Managing inland waterbodies in the face of rising sea water levels

A case study of Lauwersmeer's water system and future adaptations using the SOBEK model

Image: https://www.np-lauwersmeer.nl/opknapbeurt-voor-spuicomplex-cleveringsluizen/

UNIVERSITY OF TWENTE.

Waterschap Noorderzijlvest

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I PREFACE

I have written this thesis as the final requirement for my bachelor's degree in Civil Engineering at the University of Twente. The research was done in partnership with the Waterboard 'Noorderzijlvest'. Working with the Waterboard provided me valuable insights into the role of a civil engineer, which goes beyond just creating models or performing calculations; it involves utilizing knowledge to assist others. Witnessing the dedication of the Waterboard staff whilst addressing daily challenges and long-term issues inspired me to further pursue my passion for water management.

I am grateful to my supervisor, Vincent de Looij, for his guidance, feedback, and support throughout this journey. His profound insights have significantly contributed to my comprehension of the provided SOBEK model. Additionally, I extend my appreciation to my internal supervisor, Rick Hogeboom, for his exceptional guidance and constructive feedback.

I hope that you find my thesis report enjoyable to read, and should any queries arise, please do not hesitate to reach out to me.

Kind regards,

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II SUMMARY

The Netherlands has a history of building flood protection structures, including the Lauwersmeer, which was closed off from the sea in 1969. The lake receives water from various streams from Groningen, Friesland and Drenthe provinces. The system maintains a water level of -0.93 m NAP (Normaal Amsterdams Peil, reference height where water level is measured against). However, concerns arise that the system may become insufficient in lowering water levels in the lake due to climate change; mainly sea water level rise. This could compromise water safety in the surrounding area and further inland. Waterboards have been exploring ways to enhance the lake's resilience, such as increasing inland water storage capacity through initiatives like the Onlanden. However, this is not enough, and therefore a pumping station plan is being considered as a solution. The aim of this study is to determine the impact of climate change on the water level on the Lauwersmeer and the impact a pumping station could have on maintaining a safe water level.

To investigate this first historical sea water level data was extrapolated with sea level rise where the sea level rise is added to the historical data to get an insight into the future durations where spouting is not possible at target water level (-0,93 m NAP) and how often and how long this is not possible at different amounts of sea water level rise.

Secondly, the rainfall and sea water levels that are inputs into the model are determined. For these events a once in a ten year ten day (1/10 year 10 day) rainfall and a once in a ten year ten day sea water level event are chosen as for extreme 10 day events the KNMI (Royal Netherlands Meteorological Institute) has predictions for the increase in intensity for different climate scenarios.

Lastly, the SOBEK model (a Deltares water management software) that consist of the water system within the borders of Waterboard Noorderzijlvest is expanded to include a simplification of the water system of Waterboard Friesland This is done to be able to model the water level on the Lauwersmeer more accurately. The extension is calibrated and validated using historical data. Next to extending the model the 10 day events are adjusted to represent climate change scenarios based on the most recent climate paper of the KNMI. The extended model with the accompanying events is run for 4 different climate scenarios per considered timeframe. These timeframes are 2050 and 2100 as they are the explored timeframes in the climate paper.

The results of these methods are that the impact of sea water level rise on the unavailability to spout is visualised in graphs. At target water level (-0.93 m NAP) an average of 45.8 days of unavailability of spouting without sea level rise was found. A similar unavailability is maintained at -0.5 m NAP (48 days/year) at 45 cm sea level rise. Therefore a water level of -0,5 m NAP should be equally maintainable at 45 cm sea level rise, which can be an adaptation to the water system to adapt with climate change. The distribution of rainfall over 10 days in the 1/10 year rainfall is based on extreme rainfall on Lauwersoog. The 1/10 year sea level event based on the highest average sea water level has been chosen to be used in the SOBEK model, because this average is more reliable compared to the peak sea water level.

The addition of Friesland to the SOBEK model enables the impact of the water level on the Lauwersmeer on the discharge from Friesland to be taken into account. The simulation results show that no pumping station is needed before 2050. For 2100, the water level without a pumping station rises to 0.41 m NAP in the low emissions scenario, and a pumping station of

around 100 m3/s (2100 Hd) or more is necessary in the high emission scenario if no other adaptations are put in place.

However, there is a large chance that the determined event is not the worst-case scenario that has a return period of once per hundred years (1/100 years). Therefore, in future research the impact of other combinations and durations of historical and theoretical rainfall and sea water level events on the water level on the Lauwersmeer should be investigated.

III SAMENVATTING

Nederland heeft een geschiedenis van het bouwen van waterkeringen, waaronder het Lauwersmeer, dat in 1969 van de zee werd afgesloten. Het meer ontvangt water uit verschillende waterlopen uit de provincies Groningen, Friesland en Drenthe. Het systeem handhaaft een waterpeil van -0.93 m NAP (Normaal Amsterdams Peil, referentiehoogte waartegen het waterpeil wordt gemeten). Er bestaat echter bezorgdheid dat het systeem te kort kan gaan komen in het verlagen van het waterpeil in het meer als gevolg van klimaatverandering, voornamelijk zeespiegelstijging. Dit zou de waterveiligheid in de omgeving en verder landinwaarts in gevaar kunnen brengen. Waterschappen hebben manieren onderzocht om de veerkracht van het meer te vergroten, zoals het vergroten van de binnenlandse wateropslagcapaciteit door initiatieven zoals de Onlanden. Dit is echter niet voldoende en daarom wordt een gemaal als oplossing overwogen. Het doel van deze studie is het bepalen van de invloed van klimaatverandering op het waterpeil in het Lauwersmeer en de invloed die een gemaal zou kunnen hebben op het handhaven van een veilig waterpeil.

Om dit te onderzoeken zijn eerst historische zeewaterstand gegevens geëxtrapoleerd met zeespiegelstijging, waarbij de zeespiegelstijging is toegevoegd aan de historische gegevens om inzicht te krijgen in de toekomstige tijdsduur waarin spuien niet mogelijk is bij streefpeil (-0.93 m NAP) en hoe vaak en hoe lang dit niet mogelijk is bij verschillende hoeveelheden zeespiegelstijging.

Ten tweede worden de neerslag en zeewaterstanden bepaald die in het model worden ingevoerd. Voor deze gebeurtenissen is gekozen voor een neerslaggebeurtenis met een herhalingstijd van eens in de tien jaar (1/10 jaar) en een zeewaterstand gebeurtenis van eens in de tien jaar, omdat het KNMI (Koninklijk Nederlands Meteorologisch Instituut) voor extreme tien-daagse gebeurtenissen voorspellingen heeft voor de toename in intensiteit voor verschillende klimaatscenario's.

Ten slotte is het SOBEK-model (een watermanagementsoftware van Deltares) dat bestaat uit het watersysteem binnen de grenzen van waterschap Noorderzijlvest uitgebreid met een vereenvoudiging van het watersysteem van waterschap Friesland. Dit is gedaan om het waterpeil op het Lauwersmeer nauwkeuriger te kunnen modelleren. De uitbreiding is gekalibreerd en gevalideerd met behulp van historische gegevens. Naast de uitbreiding van het model worden de tien-daagse gebeurtenissen aangepast om klimaatveranderingsscenario’s te representeren basis van het meest recente klimaat rapport van het KNMI. Het uitgebreide model met de bijbehorende gebeurtenissen wordt uitgevoerd voor 4 verschillende klimaatscenario's per beschouwde moment. Deze momenten zijn 2050 en 2100 omdat dit de onderzochte momenten zijn in het klimaat rapport.

Het resultaat van de eerste methode is de invloed van zeespiegelstijging op de niet-beschikbaarheid om te spuien, gevisualiseerd in grafieken. Bij steefpeil (-0.93 m NAP) is spuien gemiddeld 45.8 dagen niet beschikbaar zonder zeespiegelstijging. Bij -0.5 m NAP en zeespiegelstijging van 45 cm is de beschikbaarheid vergelijkbaar namelijk 48 dagen per jaar. Daarom zou een waterpeil van -0.5 m NAP even goed gehandhaafd moeten kunnen worden bij een zeespiegelstijging van 45 cm als streefpeil zonder zeespiegelstijging, wat een aanpassing aan het watersysteem zou kunnen zijn om mee te bewegen met klimaatverandering. De 1/10 jaar regen- en zeespiegel gebeurtenissen worden samengevat in twee grafieken. De verdeling van regen over 10 dagen in de 1/10 jaar regengebeurtenis is gebaseerd op extreme regenval op

Lauwersoog. De 1/10 jaar zeespiegel gebeurtenis op basis van de hoogste gemiddelde zeewaterstand is daarnaast gekozen om in het SOBEK model te gebruiken op basis van de betrouwbaarheid.

De toevoeging van Friesland aan het SOBEK-model maakt het mogelijk om de invloed van de waterstand op het Lauwersmeer op de afvoer vanuit Friesland mee te nemen. De resultaten van de simulatie laten zien dat er voor 2050 in dit scenario geen gemaal nodig is. Voor 2100 stijgt het waterpeil zonder gemaal tot 0.41 m NAP in het lage emissiescenario, en een gemaal van ongeveer 100 m3/s (2100 Hd) of meer is nodig in het hoge emissiescenario als er geen andere aanpassingen worden gedaan.

Er is echter een grote kans dat de bepaalde gebeurtenis niet het ergste scenario is met een terugkeerperiode van eens in de honderd jaar (1/100 jaar). Daarom moet in toekomstig onderzoek de invloed van andere combinaties en duren van historische en theoretische neerslag- en zeewaterstand gebeurtenissen op het waterpeil in het Lauwersmeer worden onderzocht.

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1 INTRODUCTION

The sea water level will rise at an increased rate as has been found by multiple research groups (Cazenave et al., 2014) (Nerem et al., 2018). Valuable assets such as residences, agricultural land and infrastructure in river deltas close to the sea will be under threat from the sea when the sea water levels will raise in the coming years. At these places, a range of solutions are possible to protect the inland against the sea. One of these options is to build a dam in the sea in front of the river outlets to protect the inland water fronts (former coastline). The dam will be connected on both sides to the exiting coastline and will become the new coastline and the inland waterbody will become a lake. Water from this lake needs to be discharged. As in the former situation the river water was discharged into the sea. This method has already been used in the Netherlands, resulting in the IJsselmeer and the Lauwersmeer, to shorten the coastline and protect the inland. Here the discharge takes place under freefall via sluices. This is a more energy efficient way to dispose the water instead of pumping water out of this lake area. Disposing water at free fall will become more challenging in the future with sea level rise; where a lower sea water level than the level on the lake is needed for the water to flow under freefall into the sea.

The Netherlands boasts a rich history of constructing protective structures against flooding to safeguard its residents. Like later at the Lauwersmeer, in 1920, the construction of the Afsluitdijk (a) was initiated to shield the coastline inland and enclose the then Zuiderzee from the Waddenzee, thereby converting it into the IJsselmeer (i) which can be seen in Figure 1 below with the corresponding letters. The Lorentzsluizen sluice complex in the Afsluitdijk serves to release surplus water flowing into the 'IJsselmeer' from the IJssel and Vecht rivers. The discharge of excess water through the sluices to the sea is only possible when the water level on the 'IJsselmeer' is higher than the water level of the sea.

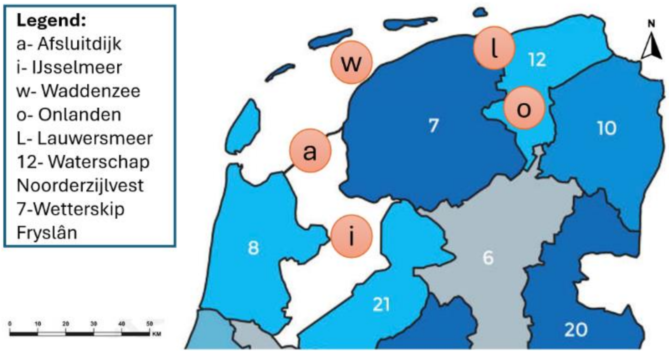

*Figure 1: Map of the North of the Netherlands with places highlighted mentioned in the text (*Waterschappen Op de Kaart van Nederland*, n.d.)*

With the impact of climate change, the instances of the water level being sufficiently low for discharge at sluices connected with the sea will decrease as can be seen in Figure 2. This poses a threat to water safety in the vicinity of the lake and further inland. Consequently, a new pumping station is being constructed at Den Oever at the west end of the Afsluitdijk to enable independent water discharge regardless of sea water level. Whether and which size pumping station would be necessary for the Ijsselmeer has been researched by Verboom in 2010 (*Voorverkenning lange termijn peilbeheer IJsselmeer*, 2010). In this study 14 different cases are considered, where different pumping capacities at the opposite ends of the Afsluitdijk are modelled with different climate change scenarios. The most impactful scenarios for 2050 and

2100, with sea level rise of 35 cm for 2050 and 85 cm for 2100 estimated to be the worst case scenario by in the climate paper from the KNMI of 2006 (Hurk et al., 2006) and 130 cm which was the worst case scenario the Deltacommissie, (2008) prescribed for 2100 to take into account. where the minimal required capacity was 500 m^3/s for 2050. It could be that there are plans to install an extra pumping station in the future, to fulfil this calculated expected capacity of the pumping station.

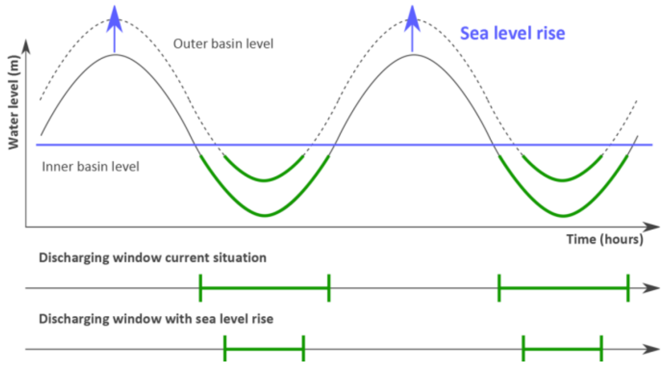

Figure 2: Graph to illustrate impact of sea water level rise on spouting capacity (Image taken from (Van Manen, 2014))

At the Lauwersmeer, the current system is operating effectively, maintaining a water level close to the target water level most of the time. However, there are concerns about its future adequacy in lowering the water level due to climate change and rising sea water levels. It is anticipated that in the future it will be impossible to discharge water into the Waddenzee (w) because the sea water level does not drop below the water level on the Lauwersmeer (l). If heavy precipitation occurs in the Lauwersmeer catchment during this period, water safety in the area and further inland could be compromised. Waterboards have been exploring ways to enhance the Lauwersmeer's functionality for the future, such as increasing inland water storage in places like the Onlanden (o); close to the city of Groningen or increasing the height of the regional water defence structures around the Lauwersmeer. Despite these research efforts, the installation of a pumping station has been proposed as the ultimate solution, although it is considered costly and was not deemed feasible in 2010 (Dahm et al., 2010).

From literature study conducted for this thesis only one comparable case where dams have been built to protect the inner land from the sea. In Bangladesh, the Feni dam has been constructed in 1985 to protect the inland areas form typhoons and floods (Stroeve, 1993). Investigations on the construction and robustness of the dam have been conducted in this master thesis. However, no investigation was found on the impact of climate change on the functioning and future of this dam.

1.1 REPORT OUTLINE

The structure of the rest of this report is as follows. The subsequent chapter will delve more into the context regarding the increasing water level issue. This includes details about the parties involved, the study area, an in-depth look at how the Lauwersmeer became how it is nowadays and the current functionality of the Lauwersmeer and last the formulation of the research objective based on the problem statement. Chapter three will present the research framework, outlining the steps taken in this study, followed by the research methods that details how the research has been done. Chapters four, five, and six will highlight the results of the three research questions. Chapter seven will present the conclusions, followed by the discussion in chapter eight. Subsequently, recommendations for the Waterboard as well as for future research will be provided in chapter nine. Finally, the report will conclude with the bibliography and appendices.

2 PROJECT CONTEXT

Within this chapter, the research context is clarified. Initially, an overview of the stakeholders engaged in the project is outlined, providing their perspectives and requirements. The subsequent section starts with a broad overview, then delves into a detailed description of the research area (Lauwersmeer) relevant to this thesis. The chapter on context wraps up with the problem statement, research objective and lastly the research questions.

2.1 INVOLVED PARTIES

Waterboard Noorderzijlvest has commissioned this project. The outcome of this project is among others important for the inhabitants of the region and the catchment in the northern part of the Netherlands, therefore it is important for the provinces Groningen and Friesland as well as waterboards Noorderzijlvest and Fryslân. These governmental bodies are responsible for the safety of their inhabitants. The national government as well as Rijkswaterstaat are included for big projects surrounding the safety of the people and should be included in the process to be able to finance large civil engineering projects. Next to this, the European Union supports projects like this with loans with longer maturities, grace periods and low interest rates to include side projects like fish migration solutions and protecting nature in the process (Vertegenwoordiging in Nederland, 2024).

Also, local businesses and farmers could experience a substantial impact when the conditions on the Lauwersmeer change. When the area becomes more flood prone and higher water levels will be more frequent, farmers will need to adapt to the new circumstances when for example the target water level on the Lauwersmeer is adjusted.

The commissioner of this project: Waterboard Noorderzijlvest is responsible for regional waters, such as canals and polder waterways. They also protect the land from floods and make sure farmers have enough water for their crops. It is a governmental body that collects taxes with which they service their inhabitants as best as they can.

2.2 AREA AND WATER SYSTEM DESCRIPTION

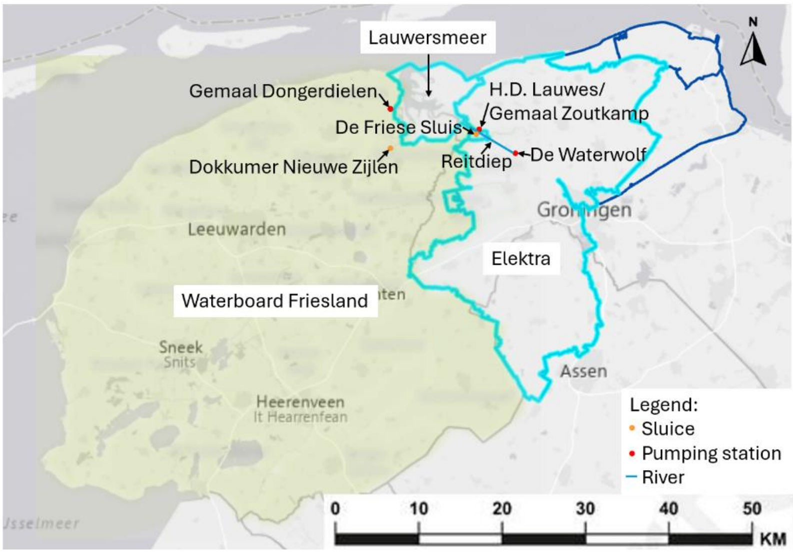

Figure 3: Study area

The study area is shown in Figure 3 in bordered in light blue and green. Elektra is the water system leading to the Lauwersmeer from Groningen. The water from catchment Elektra flows trough the Reitdiep; a canal in the Province of Groningen. Pumping station H.D. Lauwes (1050 m^3/min (Gemalendatabase, n.d.)) at Zoutkamp which will soon be replaced by the new Gemaal Zoutkamp (1600 m^3/min) are positioned at the south end of the Lauwersmeer. Together with the pumingstation De Waterwolf, located in Lauwerzijl, with a capacity of 4500 m^3/min, the new gemaal Zoutkamp pumps the water towards the Lauwersmeer when the water level in the hinterland becomes too high (Waterbeheerplan Lauwersmeergebied 2003-2007, 2007). There are no specific rules for spouting. A combination of several criteria determines if the pumping stations will be turned on. Those criteria are;

- The water level in the hinterland;
- The water level on the Lauwersmeer;
- The conditions at the R.J. Cleveringsluizen; can the water be discharged to the Waddenzee or not;
- Expected precipitation

Next to the catchment Elektra and Lauwersmeer, there is water coming in form Waterboard Fryslân. This is however not in control of the Waterboard Noorderzijlvest so will be considered an outside influence but will be taken into account in this study. This research will mainly focus on the water level of the Lauwersmeer, which is situated at the top of Figure 3 and is shown in greater detail in Figure 4 below. The evolution of this area is explained in detail in Appendix A.

*Figure 4: Study area zoomed in (*Geo Portaal Noorderzijlvest*, n.d.)*

In this Lauwersmeer area the main interest of this research focuses on 4 things:

- The quantity of water the R.J. Cleveringsluizen, red circle in Figure 4, can discharge from the Lauwersmeer to the Waddenzee
- The sea water level at the Waddenzee at the R.J. Cleveringsluizen
- The impact of climate change on the water level in the Lauwersmeer
- The impact a pumping station can have on the water level in the Lauwersmeer

Current state of the area

The Lauwersmeer is of immense importance for the water safety of the Noorderzijlvest Waterboard. During times of heavy precipitation and high sea water levels, the lake acts as a temporary 'parking lot' for excess precipitation, until the water flows under free flow via the R.J. Cleveringsluizen which can be seen in Figure 5. The blue line in this figure represents the sea water level and the red line shows the water level on the Lauwersmeer. There you see the water level on the Lauwersmeer slowly rise and drops when the sea water level is below the Lauwersmeer water level.

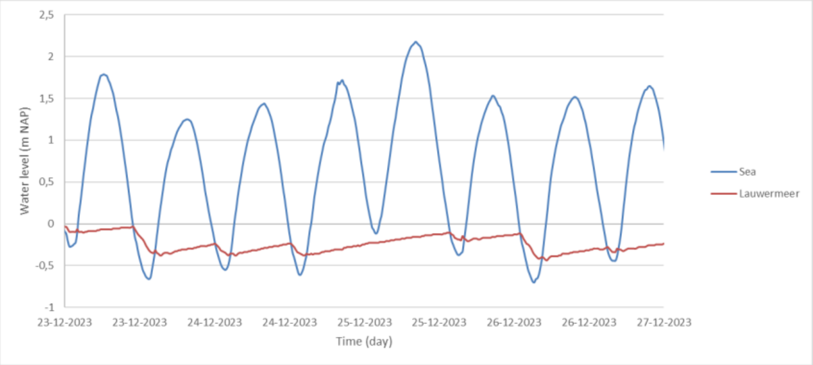

*Figure 5: Graph of sea water level compared to water level in Lauwersmeer (*WAM Portaal*, n.d.)*

However, with rising sea water levels the system described above will not work in the future. The Lauwersmeer currently has a target water level of 0.93 m beneath NAP (*Rietproef Lauwersmeer*, n.d.). From 1991 till 2020 the sea water level was beneath this target water level18 percent of the time. At a certain point, sea water levels have become so high that the sea water level at low tide is not low enough and the water from the Lauwersmeer can no longer be discharged properly under free flow. Around the change of year from 2023 to 2024 the sea water level was high and there was a lot of precipitation. Data gathered during this period with high sea water level and high precipitation provided insight in the future functioning of the Lauwersmeer. This can be seen in Figure 6 below.

