Buffering fresh water at the Volkerak-Zoommeer to mitigate drought

Developing a Decision Support system to evaluate the potential of temporarily heightening of the water level

R.P. Verboeket

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by

R.P. Verboeket

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Preface

For a long period, the Netherlands has been fighting against the threats of high water levels. High discharges in the rivers Rhine and Meuse or storms at the North Sea have resulted in solutions that protect our country against floods. After the completion of the Delta works in the provinces of Zeeland and Zuid-Holland and a national scheme to provide room for the rivers during high river discharges, it was assumed that the Netherlands were safe for any threats imposed by water. The main focus of these measures is to keep the water away from the (low-lying) cities.

However, with rising temperatures and less precipitation during the summer period, new water-related threats started to arise: lowering of the groundwater tables, lower discharges in the rivers, salinization of the Delta and higher evaporation rates. All can be summarized by the term ”drought”. In general, when we speak of droughts, we think about the desert, bush fires etc., while here in the Netherlands these manifestations are not known. However, in 2018, the Netherlands experienced the most severe drought since 1976. 2019 again, was one of the hottest summer periods ever measured in the Netherlands with low precipitation values. During these periods, farmers, nature, the shipping industry and drinking water companies experienced the consequences of these droughts.

As this is a relatively new water related threat in the Netherlands, I wondered what we could learn on this topic to be better prepared when new drought periods will occur. That's why I wanted to perform my master thesis on this topic to finish my Master programme Water Resource Management at the Delft University of Technology. After some investigation, I got the opportunity to perform my research at the Hydro Meteo Centrum of Rijkswaterstaat in Middelburg. The Hydro Meteo Centrum is the operational water manager of the Volkerak-Zoommeer, an artificial fresh water lake that was created with the completion of the Delta works. This makes it an interesting research area where the former Delta works and research into drought mitigation can be combined.

First of all, I would like to thank my graduation committee for their support and expertise during this study. From the TU Delft, Erik, Miriam and Olivier for their guidance, constructive feedback and their ability to continue challenging me to keep on critically reviewing my own work. From Rijkswaterstaat, I want to thank Stefan and Rutger for sharing their expertise and knowledge on the different topics that I encountered and introducing me to Rijkswaterstaat and the interesting topics they deal with in their daily work.

Furthermore, I would like to thank my colleagues at Rijkswaterstaat and the representatives of the water boards for their time for the interviews and providing me with the data I needed.

During this eight month period, where the university and offices were closed most of the time, I learned to adapt to changing circumstances and be creative while working from home most of the time. This would not be possible without the support of my friends and family. For which I would like to thank them for their time, inspiration and feedback. They made it possible to enjoy this research period and look back at a successful completion of studies at the TU Delft.

R.P. Verboeket
Delft, May 2021

Summary

The Volkerak-Zoommeer is a former estuary located the Rhine Meuse Delta in the southwestern part of the Netherlands. After the completion of the Volkerakdam, Philipsdam and Oesterdam as part of the Delta Works, this estuary was cut of from the Oosterschelde and a fresh water lake was formed in a sea water environment. This new lake became the Volkerak-Zoommeer: a lake that acts as a fresh water supply for the regional water systems of the water boards Hollandse Delta, Scheldestromen and Brabantse Delta as well as providing a tidal free shipping connection between Antwerp and the Rhine. The operational water manager of the lake is Rijkswaterstaat. They manage the water level and water quality by letting fresh water in from the Hollandsch Diep at the Volkeraksluizen and release it at Bath into the Westerschelde. This mechanism enables Rijkswaterstaat to flush the system and adhere to the target levels, as well as managing a maximum chloride concentration of 450 mg Cl/L during the growing season.

In 2018, the Netherlands experienced one of the most severe droughts since the beginning of weather measurements started. Low discharges at the Rhine resulted in a decreasing water supply and more salinization in the Rhine Meuse Delta. When the discharge of the Rhine at Lobith reach below 800 m^3/s, it is no longer allowed to let in fresh water through the Volkeraksluizen. This could lead to problems in the fresh water supply to the regional system of the water users of the Volkerak-Zoommeer. The question came up whether creating a fresh water buffer by temporarily heightening of the water level could be used to overcome a period with no fresh water supply from the Hollandsch Diep.

In autumn 2020, the dynamics of the system were researched during a practical trial. The water level was heightened up to +0.15 m NAP. Next, the inlet was closed and it was measured how long it would take until the water level reached -0.10m NAP with normal flushing operations at Bath. During a second trial, the outlet at Bath was closed too. Based on the insights of these trials, a prototype for a Decision Support System was created. This system is able to give insights in the development of the water level at the Volkerak-Zoommeer according to operational water management decisions.

This Decision Support System was used to evaluate the impact of delta and climate scenarios in 2050 and 2085 on the water level of the Volkerak-Zoommeer. The maximum possible duration for a period without a fresh water supply was researched per scenario within the target levels of -0.10 m NAP and + 0.15m NAP. Different flushing regimes at Bath were evaluated. For normal flushing operations, this duration is 5 till 7 days. For flushing every second low tide, this period could be lengthened to 8 to 13 days. When the outlet at Bath is closed, the maximum duration is 20 till 60 days. From the trials, it was found that the chloride concentration will gradually increase in this period. Unfortunately, sufficient insights in the dynamics of the chloride concentration lack at the moment to sufficiently incorporate the chloride concentration in the prototype.

From historical data, the maximum duration of a period with discharges lower than 800 m^3/s measured at Lobith was 16 days during the growing season and 82 days for all year data. Within the current target levels, this duration cannot be reached. It was therefore researched what initial water level theoretically could be achieved based on historical data. This turned out to be +0.50 m NAP. Here, the Volkerak-Zoommeer was considered as a closed system, neglecting the open connections with the Dintel and the Vliet. With an initial water level of +0.50 m NAP, the duration without fresh water supply could be significantly lengthened. With normal flushing operations, the period can take between 12 and 19 days. For flushing operations every second low tide, this period takes 20 till 34 days. When the outlet at Bath is closed, a period up to 120 days could be bridged.

