om waterschade te verminderen het gebruik van zandzakken en schotten. Dit vinden de experts meer een crisis maatregel. “Je zou dan beter meer structurele maatregelen kunnen toepassen.” Ook als het streefpeil met 20 centimeter wordt verhoogd zijn structurele maatregelen van belang. Verder vonden de experts evacueren pas echt nodig als het waterniveau in de woonwijk hoger dan 40 centimeter komt te staan.
   Bij Genemuiden helpt het verstevigen van de zomerdijk niet om waterschade te verminderen, aangezien het water bij een herhalingstijd van 1/10 jaar nog steeds over de zomerdijk zal stromen. De experts vinden mijn bedachte maatregel om de binnenste zomerdijk te verstevigen zwak.
   Tot slot vinden de experts mijn maatregel om de kades bij het krooshek en bij de inlaat op te hogen nuttig, alleen vragen ze zich af of de kosten die de maatregelen met zich mee brengen wel opwegen tegen de relatief lage waterschade.

   De experts hebben het idee dat mensen die in buitendijkse gebieden wonen niet eens weten wat buitendijks wonen betekent en de urgentie van het nemen van maatregelen niet zien. Daarom is het van belang bewoners in te lichten en met hen de maatregelen te bespreken.

2. Maatregelen kunnen sterker worden als ze structureel worden. De experts denken dat in Parkhaven de meeste waterschade kan worden voorkomen door op de oeverbescherming een kade met een hoogte van 0,5 meter aan te leggen en het talud flauwer te maken om zo golfopslag te verminderen.

3. In Parkhaven kan de straat als afvoer worden gebruikt bij golfoverslag. Onder de straat kunnen infiltratiekratten worden geïnstalleerd. Zo ontstaat er een extra waterberging die

actief kan worden weggepompt. Als het waterpeil hoger komt te staan, is het infiltratiesysteem niet meer nuttig. Een dijk bouwen rond Parkhaven vinden de experts wel een hele rigoureuze maatregel.
Het verhogen van de zomerdijk in Genemuiden naar minstens 1,5 m NAP lijkt de experts geen goed plan. Ten eerste vormt dit gebied de uiterwaarden van de rivier de IJssel, waardoor het gebied moet kunnen blijven overstromen en ten tweede lopen de kosten wel heel erg op in vergelijking met de waterschade. De huizen en boerderijen zijn gelegen op terpen en zullen minder snel onderlopen. Er moet geaccepteerd worden dat weilanden zullen overstromen en dat vee eens in de zoveel jaar moet worden geëvacueerd.
Aangezien Schellinkhout grotendeels een natuurgebied is, is de schade voor flora en fauna het grootst. Voor fauna kan een hoogwatervluchtplaats worden aangelegd en verder kan het natuurgebied doorgroeien naar een natter en drassiger natuurtype.

Op grotere schaal kunnen er meer overloopgebieden worden aangelegd, kunnen er grotere gemalen of extra keringen worden gebouwd om zo in het IJsselmeergebied hogere waterstanden te voorkomen. De pompen in de Afsluitdijk zullen in 2022 klaar zijn en zullen ervoor zorgen dat het peil beter kan worden gehandhaafd.

4. Meerlaagse veiligheid Parkhaven:
   - Laag 1: Een kade van 0,5 meter aanleggen op de al bestaande oeverbescherming en het talud flauwer maken.
   - Laag 2: De straat gebruiken als afvoer met een infiltratiesysteem voor golfoverslag.
   - Laag 3: Mensen evacueren.

   Meerlaagse veiligheid Genemuiden:
   - Laag 1: Het verstevigen en ophogen van de zomerdijken.
   - Laag 2: Ander landbouwtype kiezen.
   - Laag 3: Evacueren van koeien en bij hogere waterstanden het evacueren van bewoners.

   Meerlaagse veiligheid Schellinkhout:
   - Laag 1: Ophogen van de kades bij het krooshek en de inlaat.
   - Laag 2: Voor een ander natuurtype kiezen die beter tegen nattere omstandigheden kan.
   - Laag 3: Het gebied afsluiten voor bezoekers.

Summary
Flood risk increases in areas outside primary levees around the IJsselmeer and Markermeer by applying flexible water level management. Together with four experts from WSP, a focus group discussion is carried out to discuss water damage mitigation strategies for the case study areas. The experts do have a background in surroundings and environment, water safety, climate adaptation and ecology. The following 4 questions are discussed and answered:

1. *What do you think of my devised measures to prevent water damage? Are they useful and feasible? What do residents think of taking water damage mitigation strategies? Are my devised measures also useful when the target water level is elevated with 20 centimeters?*

For Parkhaven, sand bags and bulkheads can be used to mitigate water damage, but experts think this is a crisis measure and more structural measures are needed. Structural measures are also important when the target water level is elevated with 20 centimeters. Looking to Genemuiden, reinforcing the inner summer levee is a weak measure according to the experts.

Lastly, for Schellinkhout, the experts wonder if water damage mitigation strategies should be taken, since water damage is relatively low.

2. *How can I strengthen my devised measures?*

The measures could be improved when they become structural. The experts agree that in Parkhaven most water damage can be prevented.

3. *Which other water damage mitigation strategies can be used in the case study areas?*

In Parkhaven, below streets an infiltration system can be designed to deal with wave overtopping. Furthermore, the experts think building a levee surrounding Parkhaven is a very rigorous measure, but constructing a quay on top of the current bank protection and making it less steep is a good option. Reinforcing the inner summer levee near Genemuiden seems a bad idea. This area namely forms the floodplains of river IJssel and the costs will rise enormously with respect to water damage. In the area outside primary levees near Schellinkhout, water damage for fauna has most impact. An high tide refuge can be constructed for fauna to protect them against high water levels.

4. *Discussing multi-layered security for each case study area.*

Multi-layered security Parkhaven:
- Layer 1: Constructing a quay of 0.5 meters on top of existing bank protection and making the bank protection less steep.
- Layer 2: Designing an infiltration system below streets to deal with wave overtopping.
- Layer 3: Evacuation.

Multi-layered security Genemuiden:
- Layer 1: Reinforcing summer levees.
- Layer 2: Using a different type of farming.
- Layer 3: Evacuation of people and cattle.

Multi-layered security Schellinkhout:
- Layer 1: Heightening quays near the fence which catches duckweed and the inlet in the east.
- Layer 2: Choosing a different type of nature which can resist wet conditions.
- Layer 3: Closing the area for visitors.