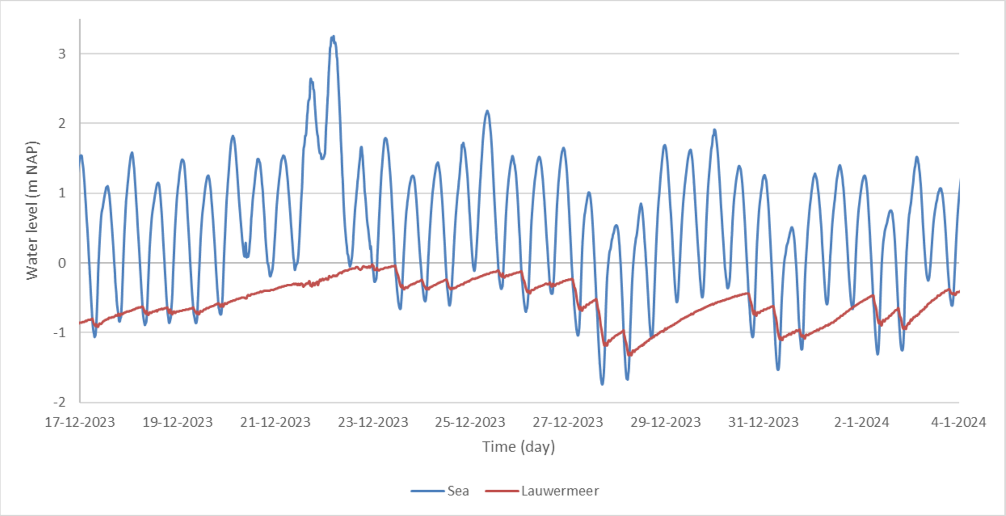

*Figure 6: Graph of sea water level compared to water level in Lauwersmeer with high sea water level (*WAM Portaal*, n.d.)*

The water level in the Lauwersmeer was at its highest around 0 m NAP. This water level is high, without an increase of sea water level, the question is how this will progress with the expected sea level rise in the future.

The government determined that it is allowed for the Lauwersmeer to be flooded with a recurrence time of once per hundred years (1/100 years). The regional water defence structures are built for a maximum water level of 0.4 m NAP (Gedeputeerde Staten van de provincie Groningen, 2017). It is unknown at which point in time this safety limit and the target water level in the Lauwersmeer (-0.93 m NAP) cannot be maintained, taken the expected climate change into consideration.

With this study an insight into what the impact of future climate change brings to the functioning of the Lauwersmeer system will be investigated and some recommendations will be given.

2.3 STUDIES CONDUCTED IN THE PAST

Some attempts have been made in the past to get a look into the future of the functioning of the Lauwersmeer and possible solution directions were proposed. One of these attempts, the most recent one, is discussed in the section below. A master thesis on a pumping station on the Afsluitdijk will be discussed as well. Next to this, the most recent Dutch climate report from the KNMI will be discussed since scenarios from this paper will be used in the research.

Similar to this thesis, Deltares did an exploratory study for Waterboard Noorderzijlvest and Waterboard Fryslân on the impact of a pumping station on the functionality of the Lauwersmeer in the future named ‘Gemaal Centraal Lauwersmeer’ in 2010 (Dahm et al., 2010). In the study described in this report, the base model used is an improved and updated version of the SOBEK model that was used for the research conducted by Deltares. They used inflow data from 2002 till 2006 as input for the model, in combination with climate change insights from around 2010. This inflow data comes from 3 inflow points onto the Lauwersmeer; Pumping station

Dongerdielen, measurement point Zoutkamp and sluice complex Dokkumer Nieuwe Zijlen. The discharge events at these places combined are analysed and the high discharge peaks above a certain threshold are considered to calculate a once per ten year (1/10 year) peak discharge. All the peak discharge events are than adjusted by adding or subtracting a certain amount of discharge, so the peak has the same height as the calculated 1/10 year peak and the adjustment is done as well for the 5 days prior as well as the 5 days after the peak. Then an average of this adjusted event is taken and transformed into a 1/10 year discharge event without climate change. For the sea water level they chose an event from historical data from the end of October of 1998, this was aligned and agreed with both the Waterboard Noorderzijlvest as well as Waterboard Fryslân. The outcome of this analyses are shown in Figure 7 below.

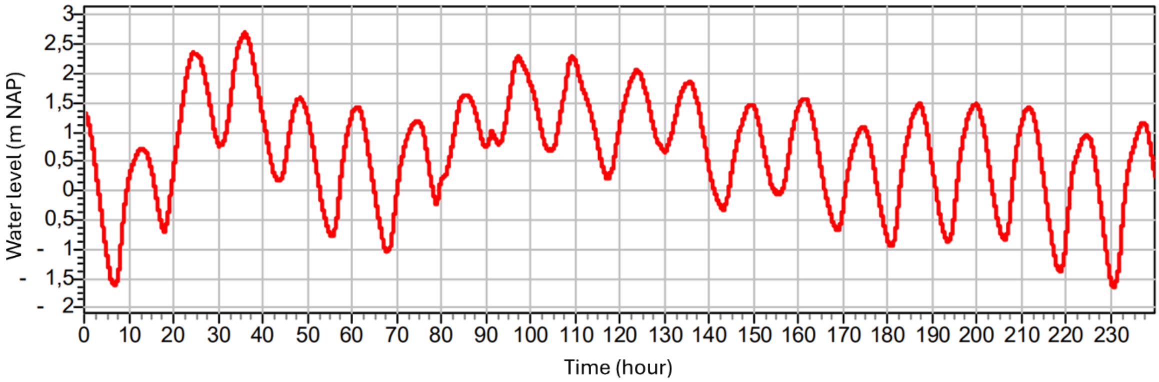

Figure 7: Historical sea water level graph (T=0 is 24th of October 1998, 12:00) (Dahm et al., 2010)

In Dahm et al. (2010), the 1/10 year peak discharge event was combined with the sea water level event of October 1998 in the SOBEK model where the events were adjusted for the different climate change scenarios based on Hurk et al., (2006), the previous paper on climate change by the KNMI.

After this simulation, a pumping station was implemented into the SOBEK model where the capacity of the pumping station increases with rising water levels on the Lauwersmeer.

The conclusion of Dahm et al. (2010) was that further research is needed. They recommended to adjust the functioning of the R.J. Cleveringsluizen in the SOBEK model to come more close to how they are managed in real live. Next to this, the impact of the water level on the Lauwersmeer on the inflow onto the Lauwersmeer should be investigated.

In addition, they did not investigate what effect the sea water level rise would have on the day-to-day water level on the Lauwersmeer when periods occur when the sea water level does not drop enough to allow water to flow freely from the Lauwersmeer into the Waddenzee at the target water level of –0.93 m NAP. The Waterboards are also interested in how many days in a row no water can be discharged at target water level, when the sea water level is too high to discharge water in free flow. Based upon the recommendations from Dahm et al the Waterboard Noorderzijlvest would like to investigate how a pumping station can impact the water system of the Lauwersmeer and what capacity the pumping station needs to have at which moment in time.

A similar study was done on the Ijsselmeer (ter Maat & van Meurs, 2010). This paper discusses the impact of 14 different cases. These cases are combinations of worst case climate change scenarios for 2050 and 2100 (with respectively 35, 85 (Hurk et al., 2006) and additionally 130 cm (Deltacommissie, 2008) for 2100) and different pumping station configurations are considered.

The precipitation, evaporation, inflow from the Rine and sea water level rise were adjusted to fit the different climate change scenarios. These scenarios were run for historical adjusted data from 1951 till 1998. For every day the average and maximal water level on the IJsselmeer were recorded. The average of the same day every year is taken and plotted for the different scenarios to visualise the effect of the scenarios. The reason for using historical data from 1951 till 1998 is not explained in this paper. The practice of using historical data and extrapolate climate change on this data can be a good method to apply in future research to determine necessary pumping capacity for different climate scenarios.

Climate scenarios play an important role in this thesis as the impact of different scenarios are investigated. The most recent climate scenarios for the Netherlands are elaborated in the latest publishing by the KNMI on the climate change scenarios and their impact on The Netherlands (van Dorland et al., 2024).

For the precipitation intensities the paper from the KNMI as mentioned above works with 2 models, RACMO and EC-Earth3. The different models ran with scenarios where the CO2 emission levels and extremely whether scenarios; where it will become wetter or dryer, were used. This has been done for different moments in time respectively 2050, 2100 and 2150. One of the results of all the scenarios that were run was a 1/10 years 10-day maximum area-average precipitation where a percentage change of the total precipitation was found. This percentage is used in the research described in this thesis. Next to this, the average sea water level change for all the different climate change scenarios are determined. The data in the paper is mostly on the years 2050 and 2100. Since it is a paper about expected climate change, there is a lot of uncertainty in the scenarios but as the most recent and relevant paper in this area, it is the most useful information available.

2.4 PROBLEM STATEMENT AND RESEARCH OBJECTIVE

In this chapter, the problem statement and the research objective will be presented.

Problem Statement:

The Lauwersmeer cannot function in the same way it currently does when sea water level will increase too much. When the R.J. Cleveringsluizen, as the only outflow point of the Lauwermeer, cannot release water onto the Waddenzee because the sea water level does not drop beneath the target water level or current water level on the Lauwersmeer. When this drop in sea water level below the Lauwersmeer water level does not occur often enough but there is precipitation, the water level on the Lauwersmeer will rise above the target water level and will keep rising until the sea water level drops beneath the water level in the Lauwersmeer. This can have substantial impact on the environment and is against water safety regulations.

Research Objective:

The primary goal of this research is to determine the threshold of the sea water level rise at which the current system for utilizing the function of the Lauwersmeer can no longer function effectively. Effectively is meant here as to when the target water level of the Lauwersmeer can be maintained on a regular basis. Next to this, the maximum water level of 0.4 m NAP should have a return period of at least once in a hundred years as decided by the Gedeputeerde Staten van de provincie Groningen, (2017).

2.5 RESEARCH QUESTIONS

Three main research questions follow from the research objective.

1. What impact do various levels of future sea water level rise have on the unavailability of spouting via the R.J. Cleveringsluizen?
2. What dimensions do a ten day per once in a ten-year (10 day 1/10 year) precipitation event (mm total) for the Lauwersmeer catchment and a 10 day 1/10 year sea water level event (cm increase) at Lauwersoog have?
3. What capacity should a pumping station on the Lauwersmeer have to be able to comply with current safety criteria in 2050 and 2100 at different climate scenarios?

These three questions take the impact of different climate change scenarios on the water level and potential future pumping stations on the Lauwersmeer into account.

3 RESEARCH DESIGN

This section provides an explanation of the research methods. It outlines the techniques and related stages for each section within the research framework, ensuring a clear understanding of the research process. The last section presents a research framework to provide a comprehensive understanding of the different steps and inputs used to get the results presented in this thesis.

The objective of this research is to get an insight into what the impact of sea water level rise is on the unavailability to spout from the Lauwersmeer to the Waddenzee. Next to this, it will be determined when a pumping station or other interventions are needed to keep the water level on the Lauwersmeer beneath the maximum water level of 0.4 m NAP.

First the methodology to answer research question 1 is explained. For this, the outcome is the average amount of days in a row per year where the sea water level does not drop beneath target water level of the Lauwersmeer (and additional higher water levels). Then the methods used to determine the 10 day 1/10 year sea water level and precipitation events are described. These events are then used as input for research question 3 where these events are adjusted to represent different climate change scenarios which have been used as input for the SOBEK model. The impact on the water level on the Lauwersmeer of these different climate change scenarios and a pumping station are added to the SOBEK model. The results of this analysis are used for the recommendation on the need of a pumping station.

3.1.1 Method to determine the impact of sea water level rise on the average unavailability to spout

In this question it was assumed that sea water level rise had no other impact on the water level of the Lauwersmeer other than the average increase. The other implications of climate change like changes in wind patterns and, more extreme weather could be taken into consideration, but this would require its own research topic. Rijkswaterstaat is trying to accomplish this research as they are trying to get more insight in the behaviour of the Waddenzee together with the impact of climate change on the Waddenzee. Leaving out these wind patterns and more extreme weather conditions has been chosen to simplify the problem and to be able to complete this research within the time given. With the assumptions that wind patterns and extreme weather conditions do not appear, the number of days where the sea water level does not drop beneath the investigated sea water level could be analysed. This has been done for the period between 1991 till 2020, which van Dorland et al. (2024) considers to be the reference period for the sea level. This investigated sea water level analysis will therefore be elaborated and explained in the sections below. The first step conducted was the collection of sea water level data. Data on sea water level at Lauwersoog has been collected since the first of January 1990. This data is accessible via the open data portal of Waterboard Noorderzijlvest via the WAM protaal (*WAM Portaal*, n.d.). This data was exported as Microsoft excel files. The time and sea water level data were extracted between 1st of January 1991 and 31st of December 2020 which was collected about every 15 minutes.

The time and sea water level data gathered in the section above was exported to Microsoft Excel where the ‘date’, ‘time’ and ‘sea water level’ at that point of time were given. For every measurement point there was a check if the sea water level at that point was lower than the target water level of the Lauwersmeer (-0.93 m NAP). If the sea water level was higher than the threshold, the time between this measurement and previous measurement was added to the time noted at the previous time step. If the sea water level was lower than the threshold, the time was reset to 0.

The time between the sea water level dropping beneath the target water level of the Lauwersmeer is the value above the time being reset to 0.

The sea water level data was extended over multiple columns where 5 cm was added to the data every step increases till 150 cm was added to the original sea water level data. 150 cm was chosen as the maximal sea water level increase as in the KNMI climate scenarios the worst case scenario for 2100 the sea water level rises with 127 cm (van Dorland et al., 2024). To get a margin and be able to look further into the future the 150 cm was chosen. These sea water levels were also subjected to the same process as proposed in the previous section to determine how much time passes between instances where the water level drops beneath -0.93 m NAP.

Next to analysing the time in between the instances where the sea water level dropped beneath the target water level on the Lauwersmeer, also sea water levels beneath -0.5 m, 0 m and 0.4 m NAP were analysed. 0.4 m NAP was chosen as the highest considered water level on the Lauwersmeer because this is the water level for the Lauwersmeer above which it is considered to be flooded. This has been done to also get an insight into what happens to the unavailability of spouting at higher water levels on the Lauwersmeer and what the influence of sea water level rise is. The steps from the 2 sections above are repeated for the higher spouting levels on the Lauwersmeer.

3.1.2 Method to determine extreme precipitation and sea water level events

The second research question is answered through a two-step approach. First step is Determining a 1/10 year 10 day precipitation event, the second step is determining a 1/10 year 10 day sea water level event. These two events were chosen as the Lauwersmeer is permitted to have a flooding reoccurring time of 1/100 years. Combining two 1/10 year events approaches a 1/100 year event. Next to this, in van Dorland et al. (2024), the impact of climate change on the heavy precipitation event during 10 days and occurring 1/10 years has been quantified. Therefore it was chosen to use two 1/10 year events to evaluate the impact of climate change on the water level on the Lauwersmeer. How these events were determined is explained in the sections below.

To determine 1/10 year 10 day precipitation event data from 1991 till 2020 had been used. These years were considered as they were the period used by the most recent climate paper for the Netherlands (van Dorland et al., 2024). These years were considered the years without climate change and those years they were the years van Dorland et al compared the impacts of climate change to.

Daily precipitation data from Middelstum, Joure, Veenhuizen, Sint Anna Parochie and Bergumerdam from the KNMI database were used (*Dagwaarden Neerslagstations*, n.d.). These are places where the KNMI has gathered precipitation data during the period of interest from 1991 till 2020. These places are spread over the catchment of the Lauwersmeer to cover the whole area and lower the impact of local rain showers that are not representative for the catchment. This data was analysed and the highest rainfall sum of 10 consecutive days per year was found.

With the max precipitation data of 10 consecutive days from 30 years, the method as described in Gumbel (2012) was used to determine 1/10 year sum of precipitation over 10 days. The basis of the method proposed by Gumbel was the relation between the probability of something occurring with the return period. This formula can be found in Appendix B.

This 10 day sum of precipitation that occurs 1/10 years was then applied to a distribution over the days and hours of the 10 days. For precipitation events of 8, 12, 24 or even 48 hours model distributions exist. However, no model precipitation event has been found for 10 consecutive day analyses. Therefore, a historical high precipitation period was used, where data per hour was available. This was scaled to the 1/10 year 10 day sum of the precipitation by using a multiplication factor. The historical precipitation event that was used has been taken from Lauwersoog as this is in the centre of the precipitation area flowing on the Lauwersmeer.

To determine the 1/10 year 10 day sea water level event, data from 1991 till 2020 was used, as the most recent climate paper for the Netherlands considered these years the years without climate change and those were the years that paper compared the impacts of climate change to (van Dorland et al., 2024).

Sea water level data measured at Lauwersoog was used. These measurements were generally taken every 15 minutes, with sometimes a few seconds difference.

For this research two approached to extract the 1/10 year 10 day event are used. The first one uses the highest sea water level recorded per year. Using Gumbel the 1/10 year peak sea water level was determined as described in Appendix B. This approach was inspired on the approach used by Dahm et al (2010), where the peak discharge into the Lauwersmeer per year was extracted and Gumbel was used to extract a 1/10 year discharge event onto the Lauwermeer. In the second approach, the highest average 10 day period was extracted from the data. This was done by summing up all the sea water levels for a period of 10 days and comparing it to all the other 10 day periods in that year and selecting the highest.

The second approach was an elaboration on the inspired approach used by Dahm et al (2010). This elaboration was chosen to check if this method gives a more impactful 1/10 year sea water level event, where spouting is not possible at target water level for more days in a row, due to a constant high sea water level as can be seen in Figure 8 below.

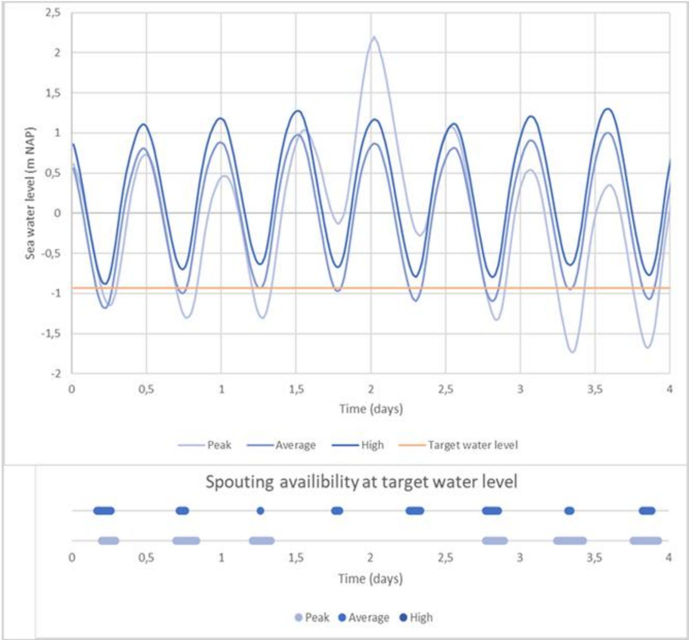

Figure 8: Impact of different sea water level events on the availability to spout at target water level

The 1/10 year peak sea water level and average sea water level have been used to create 1/10 year 10 day events. The sea water level data 5 days before and 5 days after the peak discharge have been collected as well as the sea water level during the 10 days with the highest average sea water level. An average of the extracted data for the peak sea water level as well as the average high sea water level for every timestep is taken. These average events are then adjusted by adding an artificial sea water level rise to all time steps to adjust the event to fit the 1/10 year values.

3.1.3 Method to determine the necessary pumping capacity for different climate scenarios

The method used to answer the third research question will be described below. The existing SOBEK model of Waterboard Noorderzijlvest covers the catchment of the Lauwersmeer. The part of the catchment that lays outside the boundaries of the Waterboard Noorderzijlvest is inside the boundaries of Waterboard Fryslân. The excess water from Friesland is preferably discharged onto the Lauwersmeer where the water can leave the area under freefall. The water from Friesland can also be discharged via pumping stations towards the IJsselmeer and the Waddenzee. In former research conducted on the required capacity of a pumping station on the Lauwersmeer, the inflow from Friesland was assumed to not be impacted by the water level on the Lauwersmeer. Next to that the impact on the discharge caused by climate change were assumed to be the same as the inflow from the precipitation and was implemented by adding a percentage increase meant for the precipitation onto the discharge. This is an important simplification in the SOBEK model by Dahm et al (2010) that can be improved. Therefore, in this research a compact model of Friesland was implemented into the SOBEK model to integrate the impact of the water level on the Lauwersmeer on the discharge from Friesland.

To be able to implement the inflow of water from Friesland into the SOBEK model, first some generalisations needed to be identified. This contrasts with the SOBEK model for the Lauwersmeer catchment area of the Noorderzijlvest Waterboard as this was very detailed. However, the data needed for this inflow of water from Friesland was not readily available. To gather this data would take a lot of time. As the main interest for this research regarding the Lauwersmeer catchment area is the water level on the main waterbodies and discharge onto the Lauwersmeer for a given precipitation event, the complex inner workings of the water system in Friesland was not needed to be modelled in detail. Therefore, Friesland was divided into:

- The main waterbodies that connect with each other under freefall (boezem) later called ‘waterbodies’
- The area that drains directly onto the waterbodies
- The polders that pump their water onto the waterbodies
- A higher laying area that discharges under freefall trough weirs to the waterbodies

The dimensions of the areas described above and structures, such as sluices and pumping stations, were based on documents available on these structures and areas.

The extension of the model was calibrated by adjusting the profiles and roughness coefficient of the area and functioning capacity of pumping stations. By studying the impact on the Nash-Sutcliffe Efficiency coefficient (NSE) and graphs of the discharge and water level the calibration were adjusted. The model's performance was assessed using the NSE in Equation 1 below.

$$NSE = 1 - \frac{\sum(O - M)^2}{\sum(O - \bar{O})^2}$$

Equation 1: Nash-Sutcliffe Efficiency (NSE)

Where:

O is the observed value (water level in m NAP or discharge in m^3/s)

M is the modelled value (water level in m NAP or discharge in m^3/s)

$\bar{O}$ is the mean observed value (water level in m NAP or discharge in m^3/s)

An NSE of 1 indicates a perfectly fitting model. However, if the result is below zero, a mean of the observed values is a better fit than the modelled outcome.