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Acronyms

DSS Decision Support System. 43

ECDF Emperical Cummulative Distribution Function. 33

GEV Generalized Extreme Value. 31
GPD Generalized Pareto Distribution. 31

HMC Hydro Meteo Centrum. 43

IPCC Intergovernmental Panel on Climate Change. 19

KNMI Koninklijk Nederlands Meteorologisch Instituut (English: Royal Dutch Meteorological Institute). 19

PET Potential Evaporation. 30
POT Peak Over Threshold. 31

SPEI Standardized Precipitation and Evaporation Index. 28
SPI Standardized Precipitation Index. 28

VZM Volkerak-Zoommeer. 1

WSBD Waterschap Brabantse Delta. 1
WSHD Waterschap Hollandse Delta. 1
WSSS Waterschap Scheldestromen. 1

1

Introduction

1.1. Current situation

The Volkerak-Zoommeer (VZM) is a former estuary in the southwestern part of the Netherlands. It is located in the provinces of Zeeland, Zuid-Holland and Noord-Brabant and part of the Rhine-Meuse delta. The lake is managed by Rijkswaterstaat and provides fresh water for the water boards: (1) the Waterschap Hollandse Delta (WSHD), (2) Waterschap Scheldestromen (WSSS) and (3) Waterschap Brabantse Delta (WSBD). After completion of the Delta Works in 1987 in this area of the Netherlands, the estuary was transformed into an artificial fresh water lake, surrounded by different dams that form the border with other (former) estuaries. In its current form, the VZM consist of two lakes: the Volkerak / Krammer in the north and the Zoommeer in the south. The Eendracht connects both lakes, allowing for a direct shipping route between the Scheldt and the Rhine and thereby forming a direct shipping route from Antwerp to Rotterdam and Germany. In Figure 1.1, the location and the surroundings of the VZM are presented.

Due to the proximity of the salt water Oosterschelde, the salt water Westerschelde and the brakish Grevelingen, the VZM can be regarded as a fresh water lake in a salt environment. In the deeper parts of the VZM, higher chloride concentrations can still be found while the lighter fresh water lies on top. This is a clear example of stratification and this process makes water quality management challenging. Rijkswaterstaat, as operational manager of the VZM, needs to comply with the water quality regulations that are stated in the Water Agreement (Rijksoverheid, 1 January 2016). One of the main regulations is on the maximum amount of chloride concentrations that is set for fresh water for agricultural use. Currently, operational water management of the VZM consist of a fresh water intake from the Hollandsch Diep through the Volkeraksluizen in the north. In the south, water is discharged into the Westerschelde at Bath. This mechanism enables flushing of the system, making it possible for Rijkswaterstaat to manage the water level and the chloride concentration of the VZM.

In the summer of 2018, the Netherlands experienced one of the most severe droughts (Leunissen, 2020, KNMI, 2020). The discharge of the Rhine at Lobith was below a critical value of 800 m^3/s for more than 50 days. With this low discharge values, all the available fresh water in the Dutch rivers is needed to flush through the Nieuwe Waterweg at Rotterdam to prevent salinization of the Rijn-Maasmonding as much as possible. During a period of low discharges at the Rhine, the inlet of the Volkerak needs to be closed. As a result the fresh water supply of the VZM is reduced to only precipitation and the water that comes from the rivers Dintel and Vliet in Brabant. Most of the time, this water also contains (higher) concentrations of Cyanobacteria and other nutrients.

It is expected that due to climate change, the intensity and duration of drought periods will increase. This results into less fresh water flowing into the Netherlands trough the rivers Rhine and Meuse and reducing the fresh water supply to the Netherlands. In the mean time, water demand is expected to increase with increasing population. To prevent salinization, this water is needed to flush the Nieuwe Waterweg. When the discharge at the Rhine is below the critical value of 800 m^3/s, the inlet at the Volkerak has to be closed and less water is available for the VZM.

To adapt the dutch surface waters to the influence of climate change, the programme Smart Water Management *(Dutch: Slim Watermanagement)* was initiated as part of the execution of the Delta Programme Fresh Water. The Delta Programme Fresh Water visualizes the long-term measures and interventions on the water system. Within the Smart Water Management programme, the question "how can we divide the dutch surface water even better?" is addressed. In six different regions, Rijkswaterstaat and local water boards work together to improve operational water management. This is done by exchange of knowledge in system analyses, sharing real-time data and to work on joint guidelines. For the VZM, the region within the programme of Smart Water Management is the Rhine-Meuse Estuary. One of the topics that was researched in Fall 2020 is the dynamics of the water level of the VZM during a simulated period of drought. During the practical trial Drought *(Dutch: Praktijkproef droogte)* a period of no fresh water supply into the VZM was simulated. The development of the water level as well as the chloride concentration were monitored. Based on the results, the question came up whether (temporal) heightening of the water level in the VZM can be useful as a drought mitigation measure for the water users of the VZM. This will be the main question that will be addressed in this thesis.

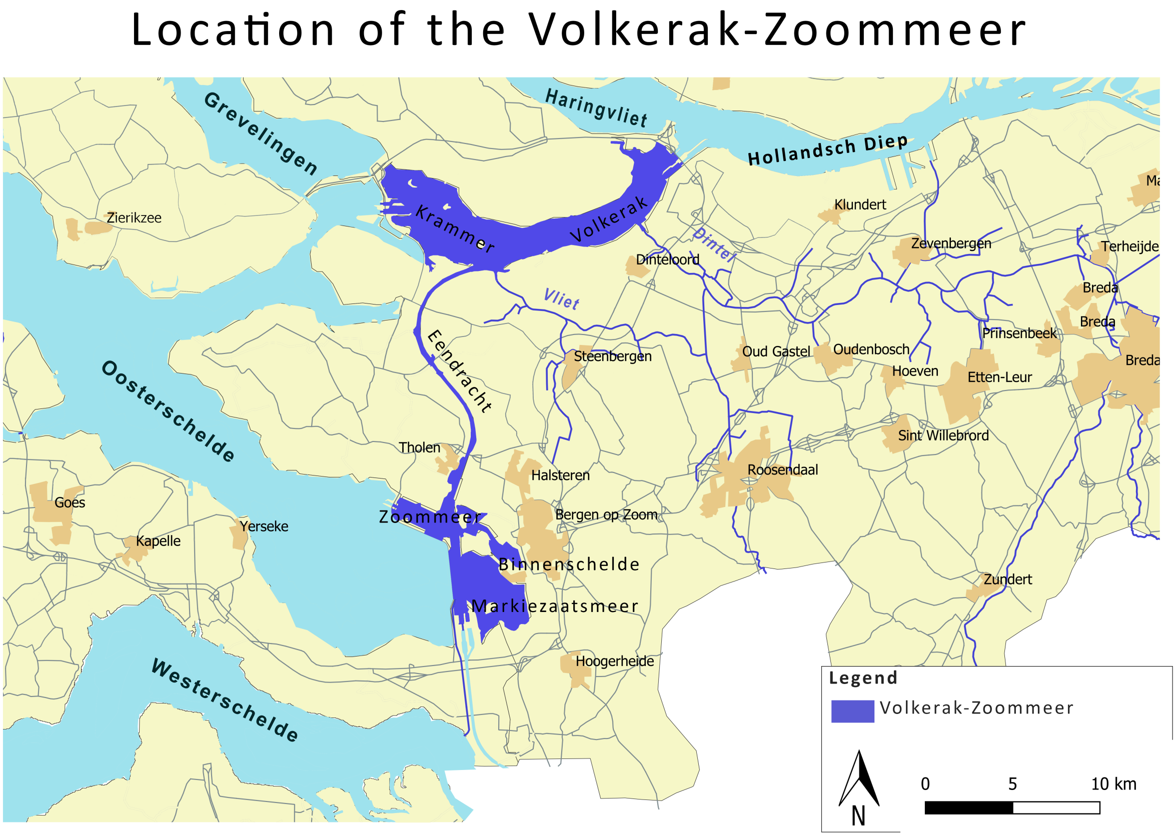

Figure 1.1: Overview of the geographical situation of the Volkerak-Zoommeer in the former Zeeuwse Delta

1.2. Research objective

The main objective of this research is to gain understanding into the development of the water level of the VZM during a period of drought and to visualize how water management interventions influence the water level of the VZM. This objective is summarized by the main research question of this thesis, that is [1]:

Could (temporarily) heightening of the water level at the Volkerak-Zoommeer be used as a drought mitigation measure for the water users of the Volkerak-Zoommeer?

In order to answer the main research question, multiple sub-questions have been defined. These questions look into (1) defining drought for the research area and users, (2) determining the water demand during a period of drought, (3) calculate duration the system is order to supply water during a period of drought and (4) provide insight in a tool to visualize the problem.

1. How is drought defined for the water users of the Volkerak-Zoommeer?
    (a) Which drought indicators are currently used to indicate drought?
    (b) Are there other indicators that could contribute to mapping drought for the water users of the Volkerak-Zoommeer?
    (c) How will the drought indicators develop between 2020 and 2100?
2. What is the water demand of the water users of the Volkerak-Zoommeer while experiencing a period of drought?
    (a) Who are the water users of the Volkerak-Zoommeer?
    (b) What is the water demand of the water users of the Volkerak-Zoommeer during a period of drought?
3. How much must the water level of the Volkerak-Zoommeer be heightened in order to comply with the water demand of the water users during a period of drought?
4. Could an implementation of a decision-support system provide better insight to the water managers of the Volkerak-Zoommeer?

1.3. Methodology

To answer the above mentioned research questions, different methods will be applied within this thesis. First, a literature study will be performed on droughts to obtain answers to the question of how drought is defined within literature and how drought can be monitored and be managed. Moreover, insights in the background of different drought indicators and indices will be obtained. These will then be computed with data from the research area to obtain feeling for the numbers. Through semi-structured interviews with representatives from the different water boards, an understanding in the drought and water management is generated. The interviewees were people that were close to the operational water level management in the polders that depend on the VZM and also take part in the discussions within the programme Smart Water Management Volkerak-Zoommeer. These interviews will provide insights in the differences and the similarities between the different water boards that use the VZM as a fresh water supply. The insights from the interviews are provided along the general information per water board in Section 2.3 and the full interviews can be found in Appendix A.1. A decision-support system will be presented as the final result of this thesis. This is a tool that will support decision-making in terms of water level management of the VZM to supply fresh water to the water users of the VZM as well as provide insight in the development of the chloride concentration.

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[1] At the start of the thesis, an extra question was formulated that looked into how water could be divided over the different water users. Due to the limitation in time and the fact the water users of the VZM were now defined as the water boards, this question is no longer used in this thesis.

1.4. Reader guide

In Chapter 2, the background information of the VZM will be introduced. An insight will be provided into the operation of the VZM and the challenges it that come up. After a short introduction into drought in the Netherlands, the experiment that is the base for this research, the Practical trial Drought, will be discussed. Chapter 3 introduces the literature study on drought. The different types of drought are introduced and evaluated. Moreover, tools to monitor drought, drought indicators and indices, will be introduced. Next, in Chapter 4, these different indicators and indices are evaluated and calculated for the research area to obtain feeling for the numbers and what they represent.

In Chapter 5, the tool that was created in during this research is introduced. The main functionalities are presented as well as different scenarios that were evaluated. Next to that, the steps towards potential implementation . Finally, in Chapter 6.2, the discussion, conclusion and recommendations are presented.

2

Volkerak-Zoommeer

This chapter will provide the necessary background information on the VZM. First, the history is described and how this former estuary was formed into a fresh water lake. Next, the water users of the VZM are identified and described. Special attention is given to local water and drought management of the water users. Next, an overview of the regulating structures of the VZM is provided. These have been divided over the regulating structures to regulate the water level at the VZM and the structures to regulate the water flow to and from the polders. A brief overview of the managing challenges at the VZM will be presented next. After that, climate change in the Netherlands is addressed as well as the different climate and delta scenarios that are used in models. Finally, a description of the drought mitigation experiment that was performed during autumn 2020 will be introduced.