At first, the first 15 days of 2023 (1st of 15th of January 2023) where the first 5 days are the warmup period were simulated and calibrated because there were a lot of variables that have different degrees of impact on the results and to make sure the addition functioned as was intended. Secondly, when the model was functional, it was calibrated to the period of 1st of January 2023 till 28th of February with a warmup period of the first 10 days.

Validating the model was an important step in ensuring the accuracy of the addition of Friesland to the model. The process consisted of using a historical event that differed from the one used for the calibration. This approach ensured that the calibration process was based on the underlying hydrological principles rather than relying on parameter fitting. By subjecting the model to a validation event, its robustness was tested by pushing it beyond the calibrated boundaries, thereby increasing its reliability. The model's performance was assessed using the Nash-Sutcliffe Efficiency coefficient (NSE) which can be seen in Equation 1 above. The discharge and water level of the Friesland waterbodies were tested as well as the water level of the Lauwersmeer to validate the model as a whole.

Van Dorland et al. (2024) quantified the impact of different climate scenarios on the sea water level rise and the percentual increase in the total 1/10 years 10 day precipitation. This paper divided climate change scenarios into low emissions (L), high emissions (H), dryer (d) and a wetter (n) scenarios for 2050 and 2100. They calculated the impact of their defined scenarios on the sea water level (cm) as well as on 1/10 year 10 day precipitation total (%) based on the reference years used in this paper (1991 till 2020). The results of those calculations can be found in Table 1 below. As for the low emission scenarios the sea level rise and rainfall intensities were identical, these scenarios have been combined.

Table 1: Impact of climate change scenarios on the average sea level and 1/10 year rain event (van Dorland et al., 2024)

	2050 L	2050 Hd	2050 Hn	2100 L	2100 Hd	2100 Hn
Average increase in sea water level (cm)	24	27	27	44	82	82
1/10 year 10 day rain event (% increase)	3	0	4	3	8	16

These numbers could be used to transform the 1/10 year rain and sea water level events into events that represent different moments in time with different climate change scenarios.

The 10-day events that had been determined in research question 2 were now adjusted to fit the climate scenarios of van Dorland et al. (2024) using Table 1. The adjustment to the sea level event was the addition of the centimetres to every water level in the event. The hourly rainfall of the 10 day event was increased with percentage increase shown in Table 1 above. To determine the magnitude of the future pumping station in the SOBEK model the capacity from other pumping stations in the area was gathered and used as a guidance. The capacity of these nearby non polder pumping stations have been listed in Table 2 below.

Table 2: Capacities other pumping stations

Name	Location	Capacity
Gemaal Hunsingo	Zoutkamp	27 m^3/s
De Waterwolf	Lammerburen	75 m^3/s
New pumpingstation on Afsluitdijk	Den Oever	275 m^3/s

Gemaal Hunsingo, which is being built from 2023 till 2025, and De Waterwolf release its discharge onto the Lauwersmeer. The first simulated pumping station in the SOBEK model had a capacity of 100 m^3/s (adding the capacity of the two pumping stations 'Gemaal Hunsingo' and 'De Waterwolf' togehter). This pumping station with a capacity of 100 m^3/s was run with the most intense climate scenario (2100 Hn), which is the worst-case scenario. The pumping station with this capacity could not handle this worst-case scenario, therefor the simulation was adjusted with pumping stations with higher capacity to see which capacity was able to handle this worst-case scenario. To also check the less extreme scenarios pumping stations with lower capacities were also simulated. The capacity of the pumping station was adjusted to the magnitude that keeps the water level on the Lauwersmeer beneath 0.4 m NAP . The pumping stations capacities used in the simulation were: 200, 100, 50, 25 and 10 m^3/s.

The pumping station turned on in the model when the water level reaches above -0.5 m NAP. This –0.5 m NAP level was chosen to have some buffer between the target water level and the activation of the pumping station. The full capacity of the pumping station was used as it was assumed that when a not often reoccurring precipitation and sea water level event takes place, no pumping capacity will be spared to mitigate the effects. The pumping station will not turn off when water can be discharged under freefall.

3.2 RESEARCH FRAMEWORK

The objective of this research is to determine the threshold of the sea water level rise at which the current system for utilizing the function of the Lauwersmeer can no longer function effectively. This has been done by getting an insight into the impact of sea water level rise on the unavailability to spout water from the Lauwersmeer onto the Waddenzee and the impact of climate change on the water level on the Lauwersmeer in the event of high precipitation and high sea water levels.

In Figure 9 below the steps that will be taken during this research are shown as well as the order in which the steps are taken. Question 1 is an independent question that answers what impact sea level rise has on the daily unavailability to spout water to maintain the target water level on the Lauwersmeer. The output of question 2 (2a and 2b) is used as input for question 3 and together they answer what impact the considered climate change scenarios have on the water level on the Lauwersmeer.

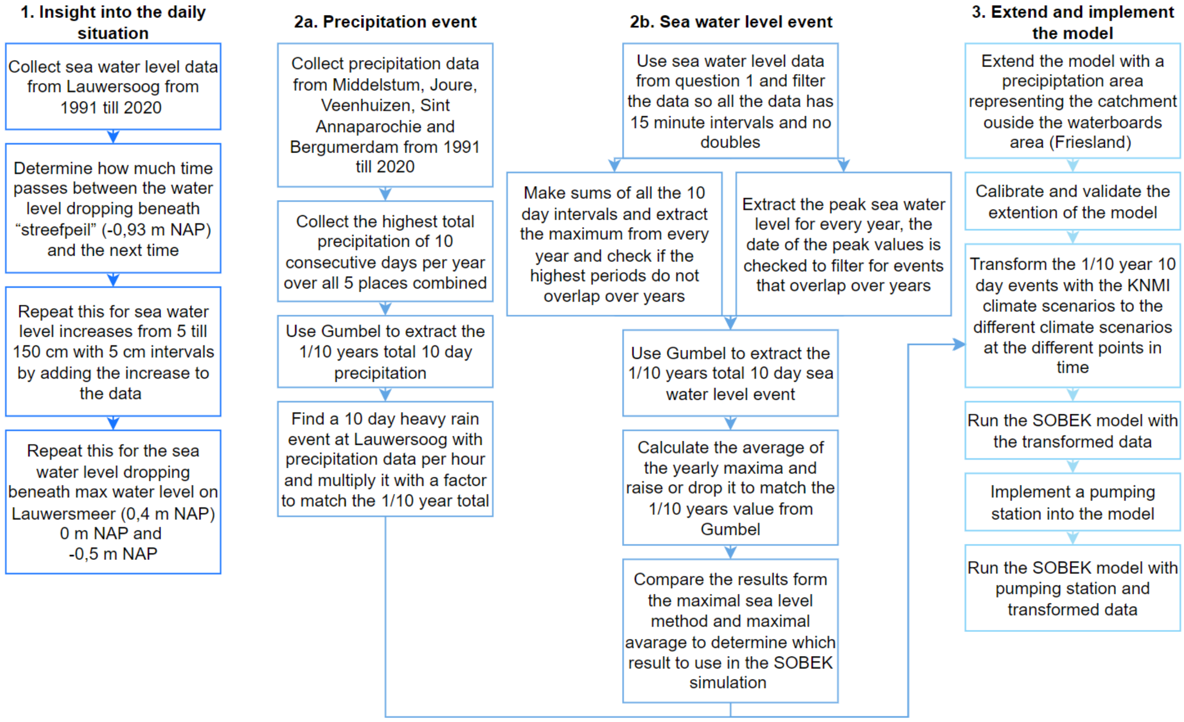

Figure 9: Research framework

4 THE IMPACT OF SEA WATER LEVEL RISE ON SLUICE SPOUTING TO THE SEA

The objective of this research was to get an insight into the impact of sea water level rise on the unavailability to open the R.J. Cleveringsluizen to answer research question 1. In Figure 10 below the results of the data analysis can be seen. Where the total number of days where the sea water level does not drop beneath different chosen water levels is shown.

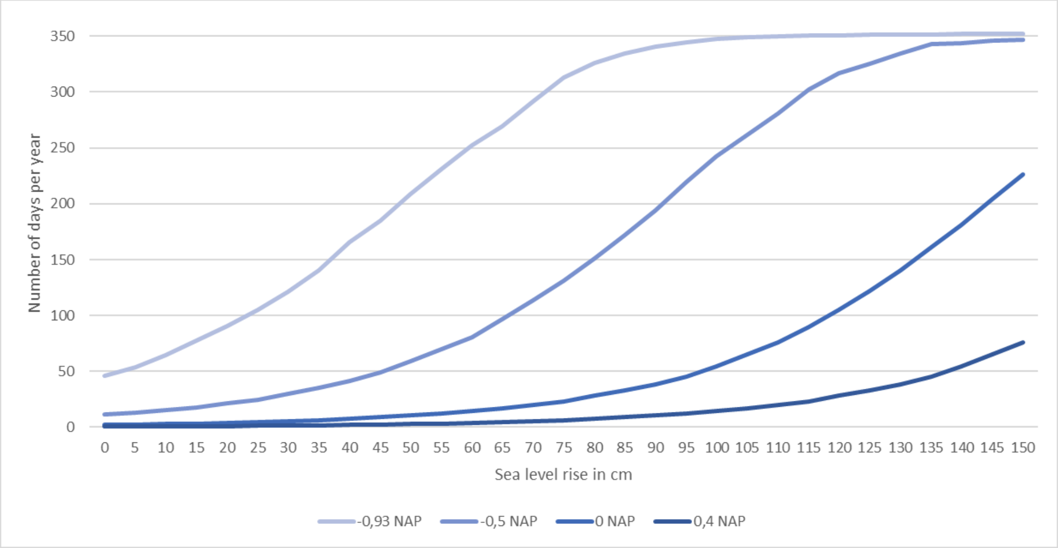

Figure 10: Average total number of days in a year at different sea level increases where the sea water level does not drop beneath -0.93, -0.5, 0 and 0.4 m NAP

For each individual duration of the non-exceedance levels at -0.93, -0.5, 0 and 0.4 m NAP that have been analysed the results can be seen in respectively Figure 11, Figure 12, Figure 13 and Figure 14 below. The data behind these graphs can be found in Appendix C.

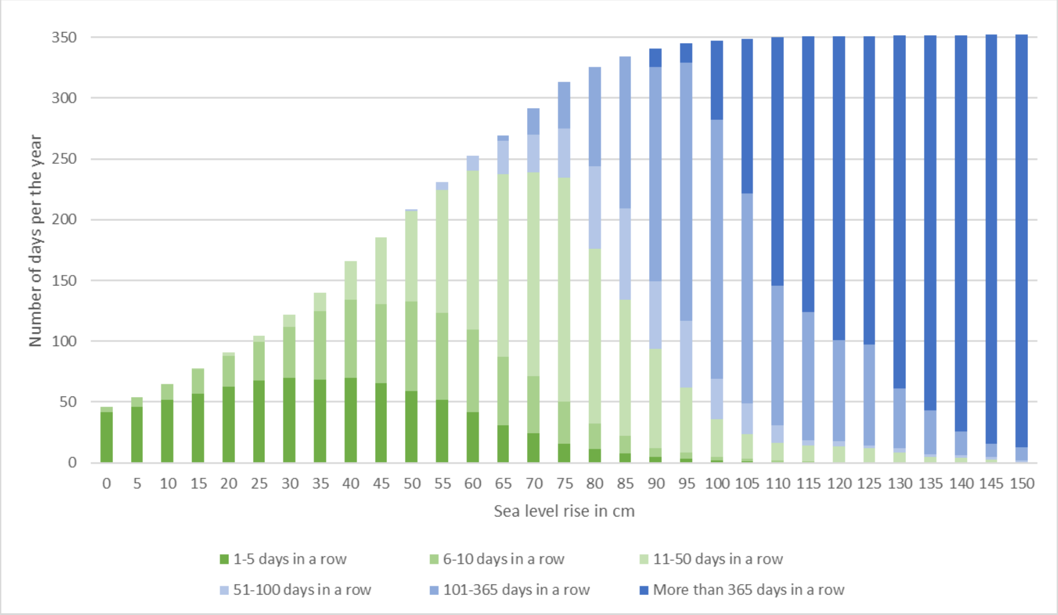

Figure 11: Average number of days in a year at different sea level increases where the sea water level does not drop beneath target water level on the Lauwersmeer (-0.93 m NAP)

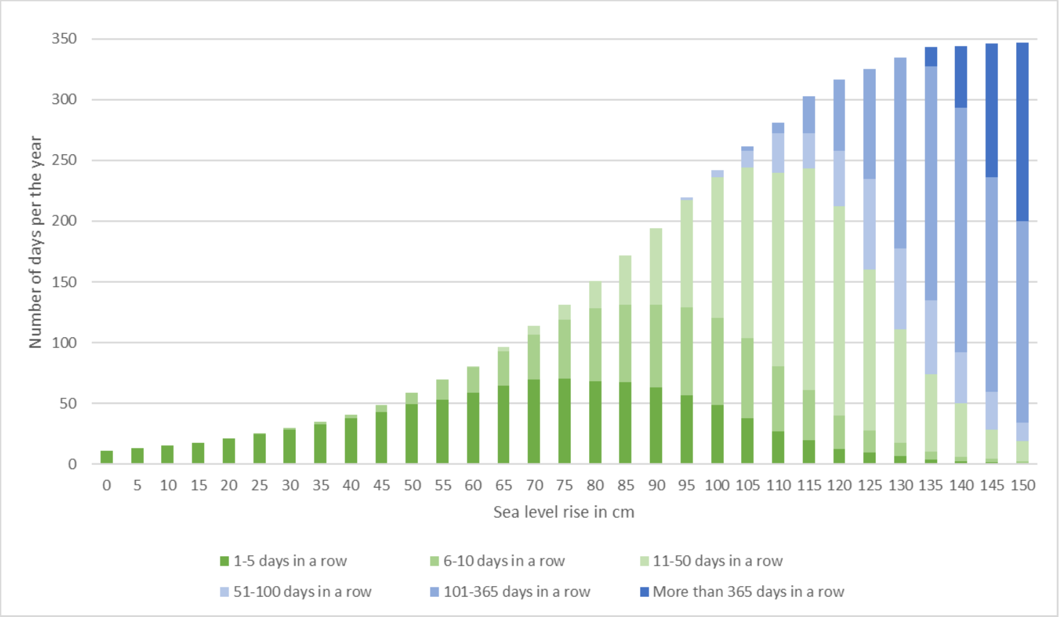

Figure 12: Average number of days in a year at different sea level increases where the sea water level does not drop beneath -0.5 m NAP

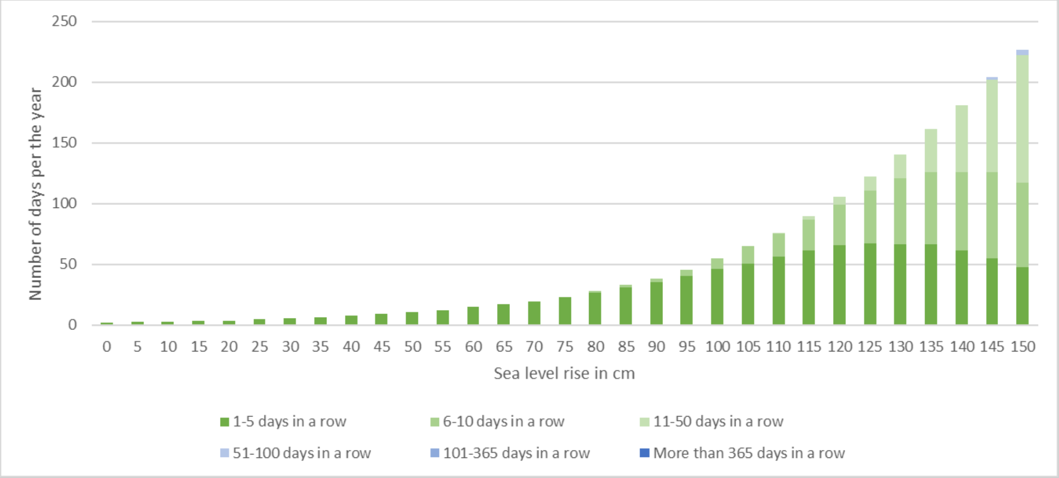

Figure 13: Average number of days in a year at different sea level increases where the sea water level does not drop beneath 0 m NAP

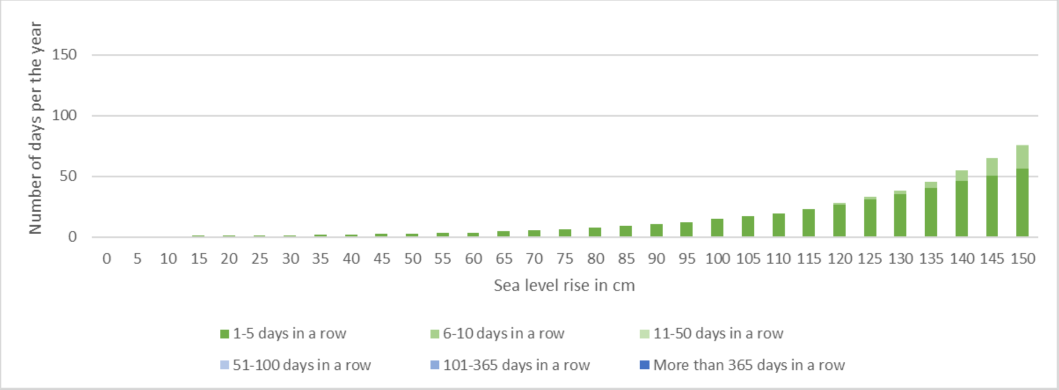

Figure 14: Average number of days in a year at different sea level increases where the sea water level does not drop beneath max water level on the Lauwersmeer (0.4 m NAP)

In these graphs the different colours indicate the duration of the unavailability to spout. All the periods where no spouting is available for more than 24 hours were noted down and the duration was rounded down to the number of days. In the graphs the average amount of days per year is categorised by duration of days in a row where spouting is unavailable (for instance 1-5 days in a row). The impact of the sea water level not dropping beneath a certain level increases with this number of days where spouting is unavailable. When the sea water level does not drop beneath target water level on the Lauwersmeer for 2 days, the water level on the Lauwersmeer can only be impacted limitedly, compared to for instance the event of 12 days of unavailability of spouting at target water level. The duration of unavailability of spouting is related to the impact on the water level on the Lauwersmeer; when the duration of unavailability of spouting increases, the bigger impact this could have on the water level on the Lauwersmeer. This depends on the precipitation and the state of the water system during those days. The worst-case scenario for a defined sea water level rise is the highest colour category for that specific sea water level rise (column in the graph). For instance, for a sea water level rise of 80cm at –0.5 m NAP (Figure 12) this highest colour category is 51-100 days in a row of unavailability of spouting.

It is evident that the number of days where spouting is unavailable rises quickly with sea water level rise. In Figure 11 at target water level of -0.93 m NAP, the increase in number of days rises with about 8 days, for the difference between 0 cm and 5 cm sea water level rise. This continues to increase until 40 cm, where the increase is around 26 days, compared to 35cm. After 40 cm increase of sea water level rise, the number of days is decreasing; the increase in days between 40 cm and 45 cm is 19 days. This means that the increase in sea water level rise has an increasing effect in the first half meter of sea water rise.

Without sea water level rise the target water level on the Lauwersmeer of -0.93 m NAP was maintained. On average 45.8 days per year spouting was unavailable at target water level during this period, see Figure 11. The chosen target water level is maintainable with this amount of days unavailable to discharge. At a water level of -0.5 m NAP on the Lauwersmeer, with 45 cm sea water level rise there is an average of 48.8 days per year where spouting is not available, see Figure 12. Increasing the target water level gradually to -0.5 m NAP when sea water level rise reaches 45 cm should result in a target water level that is theoretically equally maintainable as the target water level of -0.93 without climate change. The same is the case for 0 m NAP where with 100 cm sea level rise there are an average of 48.6 days per year where spouting is unavailable, see Figure 13.

5 DESIGN EXTREME EVENTS FOR CLIMATE SCENARIOS

This chapter is divided into two sections. The first section presents the 1/10 year 10 day rain event. Subsequently, the second section will present 2 versions of the 1/10 year 10 day sea water level event with an explanation for which one will be used in the model. This has been done to answer research question 2; What dimensions do a 10 day 1/10 year precipitation event (mm total) for the Lauwersmeer catchment and a 10 day 1/10 year sea water level event (cm increase) at Lauwersoog have.

5.1 ONCE PER TEN YEAR A TEN DAY (1/10 YEAR 10 DAY) PRECIPITATION EVENT

In van Dorland et al. (2024), the impact of climate change on the heavy precipitation event for 10 days and occurring 1/10 years has been quantified. Therefore, this 1/10 year 10 day event was chosen to be able to model the impact of climate change on the weather. As described in chapter 3.1, Research methods the 10 consecutive days within each year from 1991 till 2020 with the highest total precipitation are extracted from this data. These total precipitation events have been used to calculate the 1/10 year precipitation total over 10 days using Equation 1: Nash-Sutcliffe Efficiency (NSE). The resulting Gumbel distribution for the 1/10 year precipitation sum can be seen in Figure 15.

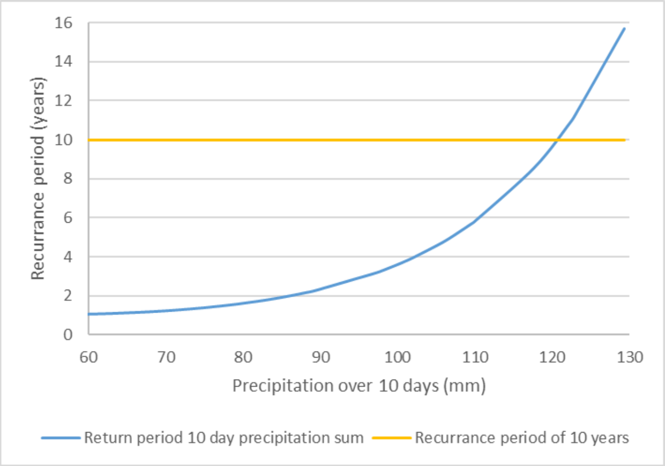

Figure 15: Return period precipitation sum of 10 days

The resulting 1/10 year 10 day precipitation total is 121 mm. This has been projected onto the historical rainfall event from the 18th of October of 2023 till the 28th of October of 2023 using a scaling factor of 1.6 to increase the total precipitation to the 1/10 year 10 day amount of 121mm, which can be seen in Figure 16. This period has been chosen because the heaviest part of the precipitation is in the beginning of the 10 days event, which increases the impact on the Lauwersmeer as more of the water ends up downstream over time, and the total amount of precipitation comes relatively close to the 1/10 year 10 day precipitation of 121 mm.