2.1. History

The Volkerak is a relatively young estuary in the southwestern part of the Netherlands. The estuary was formed after the second St. Elizabeth's flood in 1421 (van Horne, 2004). In figure 2.1, the new sea that was created during this flood near Dordrecht can be observed in the northeastern part of the map. Through this new estuary, part of the water from the Rhine and Meuse rivers flowed towards the North Sea. As the estuary was prone to significant tidal influence, deep parts arose. In these deeper parts, sand eroded due to the strong currents. This sand was then deposited at and along the plains at the coastline. Here, the flow velocities were significant lower, so the sand was able to deposit by gravity. Currently, the bottom of the deepest parts is located at -24.0 m NAP in the Volkerak (Tosserams and Platteeuw, 2000).

In the 16th century, people started reclamation of the plains from the Volkerak to use for agricultural lands (Stroming, 2008). To protect the reclaimed land, dykes were constructed and these were continuously strengthened to prevent further floods. These sea dikes can still be found in this area. The process of land reclamation ended in the 19^{th} century (van Winden et al., 2008).

In contrast to the Volkerak, the Zoommeer was located at the far end of the Oosterschelde estuary and was less prone to erosion. As a result, this shallow area slowly filled up with sand. Only small land reclamation occurred in this area. The Eendracht, a small estuary, connected the former Zoommeer with the Volkerak.

After the 1953 North Sea Flood, the Delta Commission came up with the Deltaplan to defend the Rhine-Meuse delta from future flooding disasters. The original plan was to create one big fresh water lake by building dams in the estuaries of the Haringvliet, Grevelingen and the Oosterschelde. This would significantly reduce the length of sea dykes in this part of the Netherlands that was exposed to the open sea. As a result, less dykes had to be strengthened and maintained in the next centuries. Besides from protecting the land from the possibility of flooding, it would create a buffer of fresh water for agriculture.

Figure 2.1: A map of the islands of the province of Zeeland around 1500

In 1965, the opening of the Zandkreekdam marked the end of the first part of the Deltaworks. In 1965, when the Grevelingendam was completed, the Grevelingen was cut off from the Krammer-Volkerak. In 1969, the Volkerakdam opened. As a result, the rivers upstream of the Volkerak could now be controlled by these dams to prevent salinization in the rivers as closing of the Volkerak would increase the water level and push the rivers into the direction of the Nieuwe Waterweg through Rotterdam.

When the Oosterscheldedam opened in 1986, it differed compared to the original plans. Instead of a dam, a storm surge was built, allowing water to freely pass the structure when there is no storm. This was a result of a big discussion about environmental and economic impact of changing the Oosterschelde from salty to fresh water. To keep some fresh water lakes, various dams were constructed that resulted in a fresh water Zoommeer; the Philipsdam and the Oesterdam. These dams now separate the fresh water in the VZM from the sea water in the Oosterschelde. After completion of the dams and the (discharge) locks in the dams, the VZM slowly became a fresh water lake in a salt water environment.

The VZM is part of the Rhine-Scheldt Canal, a direct route between Antwerp and the Rhine that replaced the old route through Zuid-Beveland (Wols, 11 May 2010). This canal was too small and the location of the canal was the reason that ships from the harbour of Antwerp had to make a detour in order to arrive at the Rhine. Therefore, the Belgians required a new direct route between Antwerp and Moerdijk around 1920 (Prinsen, 1975). However, the Dutch were not willing to build this connection. Around 1930, new negotiations took place and both parties agreed on the Eendrachtkanaal between Antwerp and Willemstad. Due to World War II, these plans were postponed and after the war new negotiations started.

When the proposal went to the government of the Netherlands, the Delta Law, covering all the protection of the Rhine Meuse Delta was just being discussed in 1954. To combine the work, the Dutch wanted this new canal to be part of the Deltaworks. After years of negotiation about the new shipping connection, the Netherlands and Belgium signed the Scheldt Rhine Treaty on 13th of May 1963 (Rijksoverheid, 13 May 1963).

This treaty forced the Netherlands to create a shipping route linking Antwerp with the Rhine. The canal would go from Antwerp to the Oosterschelde where the Philipsdam and the Oesterdam were planned. It would then follow the Eendracht, the small estuary between the Oosterschelde and the Volkerak. This estuary was canalized in order to provide room for the bigger cargo ships. At the Volkerak, the ships could enter the Hollandsch Diep through the Volkeraksluizen. The construction of the dams and the locks provided a tidal-free route via the VZM which is beneficial for the shipping. The decision to build a storm surge barrier at the Oosterschelde, leads to tidal amplitudes up to three meters at the Oosterschelde, while at the VZM the water level is managed and shows less variation

Figure 2.2: Overview of the different storm surge barriers and dams that were constructed as part of the Deltaworks after the 1953 North Sea Flood.

As most of the construction took place on Dutch soil, Belgium paid a significant part of the construction costs (almost 95%) (Wols, 11 May 2010). Different locks allow ships to enter the VZM and the Rhine-Scheldt Canal: the Volkeraksluizen in the Volkerakdam, the Kreekraksluizen in the south, the Krammersluizen in the Philipsdam and finally the Bergsediepsluis in the Oesterdam. These locks were constructed during the construction of the dams. More information on the infrastructure of the VZM can be found in Section 2.4.

2.2. Use and management of the Volkerak-Zoommeer

The VZM is a fresh water lake in a salt environment. It has a total area of 8000 ha, of which 6018 ha is water area (Van Rooij and Groen, 1987). Rijkswaterstaat is the operational manager of the VZM.

Together with its partners, Rijkswaterstaat recorded the managing goals and agreements of the VZM in the Water Agreement Volkerak-Zoommeer (*Dutch: Waterakkoord Volkerak-Zooommeer*) (Nolte et al., 8 July 2020). The water agreement of the VZM has been signed by the central government (*Dutch: het Rijk*) represented by Rijkswaterstaat in the name of the minister of Infrastructure and Environment, and the three water boards: WSHD, WSSS and WSBD. A Water Agreement is a voluntary agreement between water managers to aim for comprehensive and effective water management of a water body (Rijksoverheid, 1 January 2016). In a Water Agreement, the organizations define tasks and rules to aim for coherent and effective water management especially during periods of droughts or generate an efficient discharge of surplus water in periods of potential flooding. This is described in Dutch as:

> *”Waterakkoord betreffende de regeling van de uitwisseling van water tussen het Volkerak-Zoommeer, alsmede de daarmee in open verbinding staande wateren, en de omliggende beheergebieden.”*

The following institutions signed the Water Agreement of the VZM:

- Rijkswaterstaat Zee en Delta
- Waterschap Brabantse Delta
- Waterschap Hollandse Delta
- Waterschap Scheldestromen
- Rijkswaterstaat West-Nederland Zuid

- Rijkswaterstaat Zuid Nederland

Many parts of the water agreement go into details in how the different water managers need to aim for comprehensive and effective water management of the VZM and the management areas that are connected to the VZM. Examples are: lowering the water level at the VZM in cases when the city Breda is threatened by flooding and how other measures should be monitored and communicated. For the scope of this research, two aspects are important:

1. Water level
2. Chloride concentration

Rijkswaterstaat Zee en Delta is obliged to meet the requirements of the target level decision (*Dutch: peilbesluit*) in order to meet the water demand of the management areas that depend on the VZM. Rijkswaterstaat West-Nederland Zuid is obliged to enable fresh water supply from the Hollandsch Diep towards the VZM for the purpose of water level management and flushing regime. The target level decision of the VZM states that the water level in the VZM may fluctuate between -0.10 m NAP and +0.15 m NAP. When the water level exceeds these values, the calamities procedures start. Different procedures were designed as exceedance of the levels is possible due to malfunctioning of the system.

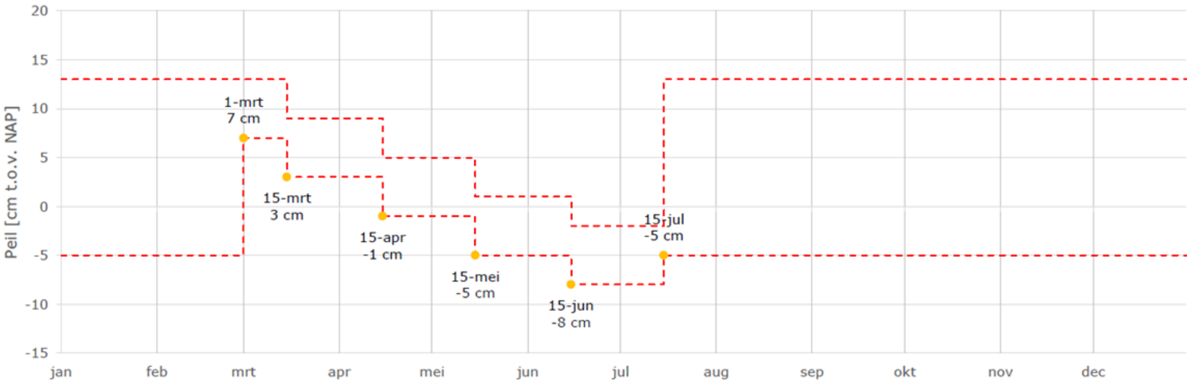
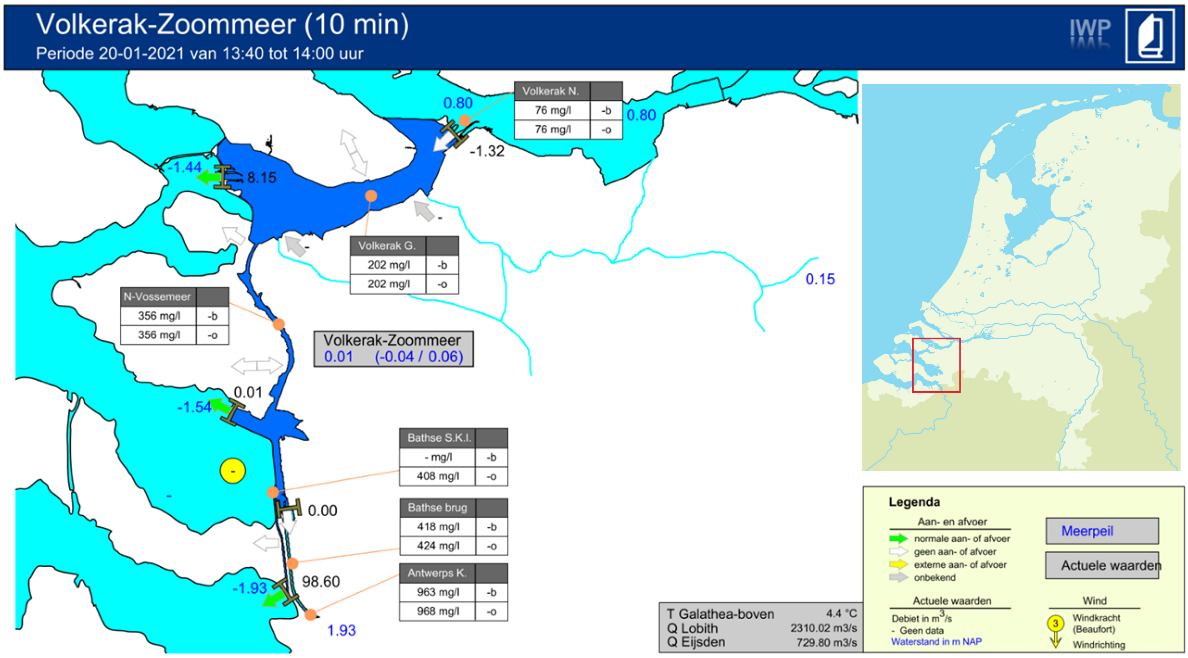


Figure 2.3: Water level indication according to the Water Agreement of the Volkerak-Zoommeer in black. The dashed red lines indicate the range in which the water level may fluctuate. The trap-wise form with lowering the water level starts at the beginning of the bird breeding season at March first and last till July 15th.