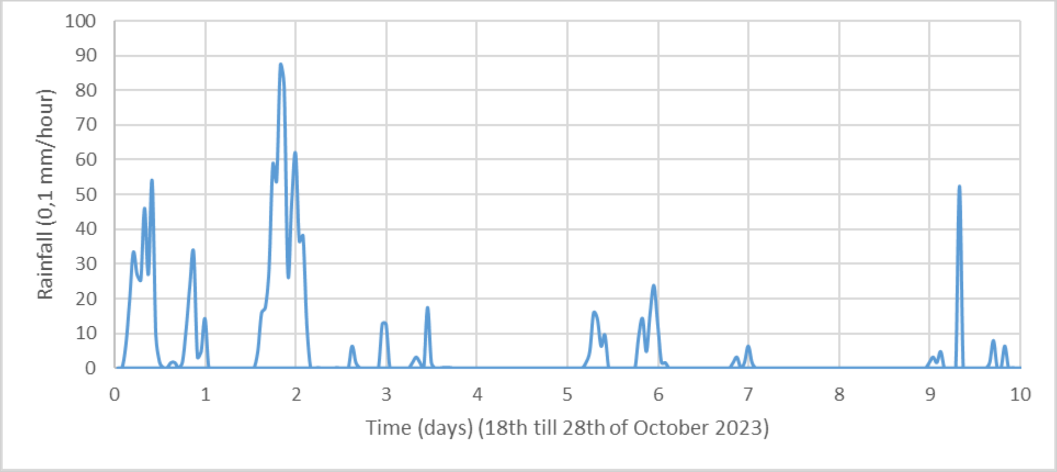

Figure 16: 1/10 year rainfall event

5.2 ONCE PER TEN YEAR A TEN DAY (1/10 YEAR 10 DAY) SEA WATER LEVEL EVENT

Two different approaches were used to extract the 1/10 year 10 day sea water level event from the data gathered between 1991 till 2020 (van Dorland et al., 2024). These two different approaches delivered different results, which has been explained in the Research Methods.

Highest peak sea water level

The peak approach was to record the peak sea water level of one year and with the Gumbel distribution a 1/10 year peak sea water level was extracted. The extracted data from the 30 year has been shown in Figure 17 below where at the middle of the graph around day '0' some of the years data does not take a logical path. This data could be faulty. Another explanation could be that by extracting the peak water levels extreme events are attracted that include events that do not take the conventional path for low and high tide.

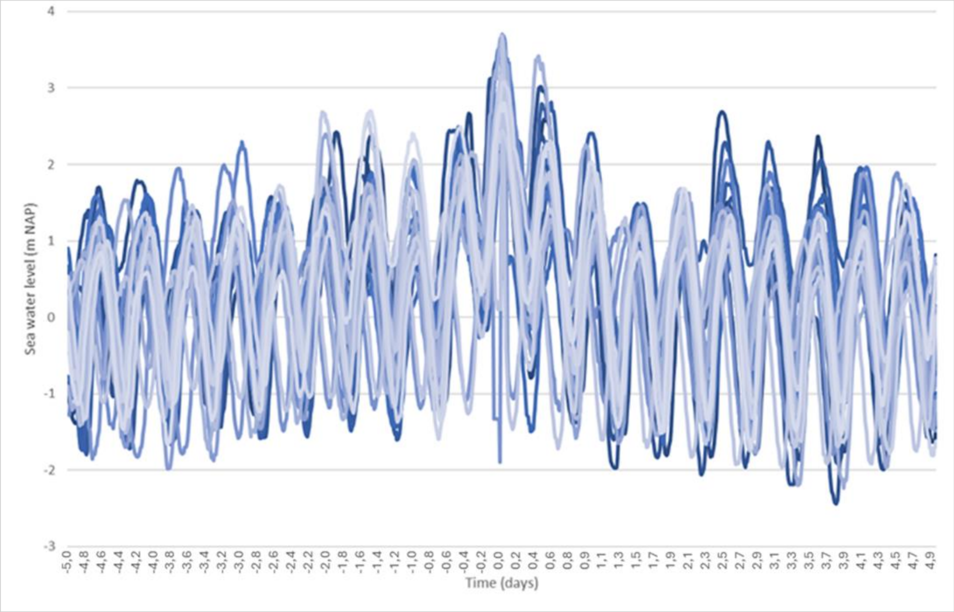

Figure 17: Historic sea water level events 5 days before and after peak water level of that year

Because of this illogical pattern, these years have not been taken into the analysis. With the years that remained the yellow line in Figure 18 shows an average sea water level from the extremes that goes to more extreme high and low tide values. This indicates that the data that has been excluded from this average are outliers that do not confirm the pattern of the tides. These outliers result in data that is less extreme in the low and high tides where the low tides are therefore less low than when the data does not have the outliers and could cause less ability to discharge when this would be implemented in the model.

This resulted in Figure 18 below, where in green the extreme sea water level event from 1992 is shown because is similar to the average of all 30 extreme events in orange. The event from 1992 is shown in the graph below to illustrate the decrease in difference in water level between high and low tide caused by waves that are not in phase. The less regular data results in an average of the data that has less high high tides and less low low tides.

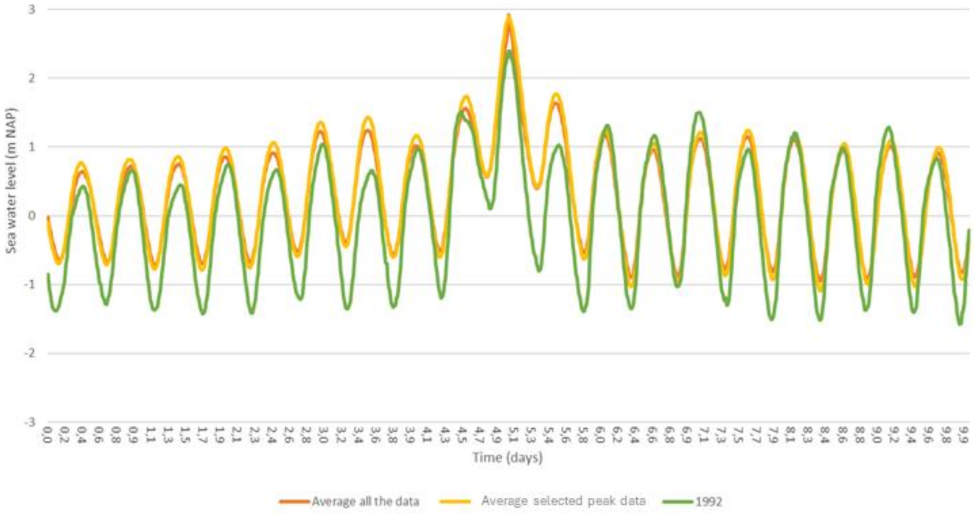

Figure 18: Peak sea water level 5 days before and 5 days after

Gumbel was used to extrapolate this average to the 1/10 year event. The Gumbel distribution for the peak water level can be seen in Figure 19 below.

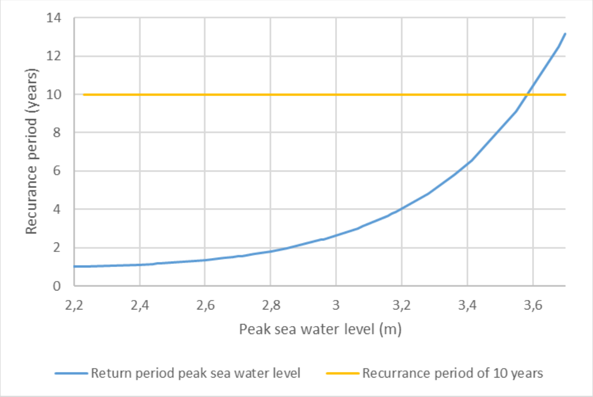

Figure 19: Return period peak sea water level

Reading Figure 19 above, the peak sea water level reached 1/10 years is about 3.5 m NAP. This minus the average of the peak data of 2.90 m NAP as shown in Figure 18, the increase is 0.63 m. This increase needs to be added to the average peak data, excluding the outliers. Figure 20 below shows the resulting 1/10 year event, where the peak is around 3.5 m NAP and the lowest level is about -0.5 m NAP. With the water level on the Lauwersmeer at target level of –0.93 m NAP spouting is unavailable during this full period.

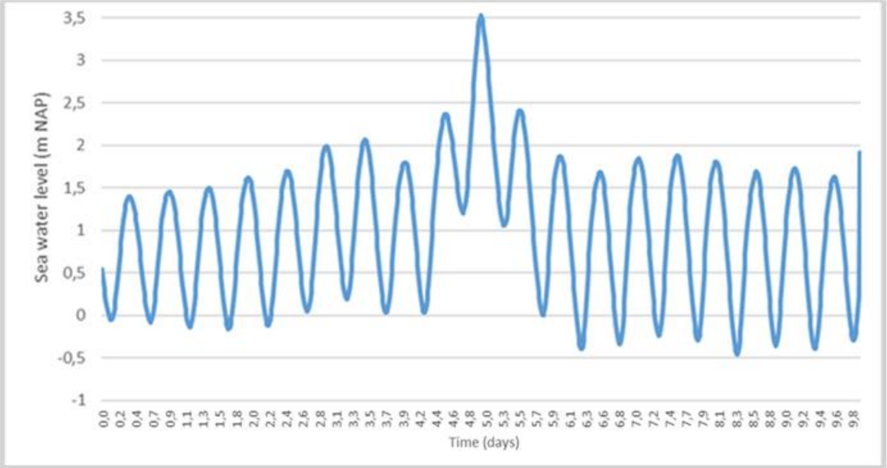

Figure 20: 1/10 year sea water level event (based on peak water level)

Highest average sea water level over 10 days

The second approach was to record the highest average sea water level of ten days per year and with the Gumbel distribution extract a 1/10 year average sea water level over ten days. The extracted data from the 30 years between 1991 and 2020 has been shown in Figure 21 below. The data does not show any distracting pattern, the tides are in line with each other.

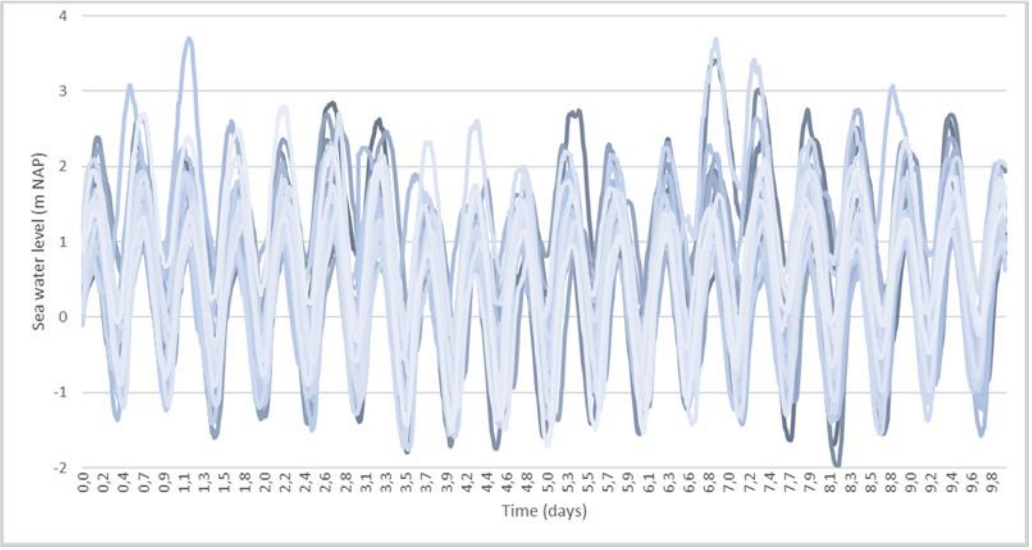

Figure 21: Historic sea water level data of highest average 10 day sea water level per year historic data

Based on this data Gumbel was used to extrapolate this average to the 1/10 year event. The Gumbel distribution for the average sea water level can be seen in Figure 22 below.

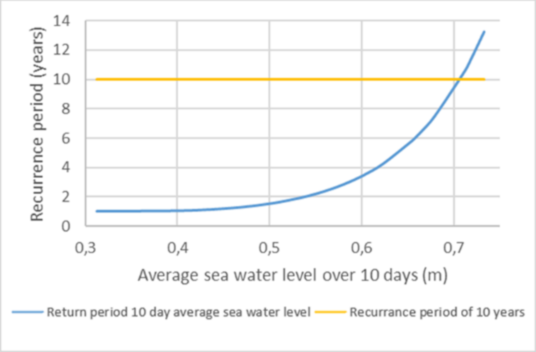

Figure 22: Return period 10 day high sea water level

Reading Figure 22 above the average sea water level reached 1/10 years is about 0.7 m NAP. This minus the average of the average data of 0.55 m NAP gives an increase of 0.15 m. This increase needs to be added to the average data to get the 1/10 year event that can be seen in Figure 23 below.

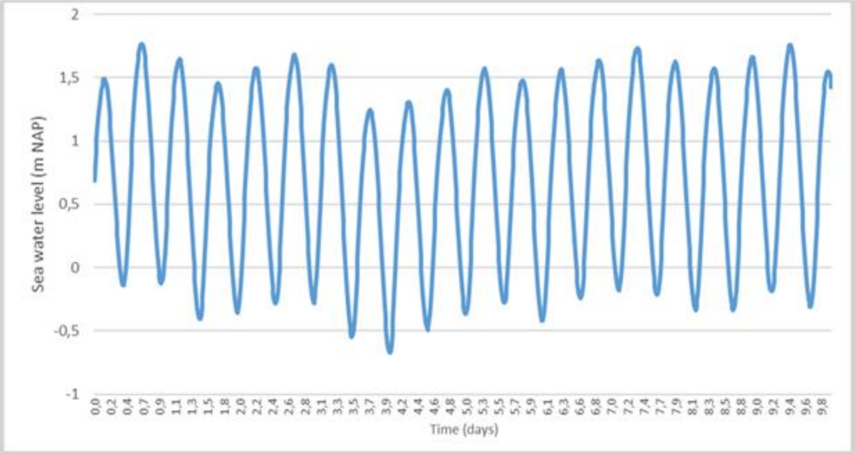

Figure 23: 1/10 year sea water level event based on the average over 10 days method

In Figure 23 the peak sea water level is around 1.7 m NAP, which is significantly lower than the 3.5 m NAP, which was found in the analyses for the 1/10 year peak sea water level. The lowest tide is around -0.35 m NAP, which was -0.5 m NAP in the analyses for the 1/10 year peak sea water level. This average sea water level event has a smaller impact on the Lauwersmeer water level compared to the peak sea water level. Water levels on the Lauwersmeer will reach higher levels with the peak event.

6 CAPACITY OF PUMPING STATIONS WITH CLIMATE CHANGE SCENARIOS

This chapter answers research question 3 on the capacity a new pumping station should have at different climate change scenarios. The model was extended, validated and the climate change scenarios were included in the model with and without pumping stations. Different capacities of these pumping stations are used.

The calibration of Friesland in the SOBEK model involved running 15-days with historical data input. This input is used to model outputs of the water level of Friesland and discharge quantities from Friesland to the Lauwersmeer. This has been put into graphs and compared with the historical output data and the NSE score has been evaluated. The results from this calibration phase were taken into longer simulation runs of two months where final adjustments were made. The adjustments made to the model for each individual evaluated model variant can be found in Table 3 below. The implementation of Friesland and an explanation on the SOBEK model can be found in Appendix D.

Table 3: Adjustments made to model for calibration of Friesland section

	Adjustments made
Variant 1	Width of the channel to the sluice complex increased (to improve flow from the waterbodies to the sluice complex)
Variant 2	The capacity of the pumping station to the North sea was changed to turn the pumps on at a lower water level and therefore have a higher pumping capacity with a lower water level on the waterbodies
Variant 3	Adjusting the profile of the waterbodies to start being wider at a higher water level
Variant 4	The sluice complex widened from around 17 to 22 meters to include the Friese Sluis as well as Dokkumer Nieuwe Zijlen
Variant 5	Pumping station to the North Sea have more capacity at lower waterbody water levels

The simulated data (blue '+'-symbols) were compared to the measured data (coloured dots) by looking at the graphs in Figure 24 below. The impact of adjustments listed in Table 3 to the model on the slope and height of the simulated data were noticed. When modelled data follows the trend of the measured data better the adjustment was implemented into future adjusted model runs. In Figure 24 and Figure 25 the legend Qsim1 / Wsim refers to Variant 1 mentioned in Table 3, Qsim 2/ Wsim 2 to Variant 2 etc.

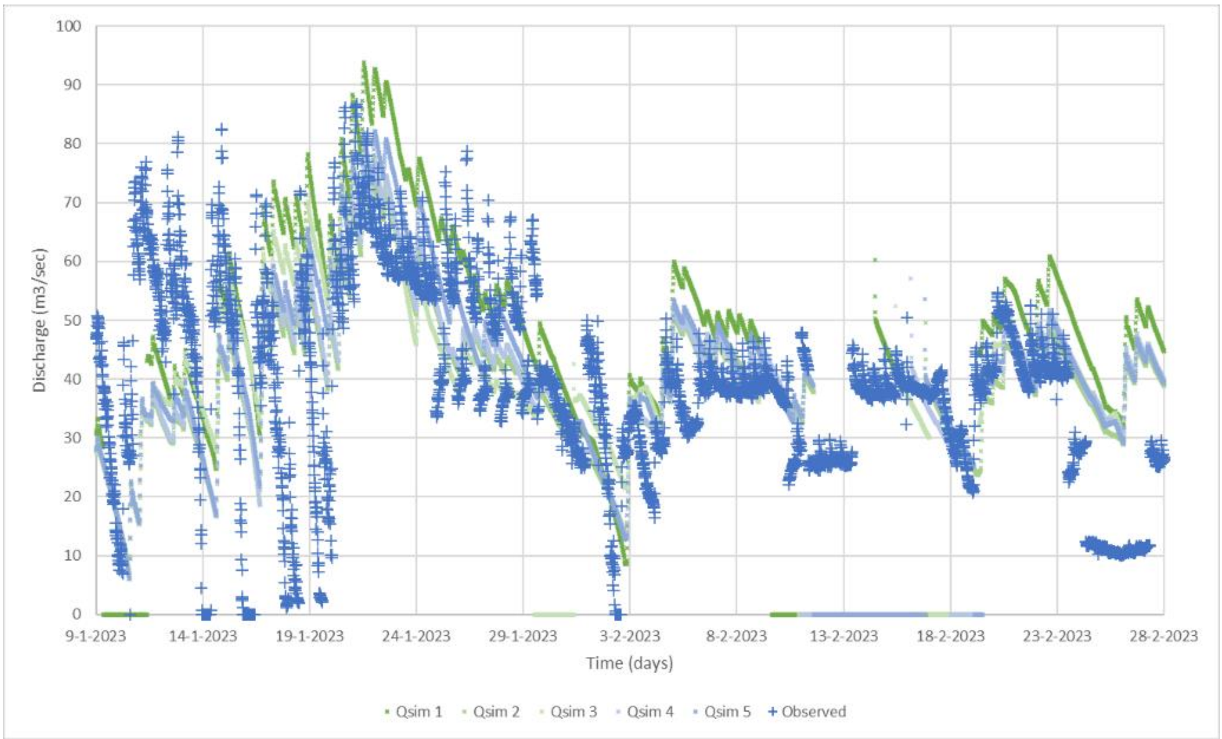

Figure 24: Simulated discharge at Dokkumer Nieuwe Zijlen Jan-Feb 2023 (calibration)

The graph with the simulated and observed water level can be seen in Figure 25 below.

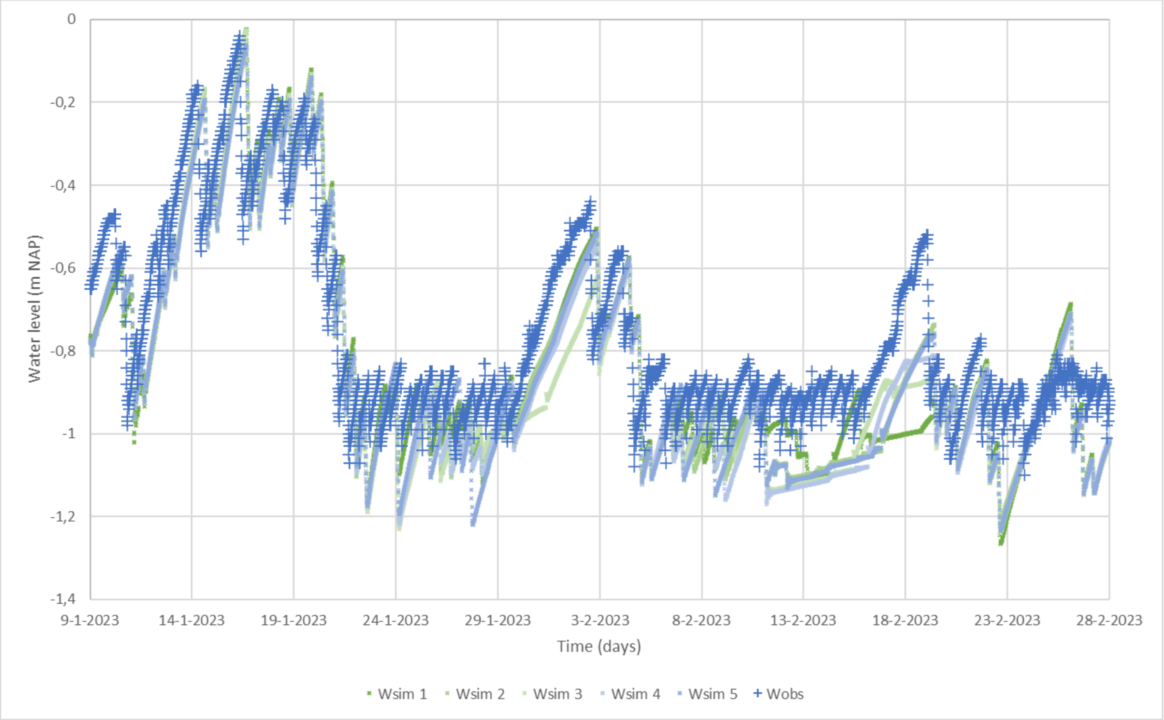

Figure 25: Simulated water level at Dokkum Nieuwe Zijlen Jan-Feb 2023 (calibration)

Both the graphs in Figure 24 and Figure 25 show a good fit between the measured and the modelled data; both data are almost overlapping each other in the graphs. For variant 1 the modelled discharge is too high in as can be seen in Figure 24.