Water Storage at the Volkerak-Zoommeer

The VZM has been assigned as a retention area in the Room for the River programme (*Dutch: Programma Ruimte voor de rivieren*) to temporarily store water from the Hollandsch Diep and the Haringvliet. This measure will be put into action when there is a combination of high river discharges in the Rhine and Meuse combined with a western storm, which leads to closing of the different storm surge barriers (e.g. Maeslantkering, Hartelkering and the Oosterscheldekering). As a result, the high water peak from the rivers cannot be flushed into the North Sea and water levels in the Dutch rivers will rise significantly. To release some pressure of the system, the water level at the VZM may be heightened to +2.30 m NAP by opening the Volkeraksluizen. This procedure is only be executed when the water level at the Hollandsch Diep at measuring point ”Rak Noord” reaches a water level of NAP +2.6 m NAP. This measure allows the water levels in the upstream part (± 30km) of the Hollandsch Diep to be reduced by several decimeters. For the cities that are located in this area, such as Dordrecht, Sliedrecht and Gorinchem, the chance on flooding is thereby reduced. Calculations show that the chance that this measure must be adapted is 1/1400 per year. It is expected that by 2050 this can increase to 1/500 due to climate change (Rijkswaterstaat, 9 November 2015). To allow the water level to be raised up to +2.30 m NAP, the dikes around the VZM were checked and at certain points strengthened and heightened. As most of the dikes were former sea dikes, not many dikes had to be improved. Different (local) locks needed measures in order to be able to cope with a water level of +2.30 m NAP (Rijkswaterstaat, January 2012). This included the constructions of higher and stronger lock doors.

Apart from the water agreement, and in collaboration with nature organisations, target levels were set to help precociality during the breeding season and prevent their nests to flood. These target levels can be found in Figure 2.3. This collaboration between Rijkswaterstaat and the nature organisations can be seen as a ”gentlemen’s agreement”, there are no consequences for Rijkswaterstaat when the water levels exceed the levels that are set during the breeding season, but Rijkswaterstaat will do its best to adhere to these levels. Maintaining the water level between -0.10m NAP and +0.15 m NAP is is the range Rijkswaterstaat does need to take into account. The water agreement clearly states that the chloride concentration in the VZM should not exceed 450 mg/L in the period between 15 March and 15 September. Rijkswaterstaat is obliged to maintain this level during this period by means of flushing the system. It is only allowed to refrain from this value when there is no possibility for a fresh water supply or when the water quality of the system desires not to take in fresh water. Rijkswaterstaat Zee en Delta is obliged to communicate with the water managers of the different water boards when the latter situation occurs. The measuring point to represent the chloride concentration of the whole system is set at Bathse Brug. In an internal memo, it was decided to use the upper of the two measurement devices as the lower measuring device provided errors and turned out to be less reliable.



Volkerak-Zoommeer (10 min)

Periode 20-01-2021 van 13:40 tot 14:00 uur

Volkerak N.	
76 mg/l	-b
76 mg/l	-o

Volkerak G.	
202 mg/l	-b
202 mg/l	-o

N-Vossemeer	
356 mg/l	-b
356 mg/l	-o

Volkerak-Zoommeer
0.01 (-0.04 / 0.06)

Bathse S.K.I.	
- mg/l	-b
408 mg/l	-o

Bathse brug	
418 mg/l	-b
424 mg/l	-o

Antwerps K.	
963 mg/l	-b
968 mg/l	-o

T Galathea-boven	4.4 °C
Q Lobith	2310.02 m3/s
Q Eijsden	729.80 m3/s

Figure 2.4: Overview of the discharge, water level and chloride concentration measuring points for the VZM

In Figure 2.4, the dashboard of the monitoring system IWP is shown. The VZM is highlighted in dark blue. The dashboard provides the location and values of measuring points for the different system indicators; water level, chloride concentration and wind speed. The dark blue values indicate the water level measurements. The chloride concentration is provided in the small tables. Chloride concentrations are measured at two depths: a lower value (o) and higher value just underneath the water level (b). The black values represent the discharge through the discharge sluices or lock operations. In the map, various arrows can be observed at the island of Goeree-Overflakkee, Sint Philipsland and Tholen. These arrows (should) represent the operation of the water boards and the discharges from the Dintel and Vliet. At the time that this screen shot was taken, no measurements were available for these points.

At the Hollandsch Diep, the water level is measured at two points: near Moerdijk and at the Volkeraksluizen (Volkerak N./RAKN). At the Volkeraksluizen, the chloride concentration is also measured at the side of the Hollandsch Diep, as well as the discharge through the locks. In the middle of the Volkerak, measuring point Volkerak G. (Volkerak Galathee) is located. Here, the chloride concentration is measured. At the Krammersluizen, the discharge through the locks and the water level at the Oosterschelde is presented. In middle of the system, measuring point N. Vossemeer (Nieuw-Vossemeer) is located, measuring the chloride concentration and the water level. At the Bergse Diepsluis, only the water level at the Oosterschelde side is measured. In the southern part of the system, different chloride measuring points are located. First, the Bathse S.K.I. (Bathse Spuikanaal Inlaat) measures the chloride concentration at the location where the discharge canal towards the outlet at Bath branches off from the canal towards the Kreekraksluizen. Close to the outlet, the measuring point Bathse Brug is located. The final chloride measuring point is located at the Antwerps K. (Antwerps Kanaal), the canal towards the harbour of Antwerp. Here, also the water level is measured.

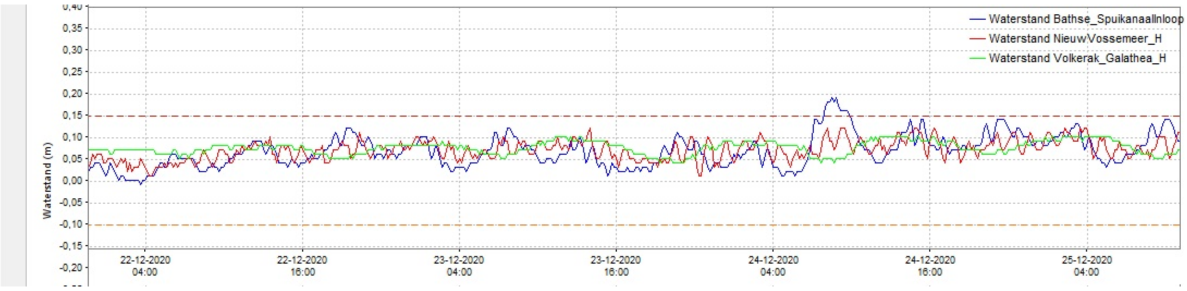


Figure 2.5: Development of the water level for measuring points Spuikanaal Inlet (blue), Nieuw Vossemeer (red) and Volkerak Galathea (green) for the period 22-12-2020 till 25-12-2020. Screenshot taken from IWP, Rijkswaterstaat.

The water level at the VZM is represented by the weighted average of the water level at Volkerak G., N-Vossemeer and Bathse S.K.I. The weighted average is based on the size of the part of the system. These different measuring points are plotted in Figure 2.5. The water levels are measured in ten minute intervals. The blue line represents the Bathse S.K.I., the red line represents N-Vossemeer and the green line represents Volkerak-Galathee. It can be observed that on December 24th, the differences between the three lines increased. This is due to the influence of wind in the system. Wind measurements show that at this day, wind was coming from the North with an highest hourly average of 7 m/s.

Table 2.1 shows the height of the different chloride measurement stations for the VZM. At each location mentioned, two measurements are performed: an upper measurement (boven) and a lower measurement (onder).

Table 2.1: Overview of the chloride measuring stations and the heights at which the chloride concentration is measured.

Full name	**Abbreviation data**	**Height with respect to NAP [cm]**
Volkerak-Galathee boven	VKb	-75
Volkerak-Galathee onder	Vko	-400
Nieuw-Vossemeer boven	VOSMb	-75
Nieuw-Vossemeer onder	VOSMo	-300
Bathse Spuikanaal boven	SPUIb	-75
Bathse Spuikanaal onder	SPUIo	-525
Bathse Brug boven	BBDTb	-75
Bathse Brug onder	BBDTo	-300

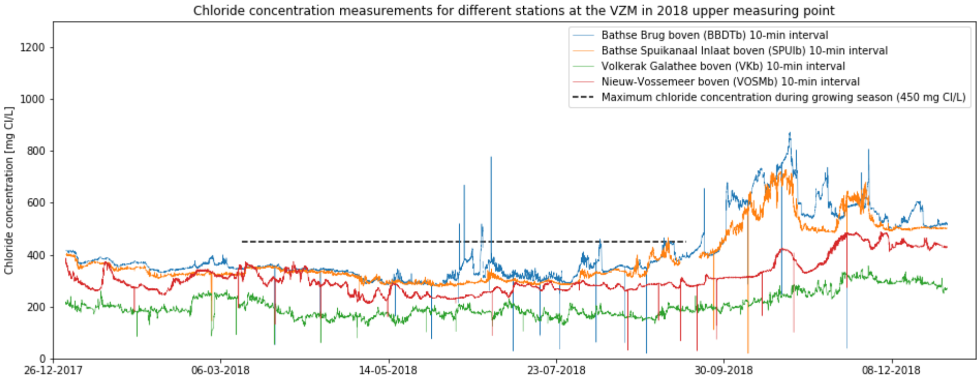


Figure 2.6: Development of chloride concentration at the upper measuring point in 2018 at the different measuring stations located across the VZM.

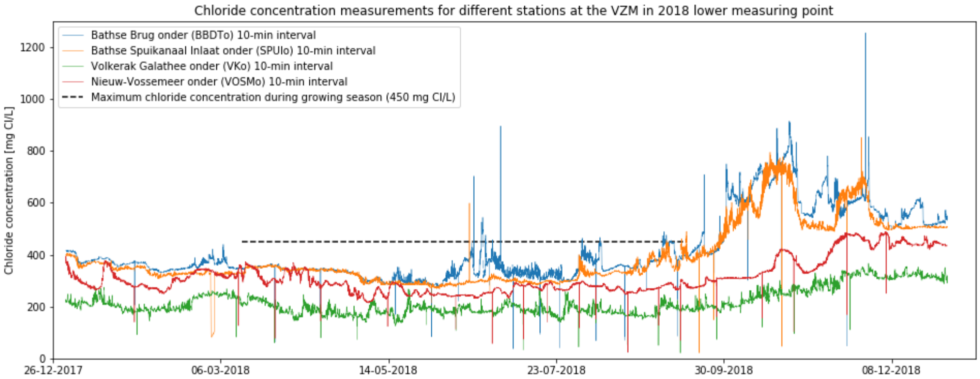


Figure 2.7: Development of chloride concentration at the lower measuring point in 2018 at the different measuring stations located across the VZM.

Figures 2.6 and 2.7 show the chloride concentrations for the different measuring stations across the VZM for the upper and lower measuring point. Measurements were taken every ten minutes. The dashed black line indicates the maximum value of 450 mg/L during the period 15 March till 15 September. From the plots, the differences in chloride concentration per location within the system can be clearly observed. The chloride concentrations at measuring points Bathse Brug and Bathse Spuiknaal Inlaat are higher than the chloride concentrations at measuring points Nieuw-Vossemeer and Volkerak-Galathee. During the growing season, the chloride concentrations at Bathse Brug and Bathse Spuikanaal Inlaat sometimes crossed the critical value of 450 mg Cl/L. After the growing season an increase can be observed as well. In this period, the discharge of the Rhine was really low, resulting in less intake of fresh water. This increases the chloride concentration in the system. The changes between the upper and lower measuring point at each location are small. The upper measuring point indicates a slightly lower chloride concentration than the lower measuring point.

The peaks that can be observed in the graphs, especially the downward peaks, can be assigned to cleaning operations of the sensors. These operations take place every two to six weeks according to people from Rijkswaterstaat. The single upward peaks that sometimes differ more than a few hundred milligrams chloride per litre, can be assigned to measuring errors and outliers.

In Appendix A.5, plots for the different measuring points for the period 2010-2020 can be observed for each measuring station. From these plots, the seasonality of the chloride concentrations is clearly visible. During the growing season, the chloride concentration is lower and mostly below 450 mg Cl/L, while during autumn, the concentration clearly increases until flushing operations start around February.

2.3. Water users of the Volkerak-Zoommeer

Various users of the VZM have been identified. For the scope of this research, the main focus will be on the water boards that provide water to the end users in the polders that depend on a fresh water supply from the VZM (e.g. farmers). It is of importance to differentiate between Rijkswaterstaat (operational manager of the VZM) and the water boards. Rijkswaterstaat is only able to supply the water boards with a water level at the VZM. The water boards subdivide the water at a regional scale. This section provides insights in how the regional systems of the water boards function and how they deal with drought management, based on interviews that were organised for this research. Next to the water boards, other users have been defined and the main requirements in terms of water levels and water quality parameters will be presented.