The calibration results from the NSE of these different variants for both the discharge as well as the water level in Friesland can be seen in Table 4 below where a 10 day warmup period was taken into account. The NSE results have been colour coded for the discharge as well as the water level where the highest score is green and the lowest score is red to visualise the impact of the different variants on the NSE score. An NSE of 1 indicates a perfectly fitting model. However, if the result is below zero, a mean of the observed values is a better fit than the modelled outcome.

Table 4: NSE coefficient of calibration runs

	Discharge	**Water level in Friesland**
Variant 1	-1.05	0.59
Variant 2	-0.25	0.62
Variant 3	-0.70	0.56
Variant 4	-0.36	0.59
Variant 5	-0.37	0.60

Next to looking at the output data, simulations of the model have been evaluated and the logic of the model over time was as expected. Variant 2 was selected as the variant to validate as the NSE scores were the highest; both have a green score in the table. This outcome will be further elaborated on in the discussion.

6.1.1 Validation of Friesland

The calibrated model was validated against observed data from October and December of 2023. The results of the simulation can be found in Figure 26 and Figure 27 below.

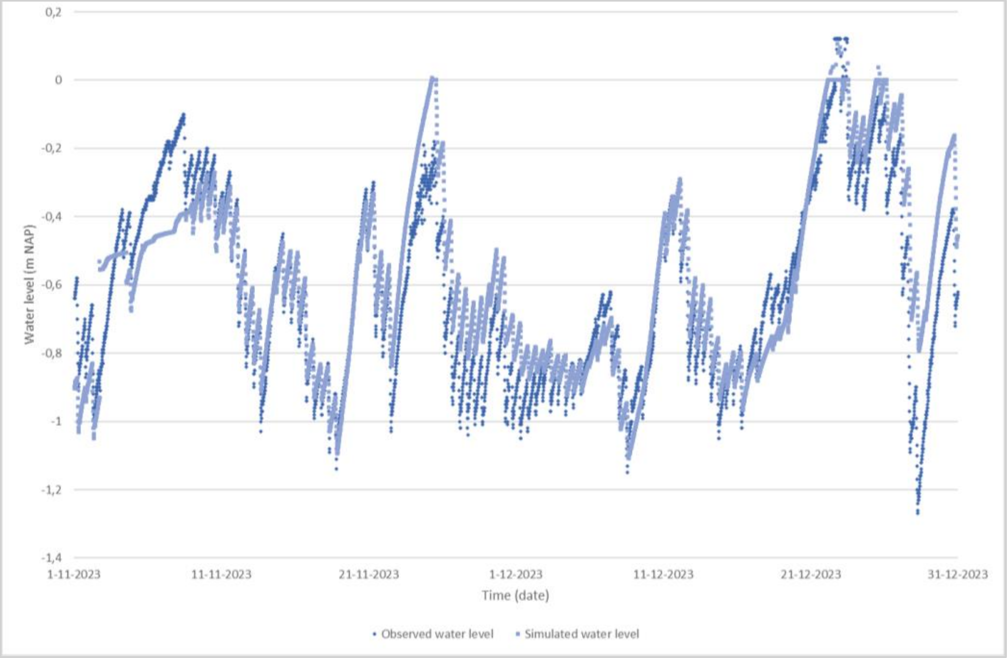

Figure 26: Simulated discharge at Dokkumer Nieuwe Zijlen compared to the observed data

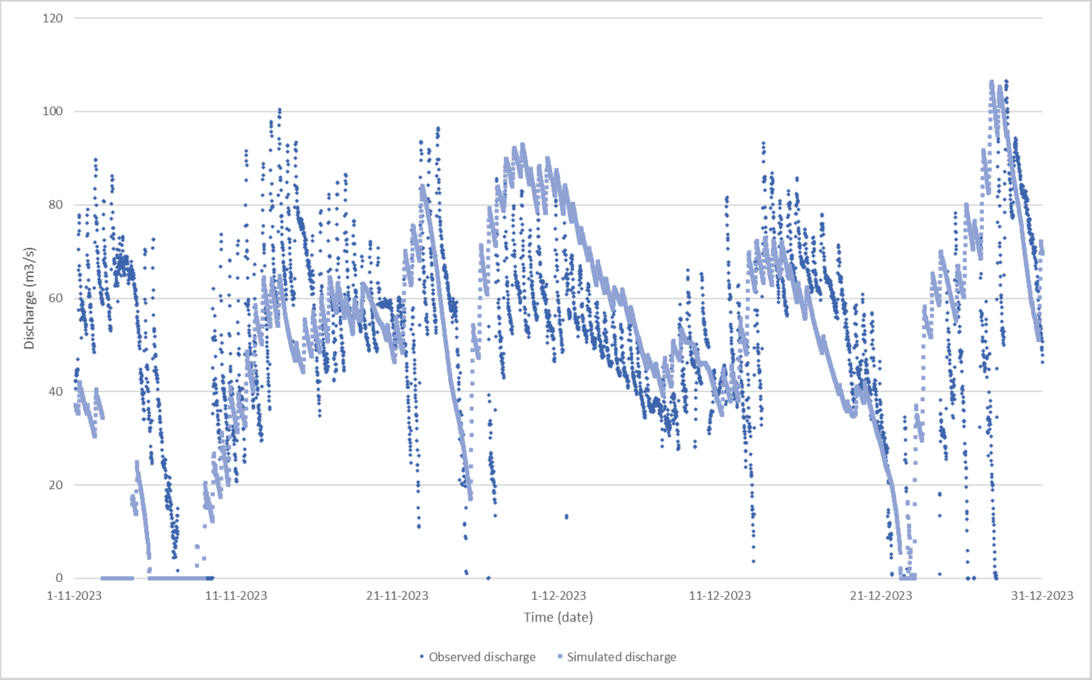

Figure 27: Simulated water level at Dokkumer Nieuwe Zijlen compared to the observed data

Besides the visual comparison between the modelled and observed values, the NSE values of the run are -0.25 for the discharge and 0.78 for the water level, which are the best fits found.

Also the performance of the water level on the Lauwersmeer was tested and the NSE score is 0.98. Both the modelled and observed water levels on the Lauwersmeer can be seen in Figure 28 below.

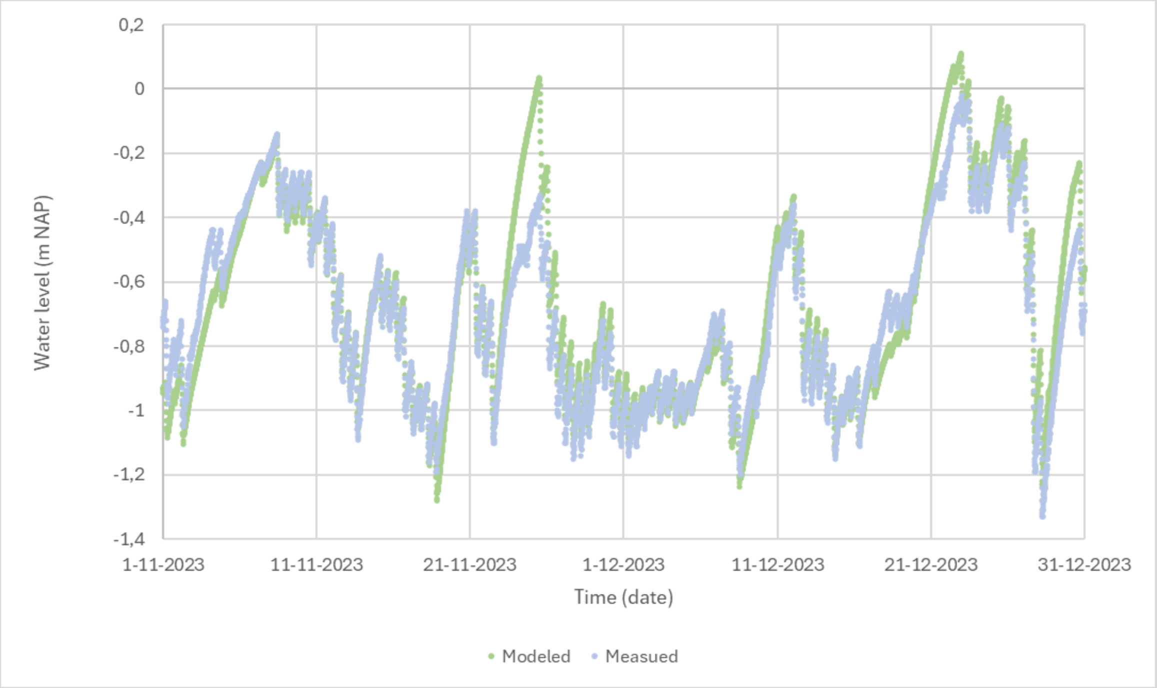

Figure 28: Water level on Lauwersmeer

Therefore, the addition of Friesland to the model increases the reliability of the outcome of the model as weather events can be used to investigate the impact of an intervention instead of manipulating the manual inflow from Friesland where the impact of the water level on the Lauwersmeer on the discharge from Friesland is not taken into account.

6.2 MODEL RESULTS CURRENT SITUATION

The 1/10 year events have been adjusted using Table 1 on page 15 and formatted to be able to import them into the SOBEK model. These different scenarios have been run in the SOBEK model where the impact on the water level on the Lauwersmeer can be seen in Figure 29 below.

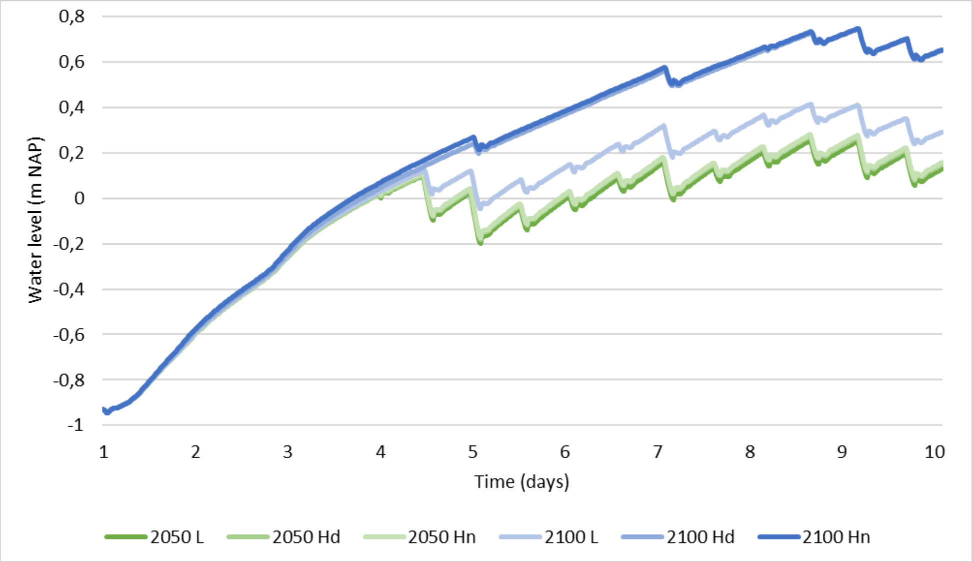

Figure 29: Climate scenarios modelled for 1/10 year scenarios

In this figure, in all scenarios during the first 3.5 days of the simulation, no significant spouting takes place. Graphs with more detail and including the sea water level can be found in Appendix E. For the scenarios of 2050, the highest water level is lower than 0.3 m NAP and the Lauwersmeer is therefore not considered flooded. Therefore, no pumping station is needed on the Lauwersmeer before 2050 based on this scenario.

With the low emission scenario of 2100, the water level on the Lauwersmeer reaches above 0.4 m NAP and is therefore considered flooded. For the low emission scenario to take place, the global emissions need to be reduced according to the agreement made in Paris in 2015 and the average global temperature is not allowed to rise more than 1.7 degrees (van Dorland et al., 2024). For the high emission scenarios, the water levels reach 0.75 m NAP. At this level the Lauwersmeer is severely flooded. In the case of the high emission scenario the average global temperature will rise with 4.9 degrees. The actual climate change will be between these extreme scenarios. Therefore, an intervention will be necessary before 2100.

6.3 MODEL RESULTS WITH PUMPING STATION

Next to the simulated scenarios, pumping stations have been added to the model. For different climate scenarios different capacities of the pumping stations have been tested to get an insight into the impact on the water level on the Lauwersmeer. The capacities run on the pumping station for the different climate scenarios and the peak water level for the run combinations can be seen in Table 5 below. In this table the resulting peak water levels equal to or higher than 0.4 m NAP on the Lauwersmeer have been marked in red as they are considered flooded scenarios.

Table 5: Peak water level on Lauwersmeer at the different climate change scenarios in combination with different pumping station capacities

		Climate change scenarios					
Pumping capacity of station (PC) (m^3/s)		2050 L	2050 Hd	2050 Hn	2100 L	2100 Hd	2100 Hn
	200						-0.27 m
	100	0.11 m	0.12 m	0.13 m	0.23 m	0.32 m	0.40 m
	50	0.19 m	0.21 m	0.21 m	0.35 m	0.60 m	0.64 m
	25	0.22 m	0.24 m	0.25 m	0.38 m	0.69 m	
	10	0.24 m	0.26 m	0.27 m	0.40 m		
	0 (base)	0.25 m	0.27 m	0.28 m	0.41 m	0.75 m	0.75 m

The runs for 2050 L, Hd and Hn have similar results for the water level on the Lauwersmeer as can be seen in Table 5 above. Therefor in Figure 30 below the results for 2050 Hn can be seen as a summary of all 2050 scenario runs.

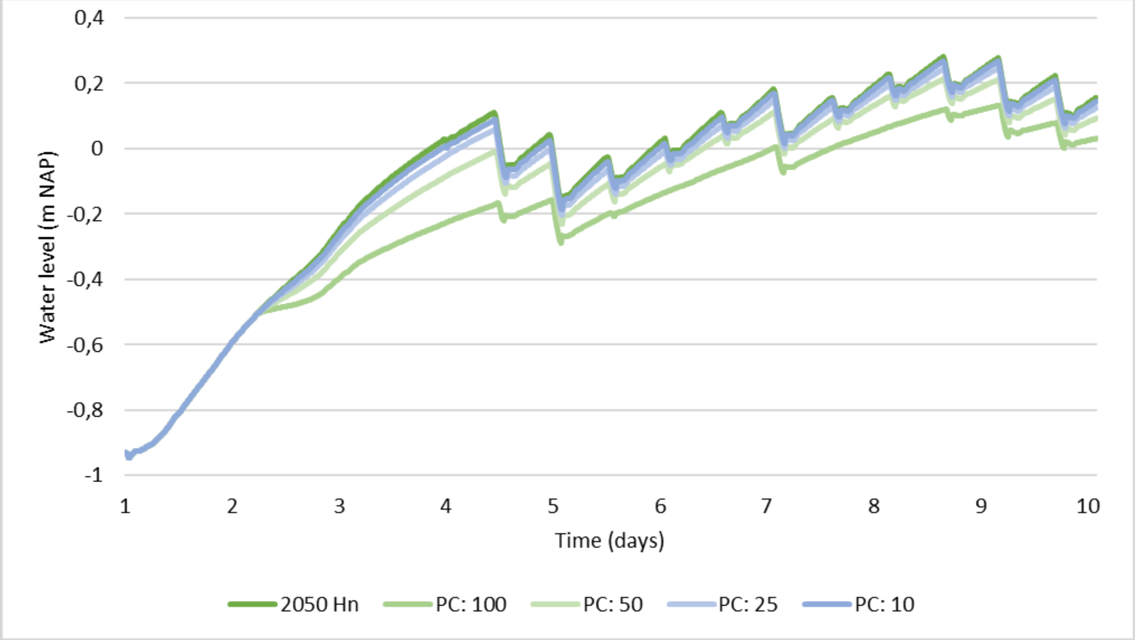

Figure 30: Water level on Lauwersmeer during climate change scenario for 2050 Hn with different pumping stations

In this figure it can be seen that spouting occurs frequently from day 4 onwards. While spouting is available at these high water levels on the Lauwersmeer, the water level does not drop beneath -0.3 m NAP even with a pumping station with a capacity of 100 m^3/s.

The impact on the water level of different pumping stations on climate scenario 2100 Hn, the most impactful climate scenario of 2100, are displayed in Figure 31 below.

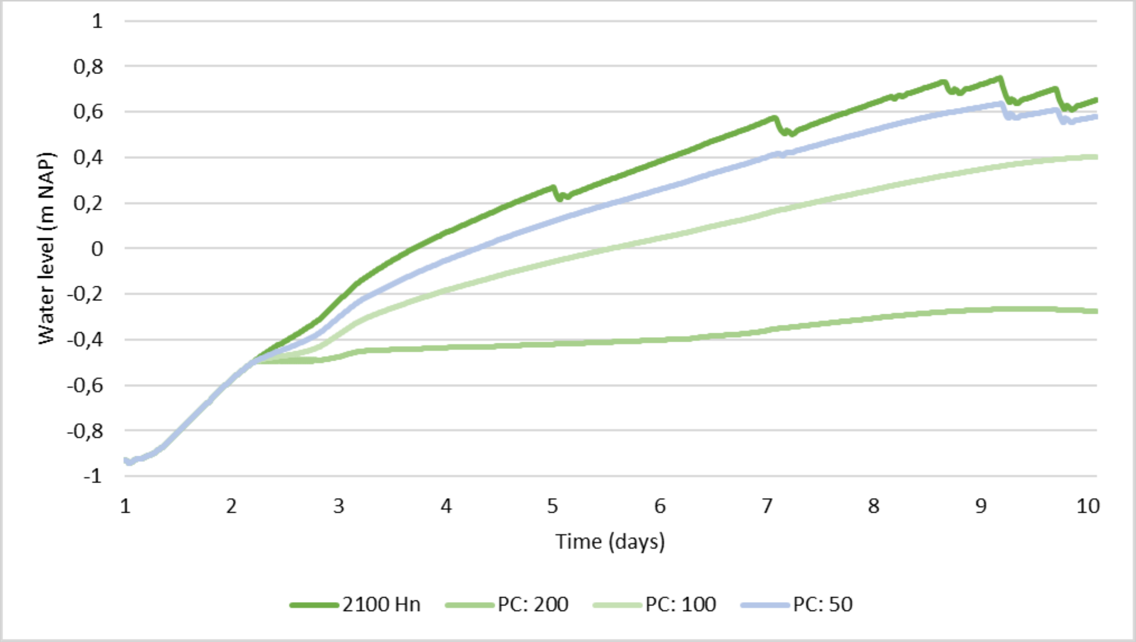

Figure 31: Water level on Lauwersmeer during climate change scenario for 2100 Hn with different pumping stations

From this figure, the impact of a pumping station of 100 m^3/s can be seen to be just enough to keep the water level on the lake at 0.4 m NAP whilst no spouting is available during the whole period. Therefore, a pumping station is the only contributor to discharge water from the Lauwersmeer to prevent it from flooding. However, expanding the runtime could result in a water level above 0.4 m NAP and the Lauwersmeer could still be flooded, since the trend of the line is still positive at day 10 of this simulation.

All the graphs of the remaining scenarios can be found in Appendix F.

7 DISCUSSION

7.1 UNAVAILABILITY OF SPOUTING AT DIFFERENT LAUWERSMEER WATER LEVELS

To start with, the workings of the water system of the Waddenzee are still unknown (*Waddenzee*, n.d.). Data is being gathered on how the water system behaves and will develop itself under the impact of climate change is under research. When the water system of the Waddenzee changes this could have an impact on the sea water levels measured and experienced at Lauwersoog and on the unavailability to spout. Therefore, the specific workings of the Waddenzee have not been taken into account in this study. When new insights are found, the analysis conducted for this research can be updated to make the results more accurate.

Next to this, when the sea water level drops beneath the water level on the Lauwersmeer, it is not per definition the case that a significant amount of water can be discharged. When the sea water level drops beneath for example target water level for 15 minutes, the period of time is in general to short to spout enough or any water when the water level on the Lauwersmeer is around target water level. Moreover, if the water level on the Lauwersmeer is above the investigated water level in the Lauwersmeer (-0.93, -0.5, 0 or 0.4 m NAP) and at this investigated water level spouting is available, the spouting at the higher water level should be significant. The higher the level difference, the higher the spouting flow. This is important to consider when working with the resulting data but has no impact on the conclusion.

Wind has a great impact on the sea water levels on the Waddenzee (*De Dynamiek van Het Wad*, n.d.). This in combination with changing weather systems due to climate change can have an extra unknown impact on the unavailability to spout (*Summer Wind Patterns in the North Are Changing Due to Climate Change*, 2024). This is similar to the unknown inner working systems on the Waddenzee. When more insight have been gathered on the impact of the wind caused by the climate change those data should be taken into consideration and could have an impact on the unavailability to spout.

To answer research question 1; the unavailability of spouting at different considered water levels 30 years from 1991 till 2020 have been considered because the KNMI report defined this period to be the reference period without climate change (van Dorland et al., 2024). This proposes that the average of 30 years can be extrapolated to a yearly average and should be considered as such. However, the sea water level has risen long before 1991 and during this period the average sea water level increased with at least 10 cm as can be seen in Figure 32 below. Therefore, in the analysed data from 1991 till 2020 there is sea water level rise present, causing more and longer unavailability to spout towards the later analysed years. This causes longer periods in a row where spouting is unavailable. These longer periods can give a more negative view on the worst-case scenario for a certain amount of sea water level rise. Therefore the worst-case scenario should not be based on the highest category (for example 101 till 365 days in a row/year) from which the measurements have been taken. When the number of days in the title of the category is not in line with the average measured number of days (for example at target water level (-0.93 m NAP) with 65 cm sea level rise spouting is unavailable for 4.4 days per year between 101 and 365 days in a row). This causes that more consideration needs to be taken with the longer durations of unavailability and that the data from these categories should be considered with more care. This has no impact on the conclusion but should be taken into account when using the data for other purposes.

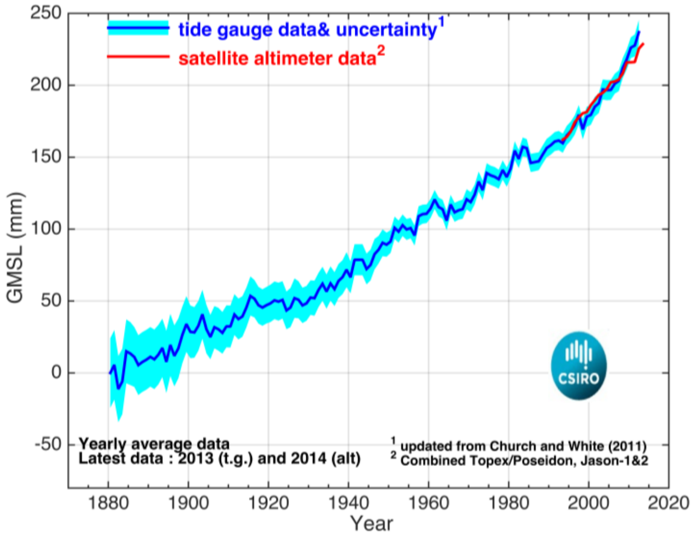

*Figure 32: Changes in global mean sea level from 1880 till 2014 (*Rates of Global Sea Level Rise Have Accelerated since 1900, Contrary to Bloggers' Claims*, n.d.)*

Consequently, these discussion points indicate that the results of this research are a preliminary expectation of the impact of sea water level rise on the unavailability to spout. These results are subject to change when the environmental influence on the sea water level changes, therefore the results for research question one must be used with caution and mainly as an indication.

7.2 EXTREME 1/10 YEAR EVENTS FOR PRECIPITATION AND SEA WATER LEVEL RISE

Events with higher amounts of precipitation earlier in the 10 day simulation will have a greater impact on the water level as the water from inner land waterbodies has more time to reach the Lauwersmeer. When the precipitation falls 1 day before the end of the simulation, there is a higher chance the water will not reach the Lauwersmeer in the SOBEK model. The impact of the chosen precipitation event to project the 1/10 year rainfall upon is therefore large, this lagging effect played a key role when choosing a precipitation event with the highest amount of rainfall at the start of the 10 day period. By implementing a higher intensity of rain at the start of the simulation, the impact on the water level in the Lauwersmeer is higher than if rain would fall at a later moment in the 10 day period chosen. The results and therefore the conclusions regarding the pumping capacity could have been lower if a more equally divided rainfall event were chosen. But it could also have been higher if a 10 day event would have had more rainfall at the beginning of this 10 day period.

The rain data used has been collected at 5 places around the catchment. Using more datapoints form the whole area would increase the precision of the 1/10 year total precipitation. This could have an impact on the resulting 1/10 year total 10 day precipitation and therefore the modelled results. The magnitude of this effect is not known but by using 5 collection locations the effects of disproportional impact of a single data point have been lowered.

Next to this, the 1/10 year precipitation event was determined using a historic precipitation event. Using this historical event proofs that the spread of the precipitation over 10 days is possible. A lot of other precipitation events could have been chosen to project the 1/10 year total precipitation. That would generate a different result in 1/10 year event as well as different outputs of the model as discussed in the first section of this 7.2 section.

To determine the 1/10 year sea water level event, two different methods were used , indicating that there is not one right method. For the first method the peak sea water level of every year is used to calculate the height of a 1/10 year peak water level. The second method considered the highest average sea water level over 10 days to calculate the average height of a 1/10 year sea water level event. The average outcome of both methods is shown in

Figure 34 below. For the peak water level method, two lines can be seen. The darker line shows the average of all the data from 30 year, including the outliers. The light blue line is also based on the peak water level but excludes outliers in the data that did not follow the flow of high and low tide. These outliers may have been caused by strong winds, which push up the sea water level at unexpected times during the tidal period. Other causes could be that the data is faulty and by extracting the peak data per year, these measurements could have been unintentional selected. Which of the explanations above is true for the excluded data has not been investigated as it was clear that the results from this approach would not be applied in the model.

The 1/10 year event based on the peak water level results in a more impactful event for the water level on the Lauwersmeer as the low tide is almost always higher than the low tide of the highest average sea water level, as can be seen in Figure 33. The highest average sea water level for the 10 days 1/10 year event is less impactful than the 1/10 year peak sea water level event, but for the average of both events, the highest average sea water level event is more impactful, which can be seen in Figure 33 and

Figure 34. This is due to the bigger increase for the peak sea level due to the calculated 1/10 year values with Gumbel. The peak water levels are highly impacted by strong winds and the results from the different years lay relatively far from each other as the extremely high tide due to wind does not occur every year. This results in a higher correction to add to the average peak sea water level. Therefore, the results from the 1/10 year precipitation event based on the peak precipitation is less reliable and should not be used. The expectation was that the 1/10 year sea water level event based on the highest average water level over 10 days would be more impactful compared to the peak water level event. However, the results showed otherwise.

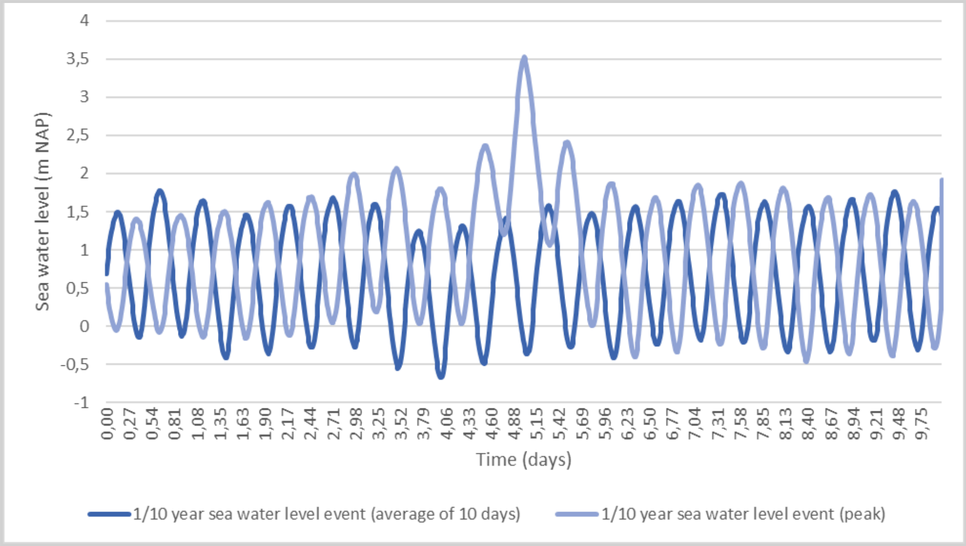

Figure 33: 1/10 year sea water level events based on both methods

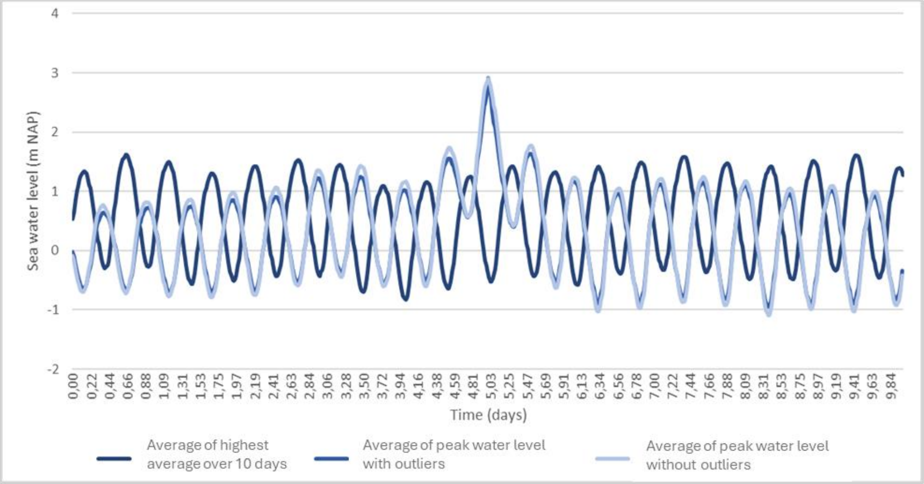

Figure 34: Average of both methods for 10 day sea water level event

The 1/10 year highest average sea water level event drops beneath -0.5 m NAP around day 4 in Figure 33, which is the lowest point in the graph and appears in the middle of the simulation time. This results in a less impactful event compared to an event where the sea water level is lower at the start of the simulation as the water level on the Lauwersmeer has then not yet had the time to rise to the lower sea water level. Choosing to adjust a selected 10 day sea water level event to the 0.7 m NAP average, calculated using Gumbel, could result in a more impactful event. This event would have an impact on the model results of this research, where the water level on the Lauwersmeer could potentially rise even further.

7.3 MODEL RUNS

To continue with the results of research question three; what capacity should a pumping station on the Lauwersmeer have to be able to comply with current safety criteria in 2050 and 2100 at different climate scenarios? The impact of the combination of a 1/10 year event with a 1/10 year event could be less than the combination of 1/20 year event with a 1/5 year event. Even a longer or shorter simulation time for the event should be considered (more or less than 10 days), because either could have a more severe impact on the water level on the Lauwersmeer; there could be very heavy rainfall for 2 days. Or there could be half a year with a lot of constant rain during this period of time. The events modelled in this research are therefore not the extreme 1/100 year events for which a 0.4 m NAP max water level is regulated to be the safety limit by the Gedeputeerde Staten van de provincie Groningen, (2017). Therefore, from this research, no defined conclusions on the pumping capacity or the impact of a 1/100 year event can be made. More research on this type of effects is needed.

To improve the model, Friesland was added to the existing SOBEK model of the Waterboard Noorderzijlvest area. The area of Friesland was simplified to be able to create, calibrate and validate the model during this project. These simplifications could cause the model to react differently to rainfall events and results in uncertainty. Next to this, the extension of the model is calibrated based on water level and discharge data. The data oscillate at some moments as can be seen in Figure 35 below. This results in data with which modelled data can be calibrated, but the model score (NSE) is lower than with more uniform data. This causes the resulting NSE score of the calibration to be negative.

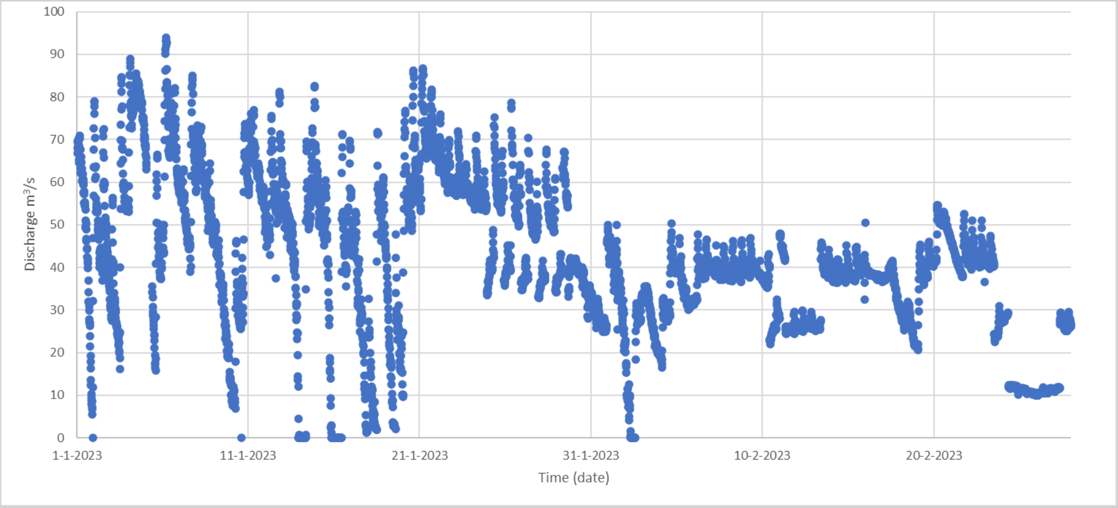

Figure 35: Discharge measurements calibration

The rain data used on the area of Friesland was historical precipitation data on the area of Noorderzijlvest. The calibration can be improved by using historical precipitation data from around Friesland as precipitation in the model, now only data from the area of Noorderzijlvest has been used. Next to this, the calibration of Friesland can be extended, because a lot of input values have been inserted into the model which can all be calibrated for. A better calibrated model can have an impact on the model results and therefore on the recommended pumping capacity. This is a part of the uncertainty associated with the modelled results.

In the fictionally installed pumping station in the model, the capacity of the pumping station is not impacted by the head difference between the Lauwersmeer and sea water level. Not taking this changing capacity into account can result in an under-estimation of the capacity a station needs to have. When a pumping station is chosen, attention needs to be given to the optimal working window which fits the current and future average and extreme head differences of which an example is pictured in Figure 36 below. In this figure the black line shows the efficiency of a hypothetical pumping station in relation to the flow rate.

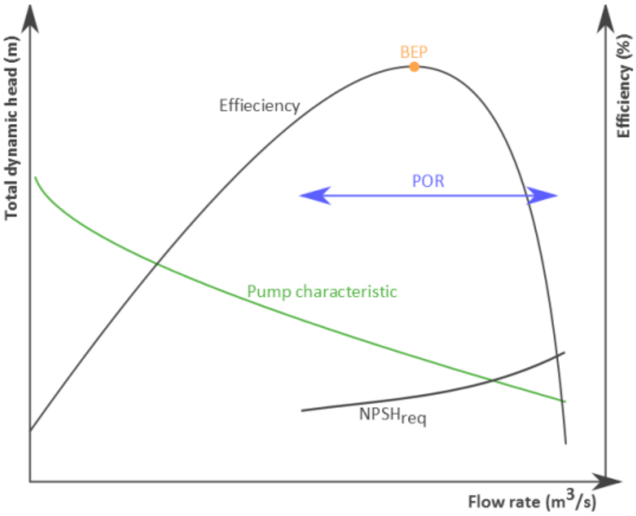

Figure 36: Hypothetical pump characteristics for a typical horizontal axial flow pump (image taken from (Van Manen, 2014))

8 CONCLUSION

The availability of spouting on a day-to-day basis decreases with sea water level rise. The unavailability to spout at target water level (-0.93 m NAP) in number of days per year increases from 0 cm sea level rise till 50 cm sea water level rise. After this first 50 cm, the added number of days where spouting is unavailable, decreases. From the results, it can be concluded that a new target water level of -0.5 m NAP would be equally maintainable with 45 cm sea level rise as the current target water level of -0.93 m NAP without climate change.

From this research, it is determined that a 1/10 year precipitation event is an event where a total rainfall of 121 mm over 10 days occurs, where it is important for the simulation, that the most precipitation occurs at the start of the 10 days, so the impact of the precipitation is included in these 10 days. where it is important to have the most precipitation in the start of 10 days in the simulation to also include the impact of the precipitation. This is recommended because precipitation can be delayed from reaching the Lauwersmeer because it must travel from far ends of the catchment. The 1/10 year sea water level event can best be based on the highest average sea water level during a 10 day period instead of peak sea water levels. Where the average for a 1/10 year event is 0.7 m NAP.

Lastly, the addition of Friesland to the SOBEK model is a useful addition as the impact of the water level on the Lauwersmeer on the discharge from Friesland can now be considered. Based on the model runs on these examined extreme events, the Lauwersmeer complies with the safety regulations in 2050. In 2100 however, a pumping station of at least 25 m^3/s is necessary. However, as discussed in chapter 7, the required pumping capacities for 2100 and maybe also 2050 can be larger when other combinations and durations of events need to be taken into consideration.

The first objective was to get more insight into when the current system can not function effectively anymore. This research does not give an exact date when the system will not comply with the safety regulations anymore has been found. The period in which this will be the case is subject to the impact climate change will have on the weather and sea water level. The simulations do show that with all determined extreme events, the current water system will not function effectively in 2100. At which moment in time between 2050 and 2100, or earlier, the situation will not comply with the safety regulations anymore, has not been found during this research.

The second research objective was to determine the required pumping capacity necessary in case of specific climate change scenarios at different time frames. A recommendation regarding the pumping capacity has been given. However, the pumping capacity determined to be necessary in this research is the minimal required capacity as possibly more impactful events (like impact of wind, workings of the Waddenzee and missing information on the amount of water that was discharged during a spouting event) have not been integrated in the model and could therefore influence the pump capacity requirements as described in the discussion.

The main lessons learned from this research, excluding the objectives, is how the unavailability to spout and the durations of these periods have been quantified for the period without climate change as well as extrapolated to different levels of sea water level rise. Lastly, an extreme sea water level event should be based on the highest average sea water level over a period of time instead of taking peak sea water levels into consideration.

9 RECOMMENDATIONS

9.1 RECOMMENDATIONS FUTURE RESEARCH

Firstly, the impact on the day to day impact of sea level rise on the availability to spout can be investigated further. A deeper look can be given into the occurrence of precipitation and the inability to spout. Next to the availability to spout, the amount of water that can be discharged is also an interesting factor to consider. When the sea water level drops beneath the target water level or any other investigated level, it is not per se the case that a significant amount of water can be discharged. This could be done by looking at the discharge window and determining a minimal duration for the discharge window to let the time reset and restart counting for a new not being able to discharge window.

Secondly, in addition to installing a pumping station, other options should be looked into to mitigate the problems caused by climate change. This could be done to mitigate the effects before a pumping station is build but also resolutions that could make a pumping station unnecessary. Some different approaches to investigate are:

- Increasing the capacity of water storage areas inland
- Elevating the target water level on the Lauwersmeer
- Increasing the regional safety measures around the Lauwersmeer to accommodate higher water levels without flooding

For these different scenarios as well as future studies into the capacity of a future pumping station, the costs should also be considered.

Thirdly, when exploring these different options, some of the scenarios that could be considered combined with the most recent climate change expectations are:

- Normal precipitation combined with high sea water levels
- Extreme precipitation event combined with normal sea water levels
- Long term historical run with climate change extrapolated on it

Fourthly, the inner workings and impact of climate change on the Waddenzee needs to be investigated. If this has been done and relevant insights have been gained, this can be implemented into the research done during this thesis.

Penultimately, the extension of the SOBEK model can be adjusted to be less simplified and represent the workings of Friesland better. When this addition had been made and the adjustment is calibrated and validated, the analysis on the impact of climate change on the water level on the Lauwersmeer.

Lastly, the impact of the head difference the pumping station must overcome and the impact on the available pumping capacity should be considered when deciding what capacity, a pumping station from the Lauwersmeer to the sea should have. When a type of pumping station has been chosen, the characteristics of this station should be implemented into the model.

9.2 RECOMMENDATIONS FOR THE WATERBOARD

My recommendations to waterboard Noorderzijlvest are to continue this research on the impact of climate change on the water level on the Lauwersmeer. Based on this research no conclusions can be taken for when a pumping station will be necessary when the only adaptation of the water system will be a pumping station. Building a pumping station would have to happen before 2100 but no definitive timeline can be given at this moment.

This can be done by doing long-term historical runs and different other scenarios as described in 9.1 should be investigated and create a clearer picture on when and with what magnitude future adaptation of the water system should have.

Lastly, a close look should be kept at the national and international plans to manage sea level rise. When scenarios are created, the implications for the regional water system should be investigated and this should be given as feedback to the decision makers on what the implications of certain decisions would be. The issue of sea level rise cannot be handled by each waterboard by themselves. Therefore, for large project and issues such as climate change, considering the plans of others is important.

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APPENDICES

APPENDIX A: HISTORY OF THE AREA

Formation of the Lauwerszee

At the current location of the Lauwersmeer there was formerly the Lauwerszee situated. The formation of the Lauwerszee a process that had started around the year 0 (*Landschapsgeschiedenis*, n.d.). This started by a change in route of the 'wadgeulen' which resulted in a greater connection between the river Lauwer and the North Sea. This connection became bigger over the years and was probably caused by a sift in the Waddeneilanden to the east. Next to this, people dug up peat to use as fuel close to the Lauwerszee which resulted in subsidence of the landscape and through this a greater area was taken by the sea. In the 11th or 12th century dikes around the Lauwerszee were constructed to reclaim land that was lost to the sea because of peat extraction. In Figure 37 below the Lauwerszee is shown where the years when some of the dike sections are build are shown.

Figure 37: Lauwerszee situation before it was closed off (Image taken from (Landschapsgeschiedenis, n.d.)

Construction of the Lauwersmeer

There have been plans to dam of the Lauwerszee since the 16th century (*Landschapsgeschiedenis*, n.d.). But only after the storm and floods of 1953 in the southern parts of the Netherlands, actions were taken. The options were dike elevation the dikes around the Lauwerszee or placing an 'Afsluitdijk' to block the waterbody of from the sea. In 1969, a dam was placed after Friesians pressured the government to choose for this option instead of the cheaper dike elevation option. This resulted in a lake which, by low tide of the sea water, discharges water to the Waddenzee by discharging water under freefall by opening sluice doors at the than constructed R.J. Cleverdingsluizen near Lauwersoog. This sluice complex consists of 3 buildings with each 4 spouting chambers with each 2 lock doors. These keep the sea water out when the sea water level is high and open up at when necessary and possible during low tide to release the water from the Lauwersmeer to the sea under freefall. The inflow into the Lauwersmeer flows from the Lauwers, Reitdiep and the Dokkumer Ee, pumping stations from the polders around the lake such as the Nieuwe Robbengat Lauwersoog and Dongerdielen Ezumazijl as well as direct precipitation on the area and nearby land which directly drain into the lake.

APPENDIX B: GUMBEL DISTRIBUTION

In this appendix the Gumbel distribution function in combination with Table 6 which needs to be used to implement Equation 2: Gumbel distribution function below (Suhaiza et al., 2007):

$$x = \bar{x} - \frac{\ln \ln \frac{T}{T-1} + y_n}{\sigma_n} \sigma$$

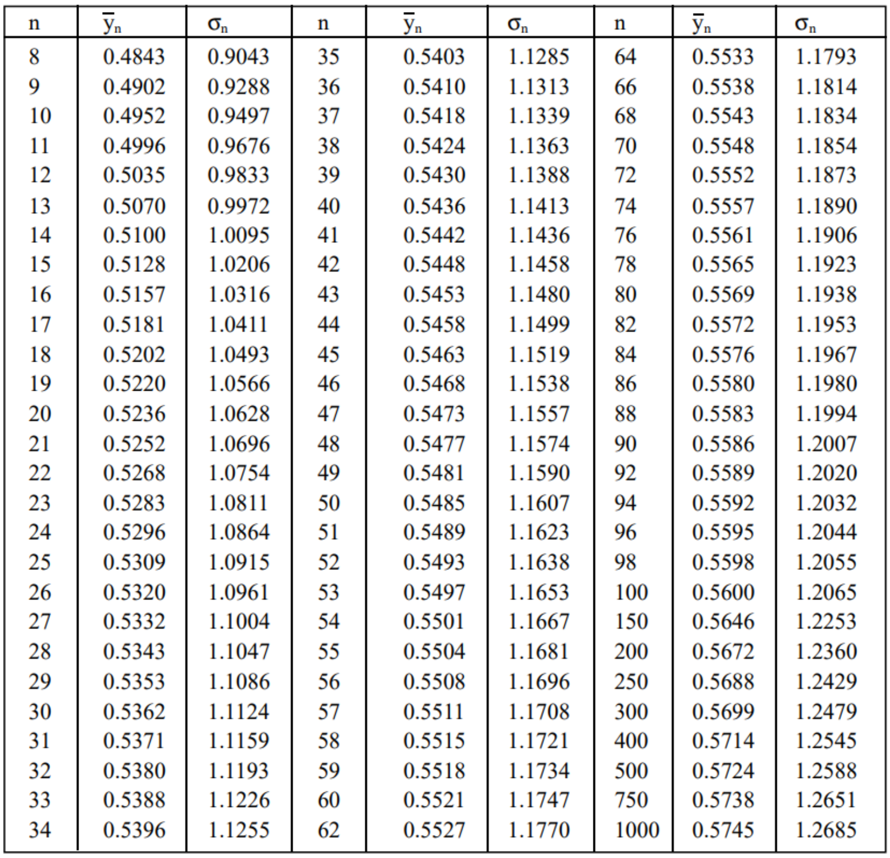
Equation 2: Gumbel distribution function

Where:

x	is the resulting sum of precipitation for the given return period
$\bar{x}$	is the mean measured sum of precipitation
T	is the return period
y_n	is the mean Gumbel Variate (see Table 6 below)
σ_n	is the Standard Deviation of the Gumbel Variate (see Table 6 below)
σ	is the Standard Deviation of the sum of precipitation data

Variables y_n and σ_n can be deducted from Table 6 below where N is 30 is used as from 30 years the highest precipitation events are extracted and this results in 30 data points.

Table 6: Mean and Standard Deviation of Gumel variate in relation to the record length (Suhaiza et al., 2007)



n	$\bar{y}_n$	σ_n	n	$\bar{y}_n$	σ_n	n	$\bar{y}_n$	σ_n
8	0.4843	0.9043	35	0.5403	1.1285	64	0.5533	1.1793
9	0.4902	0.9288	36	0.5410	1.1313	66	0.5538	1.1814
10	0.4952	0.9497	37	0.5418	1.1339	68	0.5543	1.1834
11	0.4996	0.9676	38	0.5424	1.1363	70	0.5548	1.1854
12	0.5035	0.9833	39	0.5430	1.1388	72	0.5552	1.1873
13	0.5070	0.9972	40	0.5436	1.1413	74	0.5557	1.1890
14	0.5100	1.0095	41	0.5442	1.1436	76	0.5561	1.1906
15	0.5128	1.0206	42	0.5448	1.1458	78	0.5565	1.1923
16	0.5157	1.0316	43	0.5453	1.1480	80	0.5569	1.1938
17	0.5181	1.0411	44	0.5458	1.1499	82	0.5572	1.1953
18	0.5202	1.0493	45	0.5463	1.1519	84	0.5576	1.1967
19	0.5220	1.0566	46	0.5468	1.1538	86	0.5580	1.1980
20	0.5236	1.0628	47	0.5473	1.1557	88	0.5583	1.1994
21	0.5252	1.0696	48	0.5477	1.1574	90	0.5586	1.2007
22	0.5268	1.0754	49	0.5481	1.1590	92	0.5589	1.2020
23	0.5283	1.0811	50	0.5485	1.1607	94	0.5592	1.2032
24	0.5296	1.0864	51	0.5489	1.1623	96	0.5595	1.2044
25	0.5309	1.0915	52	0.5493	1.1638	98	0.5598	1.2055
26	0.5320	1.0961	53	0.5497	1.1653	100	0.5600	1.2065
27	0.5332	1.1004	54	0.5501	1.1667	150	0.5646	1.2253
28	0.5343	1.1047	55	0.5504	1.1681	200	0.5672	1.2360
29	0.5353	1.1086	56	0.5508	1.1696	250	0.5688	1.2429
30	0.5362	1.1124	57	0.5511	1.1708	300	0.5699	1.2479
31	0.5371	1.1159	58	0.5515	1.1721	400	0.5714	1.2545
32	0.5380	1.1193	59	0.5518	1.1734	500	0.5724	1.2588
33	0.5388	1.1226	60	0.5521	1.1747	750	0.5738	1.2651
34	0.5396	1.1255	62	0.5527	1.1770	1000	0.5745	1.2685

APPENDIX C: BACKGROUND DATA AVERAGE NUMBER OF DAYS SPOUTING IS UNAVAILABLE

In this section, the data behind Figure 10 till Figure 14 are shown. These graphs show the total number of days where the sea water level does not drop beneath different chosen water levels. Note that for a day to be considered to not drop beneath the tested water level, only the days are counted where the seawater level was below the levels -0.93 (target water level on the Lauwersmeer), -0.5, 0 and 0.4 (maximal water level on the Lauwersmeer) for more than 24hrs in a row. This is based on sea water level data from 1991 till 2020 and the number of days per year a the sea water level has not dropped beneath the investigated water level per year is an average and has been categorised based on the duration of not dropping beneath the level. In the tables below, the amount of sea level rise is shown in bold at the top. In Table 7, the gathered data from sea level rise of 0 cm till 50 cm are shown. In Table 8 the gathered data from sea level rise of 55 cm till 100 cm are shown. In Table 9 the gathered data from sea level rise of 105 cm till 150 cm are shown.

Table 7: Results research question 1 (0 to 50 cm sea level rise)

-0.93	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
1-5 days in a row	41.3	46.2	51.8	56.7	62.4	67.4	69.5	68.7	69.9	65.4	59.1
6-10 days in a row	4.5	7.6	12.7	20.0	25.4	31.9	42.4	55.8	64.1	65.2	73.3
11-50 days in a row	0.0	0.0	0.0	0.4	2.6	5.4	9.5	15.7	32.0	54.5	74.5
51-100 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8
101-365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.5											
1-5 days in a row	11.2	13.0	15.5	17.9	21.1	24.5	28.6	33.1	37.7	43.0	49.4
6-10 days in a row	0.0	0.0	0.0	0.0	0.0	0.2	1.4	2.0	3.4	5.8	9.5
11-50 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51-100 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101-365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0											
1-5 days in a row	2.3	2.5	2.9	3.3	3.7	4.8	5.6	6.4	7.5	8.9	10.5
6-10 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11-50 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51-100 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101-365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.4											
1-5 days in a row	0.7	0.8	0.9	0.9	1.1	1.2	1.4	1.7	2.3	2.5	2.9
6-10 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11-50 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51-100 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101-365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum											
-0,93 m NAP	45.8	53.8	64.5	77.1	90.4	104.7	121.4	140.1	166.0	185.1	208.6
-0,5 m NAP	11.2	13.0	15.5	17.9	21.1	24.7	30.0	35.1	41.1	48.8	58.9
0 m NAP	2.3	2.5	2.9	3.3	3.7	4.8	5.6	6.4	7.5	8.9	10.5
0,4 m NAP	0.7	0.8	0.9	0.9	1.1	1.2	1.4	1.7	2.3	2.5	2.9

Table 8: Results research question 1 (55 to 100 cm sea level rise)

-0.93	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
1-5 days in a row	51.7	41.6	30.6	24.3	15.9	11.1	7.8	4.9	3.3	2.0
6-10 days in a row	71.8	68.2	56.3	46.8	34.4	21.2	14.4	7.0	5.1	3.1
11-50 days in a row	101.3	130.2	150.5	167.5	183.9	144.1	111.7	82.0	53.1	30.8
51-100 days in a row	6.1	12.6	27.7	31.7	40.7	67.9	75.2	55.5	54.9	33.4
101-365 days in a row	0.0	0.0	4.4	21.3	38.2	81.7	125.2	175.8	212.6	213.3
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.7	15.7	65.1
-0.5										
1-5 days in a row	53.4	58.7	65.0	69.7	70.6	68.6	67.7	63.3	56.4	48.6
6-10 days in a row	16.7	21.5	27.8	37.1	48.5	60.1	63.7	68.1	72.8	71.6
11-50 days in a row	0.0	0.8	3.7	6.7	12.4	22.4	40.4	63.0	88.1	116.0
51-100 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	6.1
101-365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0										
1-5 days in a row	12.3	14.8	16.9	19.7	23.1	26.9	31.0	35.1	40.2	46.1
6-10 days in a row	0.0	0.0	0.0	0.0	0.0	1.2	1.8	3.1	5.4	8.6
11-50 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51-100 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101-365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.4										
1-5 days in a row	3.3	3.7	4.8	5.6	6.4	7.5	8.9	10.5	12.3	14.8
6-10 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11-50 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51-100 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101-365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum										
-0,93 m NAP	230.8	252.6	269.5	291.5	313.2	325.9	334.3	341.0	344.8	347.6
-0,5 m NAP	70.0	80.9	96.5	113.5	131.5	151.1	171.8	194.4	219.2	242.3
0 m NAP	11.9	14.3	16.1	18.4	21.2	26.5	30.7	34.7	40.7	48.7
0,4 m NAP	3.3	3.7	4.8	5.6	6.4	7.1	8.6	10.2	11.9	14.3

Table 9: Results research question 1 (105 to 150 cm sea level rise)

-0.93	**105**	**110**	**115**	**120**	**125**	**130**	**135**	**140**	**145**	**150**
1-5 days in a row	1.4	0.6	0.3	0.2	0.2	0.2	0.1	0.1	0.0	0.0
6-10 days in a row	1.9	1.0	0.7	0.2	0.3	0.3	0.0	0.0	0.0	0.0
11-50 days in a row	20.1	14.7	13.4	12.8	11.4	7.6	4.6	3.9	2.6	0.0
51-100 days in a row	25.1	14.7	4.1	4.6	2.2	4.1	1.9	1.9	1.9	1.9
101-365 days in a row	173.0	114.8	105.6	83.3	83.3	48.6	36.1	19.8	10.8	10.8
More than 365 days in a row	127.4	204.0	226.4	249.9	253.9	290.7	309.0	326.3	336.7	339.5
-0.5										
1-5 days in a row	37.9	27.1	19.7	12.7	9.8	6.8	4.0	2.5	1.7	1.1
6-10 days in a row	66.0	53.6	41.4	27.6	18.2	11.0	6.2	3.6	2.6	1.6
11-50 days in a row	140.0	158.8	182.1	171.6	132.3	93.0	63.7	44.1	24.0	16.6
51-100 days in a row	14.1	33.0	29.2	46.1	74.2	66.4	61.1	42.2	31.3	15.1
101-365 days in a row	3.7	8.4	30.1	58.6	90.8	157.4	192.6	201.2	176.2	165.8
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	15.7	50.3	110.1	147.0
0										
1-5 days in a row	50.3	56.4	61.7	65.9	67.1	66.8	66.1	61.5	55.0	47.4
6-10 days in a row	14.8	18.7	25.1	33.5	43.7	54.0	60.0	64.2	70.6	70.0
11-50 days in a row	0.0	0.8	2.9	5.9	11.2	19.7	35.0	55.2	76.5	104.7
51-100 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	4.2
101-365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.4										
1-5 days in a row	16.9	19.7	23.1	26.9	31.0	35.1	40.2	46.1	50.3	56.4
6-10 days in a row	0.0	0.0	0.0	1.2	1.8	3.1	5.4	8.6	14.8	18.7
11-50 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8
51-100 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101-365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
More than 365 days in a row	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum										
-0,93 m NAP	348.9	349.9	350.5	351.0	351.2	351.5	351.8	351.9	352.1	352.2
-0,5 m NAP	261.7	280.9	302.5	316.7	325.4	334.7	343.3	343.9	345.9	347.1
0 m NAP	65.1	75.9	89.7	105.2	122.0	140.5	161.1	180.9	204.1	226.3
0,4 m NAP	16.9	19.7	23.1	28.1	32.9	38.2	45.5	54.7	65.1	75.9

APPENDIX D: IMPLEMENTATION OF FRIESLAND

The software, SOBEK, that has been used in this thesis was used as a representation of the water system of waterboard Noorderzijlvest was available. The model works by inputting characteristics such as land coverage, dimensions of civil engineering constructions, water way profiles and precipitation. This information is than processed and different outputs can than be generated such as the water depth and discharges. An oversight of this process can be seen in Figure 38 below.

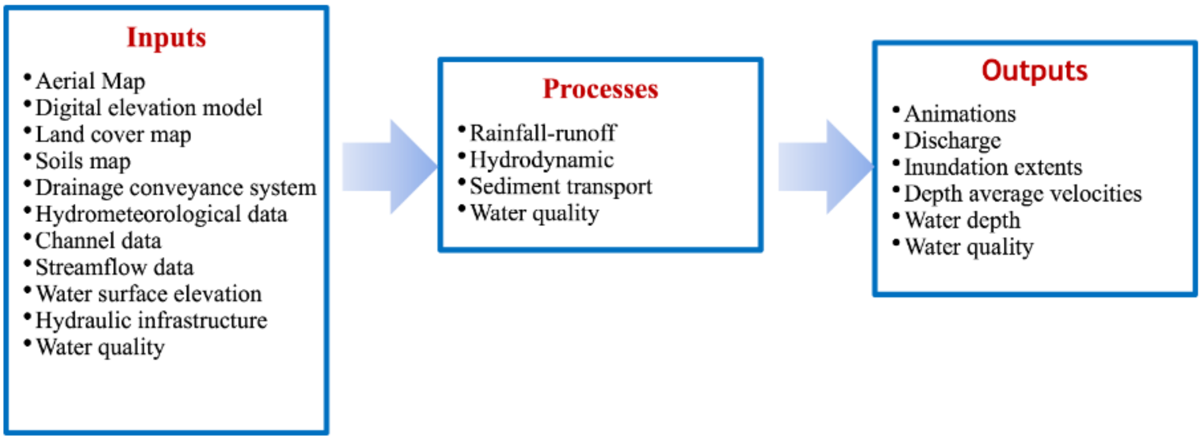


Figure 38: General process of SOBEK (SOBEK, *2013)*

For the extension of the model by adding Friesland. The dimensions of the different area types and their average height have been found in (Waterbeheerplan Lauwersmeergebied 2003-2007, (2007) and shown Figure 39.

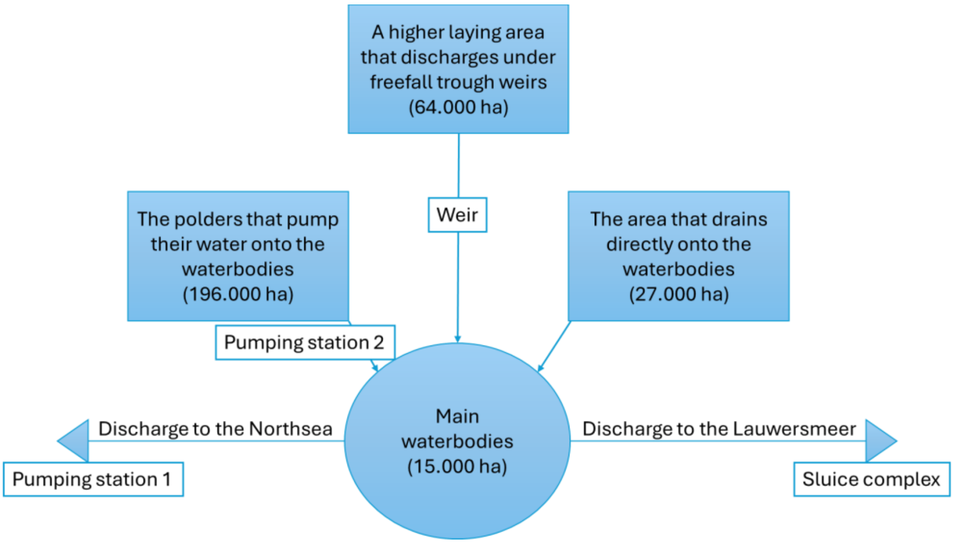


Figure 39: Graph of how Friesland has been simplified into SOBEK

The civil engineering structures in the wite boxes of Figure 39 will be will be explained below.

- Pumping station 1 is a combination of the Hooglandgemaal, Woudagemaal and Gemaal Vijfhuizen. These pumping stations have the capacities shown in Table 10 below. These have been added up and scaled to turn on when the water level reaches -0.3 m NAP on the waterbodies in Friesland. The pumping capacities have been found on (*Gemalendatabase*, n.d.).

Table 10: Capacity pumping stations to the Noordzee

	Capacity (m^3/min)	Capacity (m^3/s)
Hooglandgemaal	7340	122,33
Woudagemaal	4000	66,67
Gemaal Vijfhuizen	252	4,2
Total	**11592**	**193,2**

- Pumping station 2 is a combination of all the pumping stations that pump the water from the individual polders to the main waterbodies. To determine the capacity this pumping station 2 some pumping station of polders in Friesland with a publicized pumping capacity and area which they pump from have been compared. 3 pumping stations were found that had publicized both characteristics and can be found in Table 11 below. The pumping capacities have been found on as well (*Gemalendatabase*, n.d.).

Table 11: Specifications pumping stations in Friesland

Name pumping station	Name pumping area	Size area	Pumping capacity	$m^3/min/m^2$
Koai	Stienser Oudland	6.76 km2	140 m^3/min	$2{,}07*10^{-5}$
Huinsermolen	Huinserpolder	6.45 km2	50 m^3/min	$7{,}75*10^{-6}$
Het Workumer Nieuwland	Polder Het Workumer Nieuwland	442 ha	41 m^3/min	$9{,}28*10^{-6}$

The average pumping capacity per m^2 has been calculated from which a capacity for a pumping station for all the polders. This is $1.96*10^9$ (the area) times $1.25*10^{-5}$ which equals 24655.5 m^3/min. This has been translated to a 400 m^3/s pumping station at its peak.

- The weir connects the higher lands with the water bodies. The dimensions of the weir have been estimated to be 1000 meters wide and have a height of 10 meters
- The width of the sluice complex where water can flow through is 17.87m (Nouta, 1995) in runs 1 through 3 and the width of the Friese Sluis of 5.88m is added in runs 4 and 5 (*Friese Sluis, Zoutkamp, Brug over Binnenhoofd, in Zoutkamp: Openingstijden En Contact*, n.d.). The depth of the sluice complex is estimated to be -3 m NAP and the sluice closes when the water level on the Lauwersmeer is higher than on the Frisian waterbodies as well as when the water level on the Frisian waterbodies drops below -0.53 m NAP. The width of the sluices is absolute.

A visual representation of the SOBEK model including the extension of Friesland is shown below. In Figure 40 the whole model is show. In the figure the part of the model inside the blue square represents the R.J. Cleveringsluizen and a green square is visible in which the extension of the model is visible. A zoomed in picture of this model is visible in Figure 41. In the green square the area of Friesland is modelled and this part is zoomed into in Figure 42.

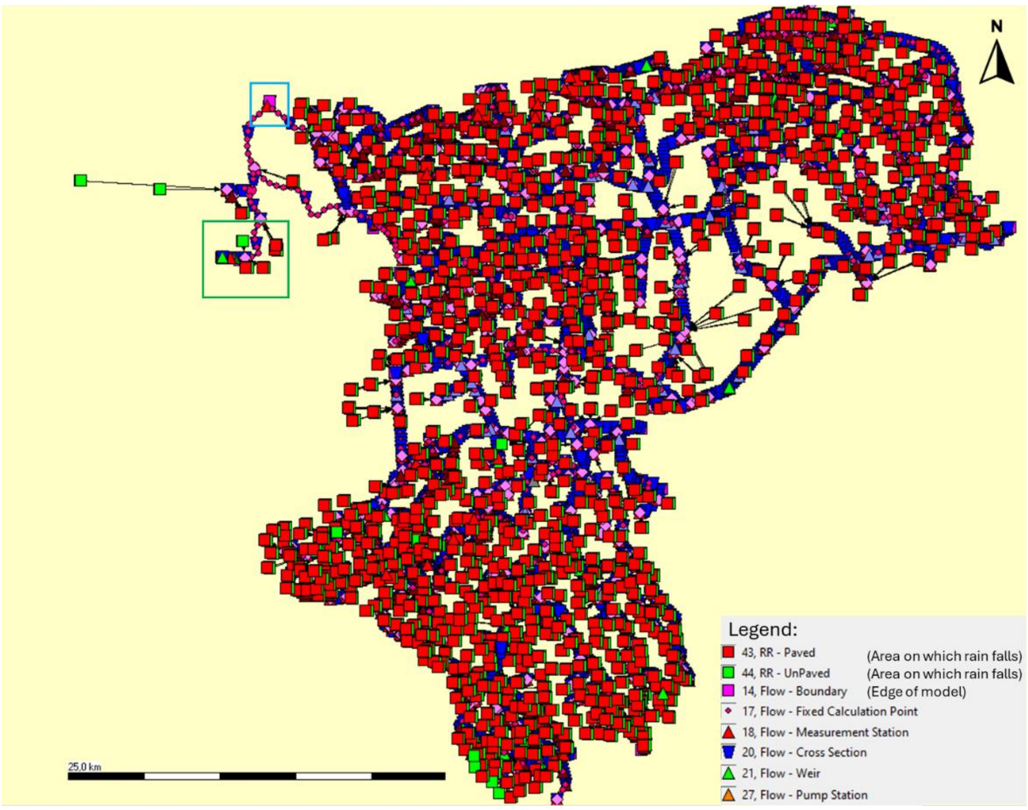


Figure 40: SOBEK model of Noorderzijlvest

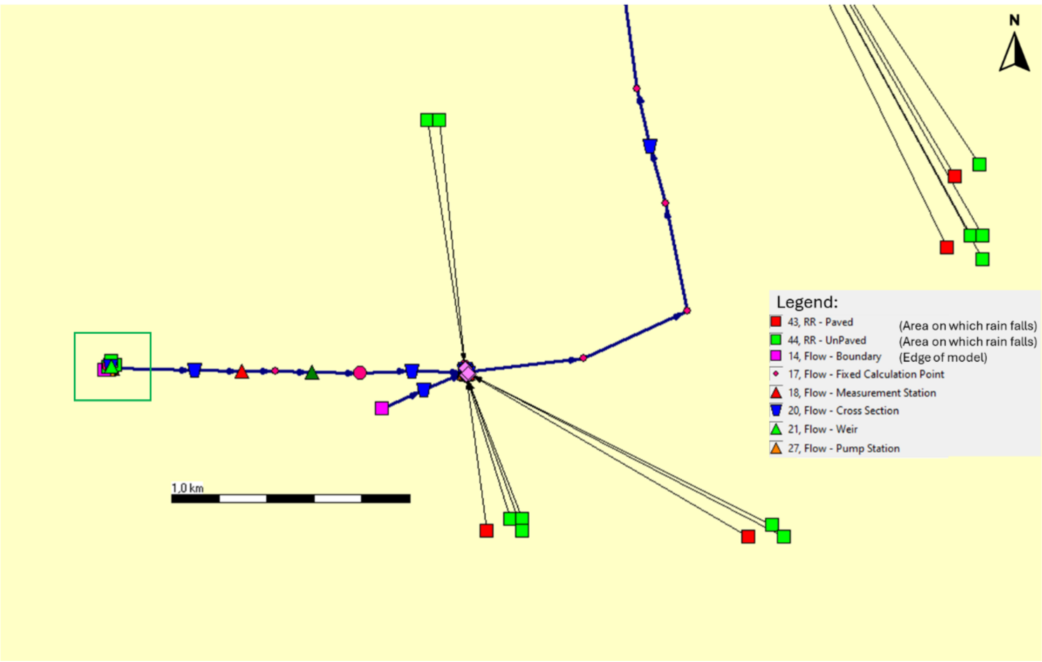


Figure 41: SOBEK model zoomed into extension of model

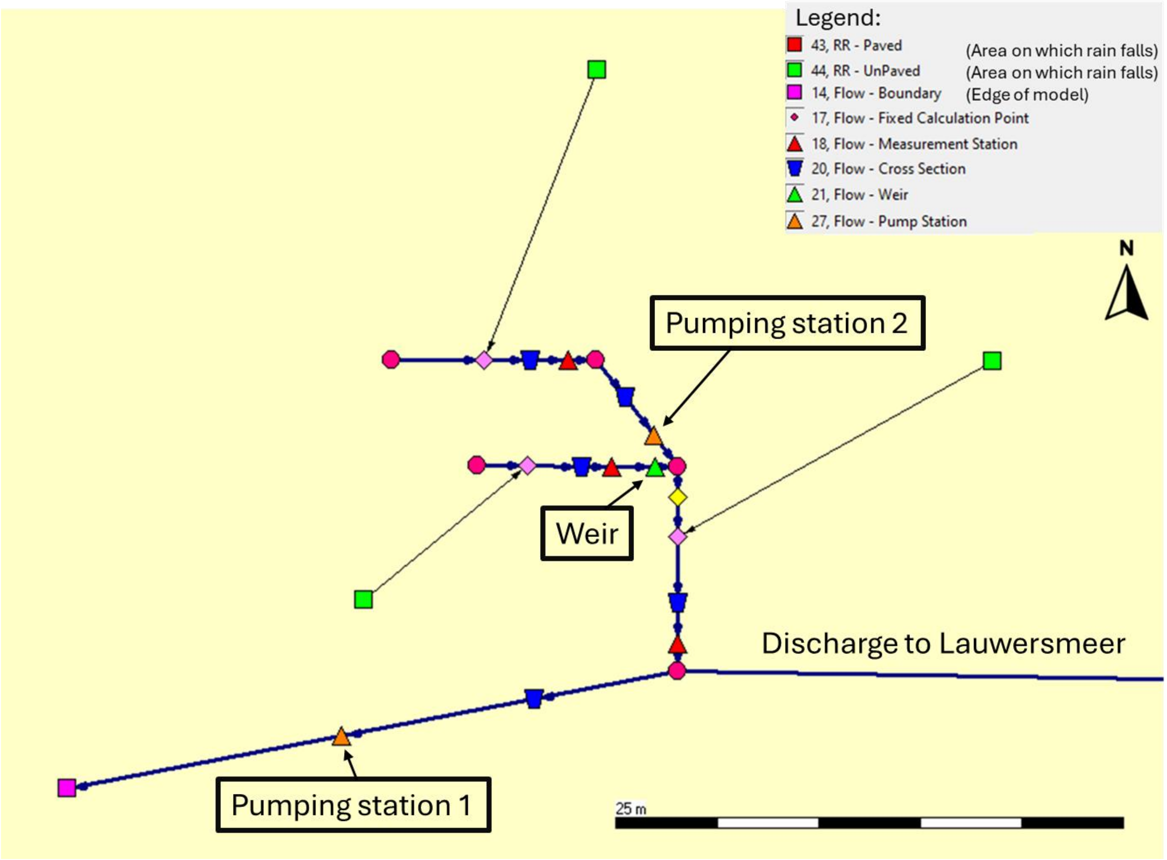


Figure 42: SOBEK model zoomed into the area of Friesland

APPENDIX E: ADDITIONAL GRAPHS MODELLED CLIMATE SCENARIOS

In Figure 43 below the impact of the different climate scenarios on the water level on the Lauwersmeer can be seen with the highest and lowest sea water level events. Here the impact of sea level rise can clearly be seen as with the higher sea water levels spouting is more often unavailable.

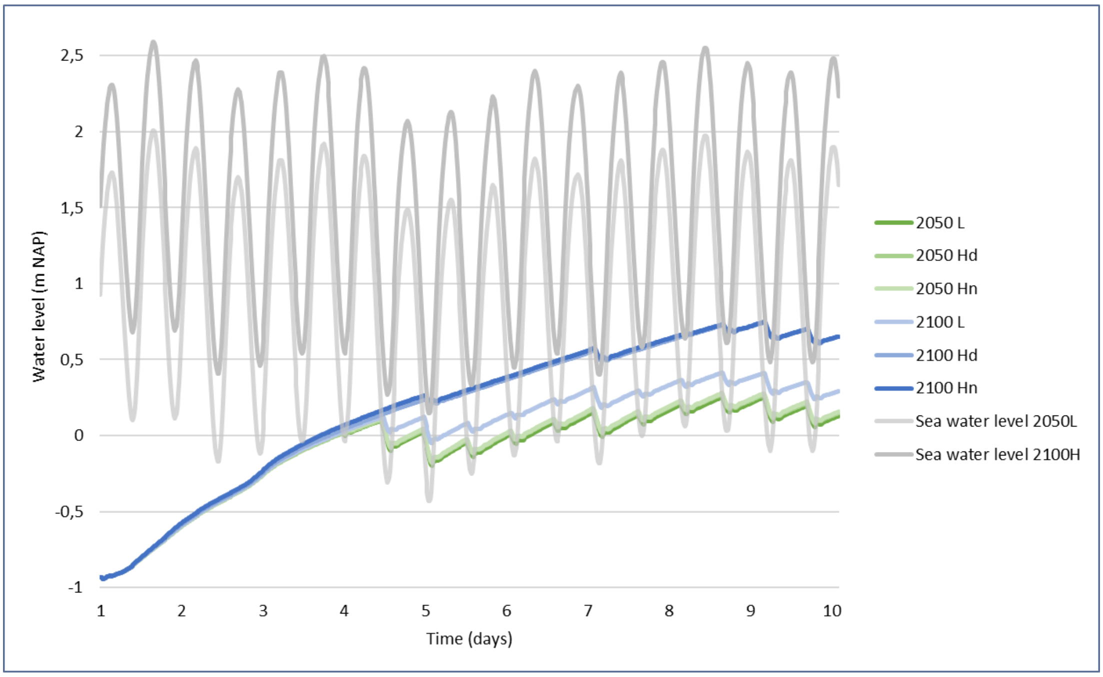


Figure 43: Climate change scenarios run for 1/10 year 10 day events including highest and lowest sea water level events

Next to this, the differences between the scenarios cannot be seen clearly in these graphs, therefore, in Figure 44 and Figure 45 respectively the water levels on the Lauwersmeer with the climate scenarios from 2050 and 2100 can be seen.

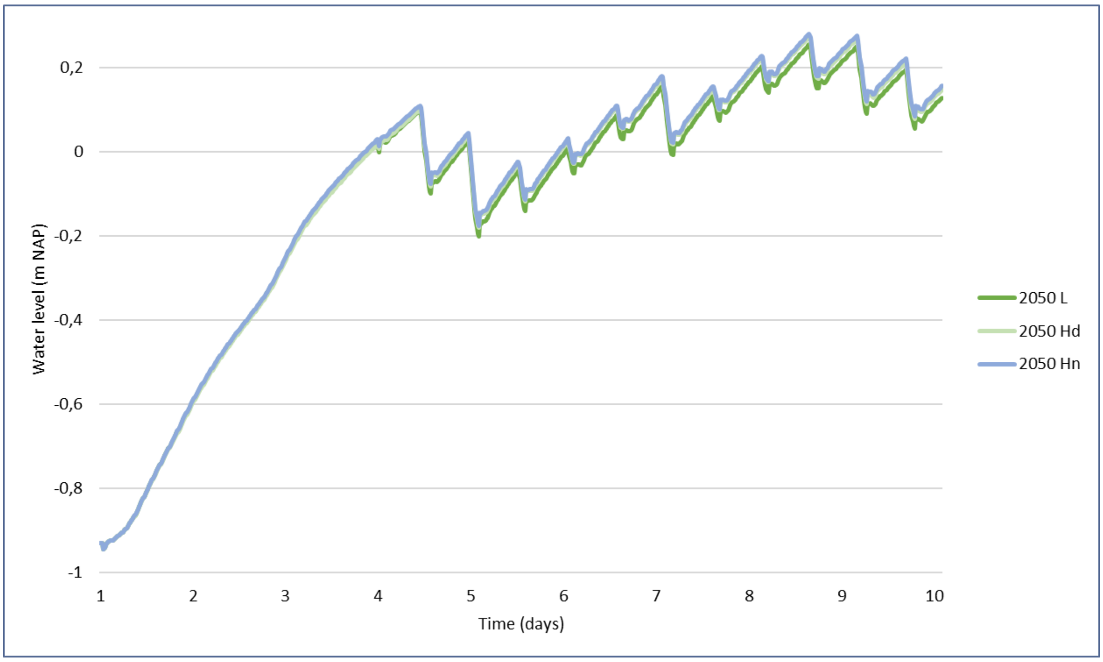


Figure 44: Climate change scenarios of 2050 run for 1/10 year 10 day events

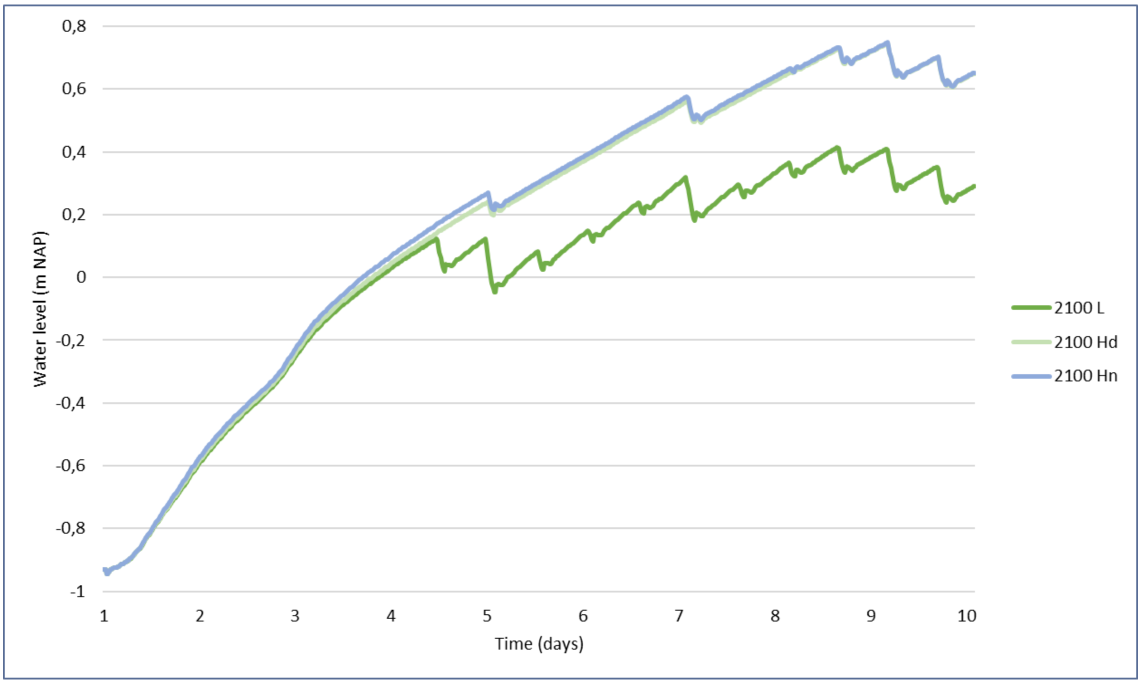


Figure 45: Climate change scenarios of 2100 run for 1/10 year 10 day events

APPENDIX F: WATER LEVEL LAUWERSMEER GRAPHS OF CLIMATE SCENARIOS IN COMBINATION WITH PUMPING STATIONS

In this paragraph, the water level on the Lauwersmeer during the predefined climate scenarios in combination with pumping stations with different capacities. The results of 250 Hn and 2100 Hn have been shown in subchapter 6.3.. Therefore below the resulting water levels of respectively 2050 L, 2050 Hd, 2100 L and 2100 Hn are shown in Figure 46, Figure 47, Figure 48 and Figure 49 below.

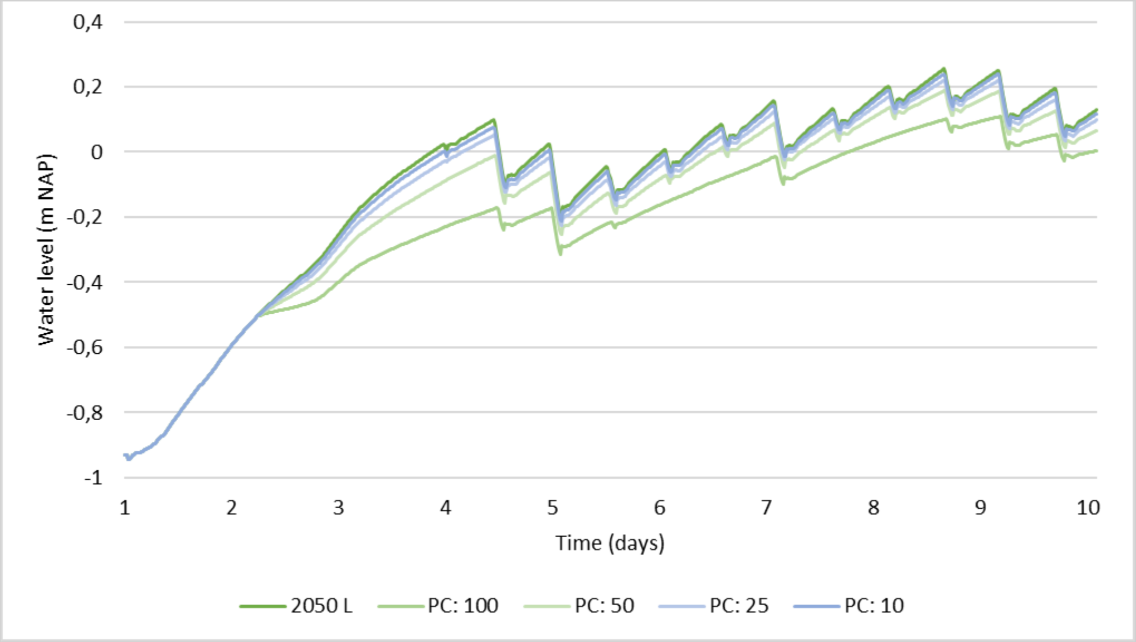


Figure 46: Water level on Lauwersmeer during climate change scenario for 2050 L with different pumping stations

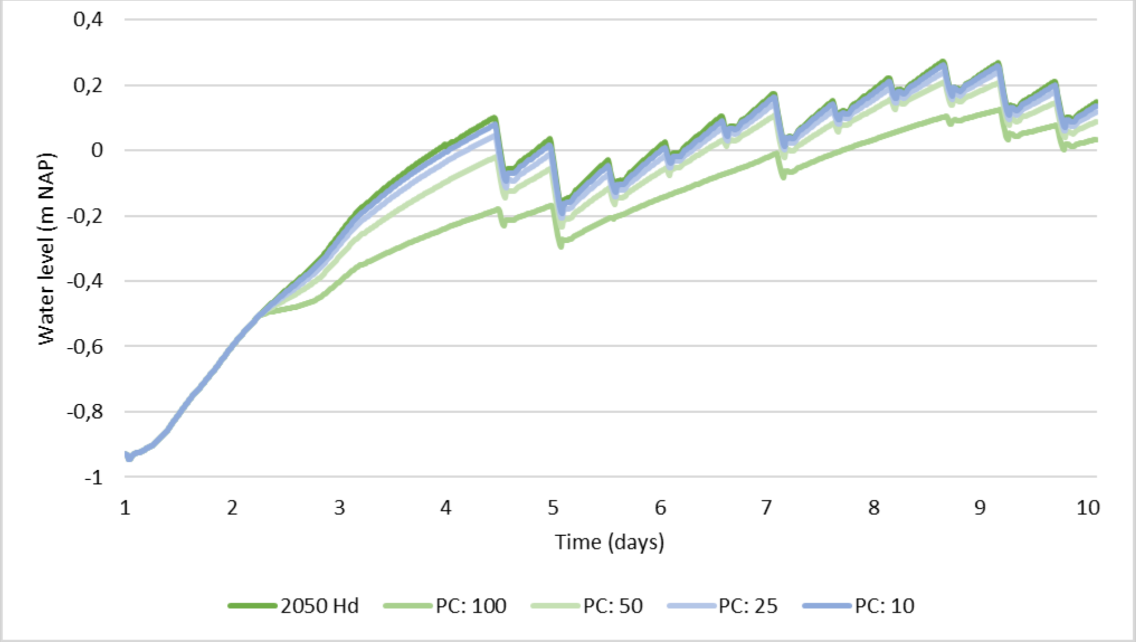


Figure 47: Water level on Lauwersmeer during climate change scenario for 2050 Hd with different pumping stations

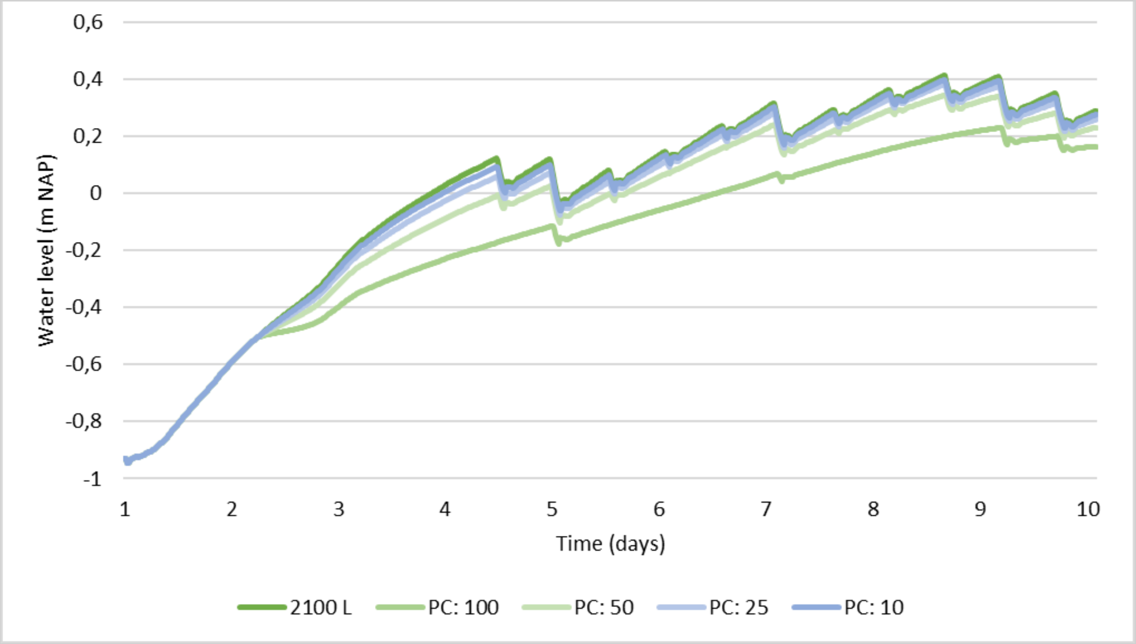


Figure 48: Water level on Lauwersmeer during climate change scenario for 2100 L with different pumping stations

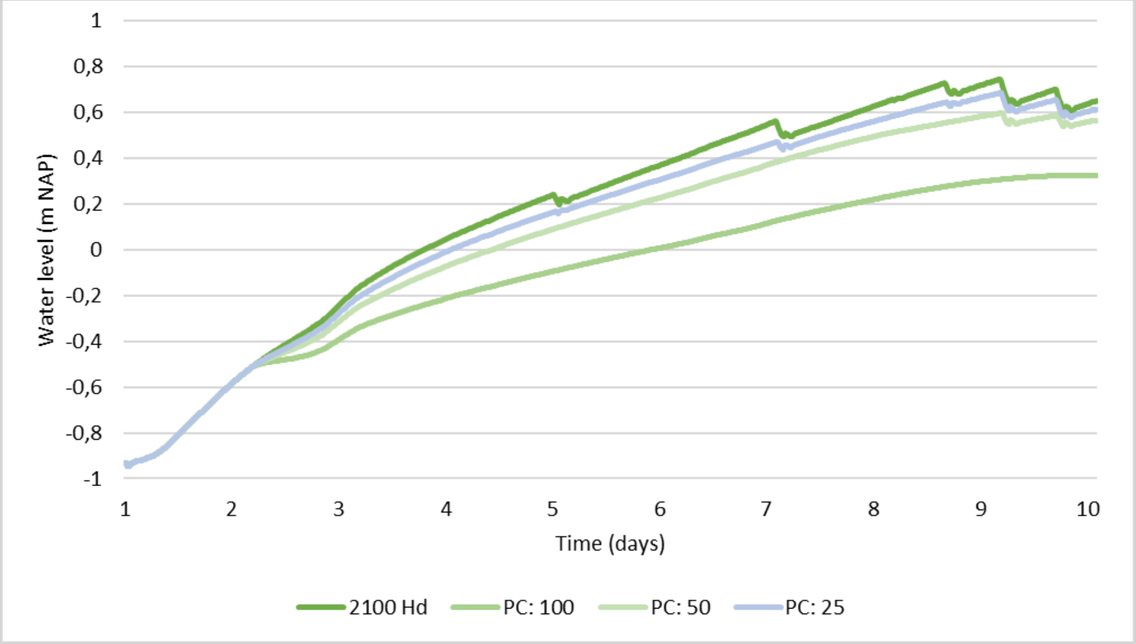


Figure 49: Water level on Lauwersmeer during climate change scenario for 2100 Hd with different pumping stations