2.3.1. Waterschap Hollandse Delta

For Waterschap Hollandse Delta, only the eastern part of Goeree-Overflakkee depends on fresh water supply from the VZM. Their system also allows a bypass and lets in fresh water from the Haringvliet into the same area, making the dependence of fresh water supply from the VZM for this area minor. This bypass can be applied when the water quality of the water from the VZM is not good enough or the water levels are too low. The area that depends on a fresh water supply from the VZM has a surface of 3443 hectares.

From the interview with a representative of the water board, insights in the drought management and operation was obtained. The only drought indicator that is applied is the water level in the polders and water quality at the inlets. Management is based on the experience and insight of the water level managers (*Dutch: peilbeheerders*). An important issue is the fact that sometimes the waterboard is forced to let in water with a worse water quality during a period of drought. This is mostly due to the Cyanobacteria that float on the VZM. An important factor is the wind direction. When the decision is taken to let in water with a worse water quality, it is important to communicate with the water users (e.g. the public, farmers, etc). that the surface water in certain areas will contain Cyanobacteria. The idea is that as this area consists mostly of farmland, the farmland does not suffer that much of irrigation with water containing Cyanobacteria and the Cyanobacteria will die within 24 hours. The waterboard needs to take this decision in order to maintain embankments of the canals within the system. Water quality is therefore not the relevant factor, but water quantity is.

2.3.2. Waterschap Schelde Stromen

The water board Schelde Stromen is responsible for the area that is the same as the province of Zeeland. For the research area, only the islands of Tholen and St. Philipsland are of interest as they rely on the VZM as fresh water supply besides precipitation and sometimes ground water. A small polder, the Reigenbergse Polder in Zuid-Beveland also takes in water from the VZM. Tholen is the biggest island with an area of 10754 hectares. St.Philipsland has an area of 1930 hectares and the Reigenbergse Polder 1248 hectares.

The water board tries to fill up fresh ground water bubbles as much as possible during the winter time to prevent salinization of the ground water. In doing so, they are able to provide some extra fresh water supply during the summer time on the islands that have no fresh surface water supply. Water management for the islands of Zeeland is difficult as the differences between water surplus and drought can be really small. For example, when the water levels in the system are not lowered enough before a rainfall event, problems can occur with too high water levels. While, lowering the water levels too much, excess fresh water was released into the Oosterschelde.

Currently, the waterboard does not make use of drought indicators for drought management. They are currently looking at different techniques to implement. The water board is looking for drought indicators for two reasons. One is to have tools to get better insight in dry periods. The second reason is to underline different measures taken and use it as argumentation towards the board, farmers and other water users on why they took certain measures. Drought Management is performed based on the experience and anticipation of the water managers. The water board does allow a higher maximum chloride concentration than WSHD and WSBD to flush the regional system.

2.3.3. Waterschap Brabantse Delta

The water board of Brabantse Delta manages the area between Tilburg and the VZM as presented in Figure 2.8. The area that is located west of the Julianakanaal is the so-called Mark-Dintel-Vliet-Boezem. This system consists of the Mark, Dintel and the Vliet rivers and under normal conditions discharges into the VZM. To get a better understanding of the system, one has to draw a line between Bergen op Zoom and Waalwijk. In the south, there are the sandy grounds that freely discharge water into the system. North of this line, polders are located where the water levels are managed and water is taken in from the Mark, Dintel and the Vliet. The water supply of this system consist of three parts: (1) freely flowing rivers upstream of Breda from the higher sandy grounds, (2) the culvert at Oosterhout and (3) a new fresh water supply at the Roode Vaart in Moerdijk. Furthermore, during a period of drought, it is possible to open the Marksluis at Oosterhout to let in extra water from the Julianakanaal. This measure is only adapted during extreme drought scenarios. The VZM is only a water supply for three small polders next to the Eendracht, the PAN-polders: the Prins-Hendrik polder, the Auvergnepolder and the Nieuw-Vossemeer polder. Together, they have a total surface of 2700 hectares. For this water board, the VZM is a water source, but also a destination of the water that is flushed from the system of WSBD. The culvert at Oosterhout takes in water from the Wilhelminakanaal. The amount of water that can flow through the culvert depends on the potential water level difference between both sides of the culvert. As the Mark is directly linked to the VZM, the water level in the VZM indirectly influences the discharge through the culvert.

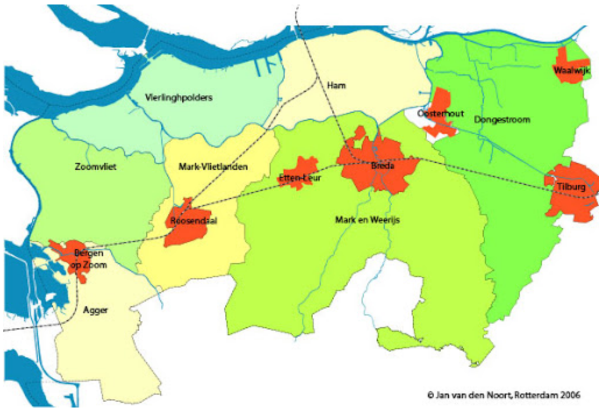


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Figure 2.8: Manage area of Waterschap Brabantse Delta.

WSBD makes use of drought indicators that are Cyanobacteria driven: water temperature, discharge and retention time. The idea is that the water management must prevent blooming of Cyanobacteria. Therefore, the retention time must not be too high, and flushing is required. In the summer of 2018, the water board asked Rijkswaterstaat to let in extra water through the Marksluizen in Oosterhout. With this measure, they were able to sufficiently flush its network. Based on earlier drought experiences, a new fresh water supply is constructed in the Roode Vaart in Zevenhuizen. This new fresh water supply is able to add 3.5 m^3/s and can be expanded till 10 m^3/s. From the interviews it turned out that the water board does expect that during excessive drought periods the Marksluis will sometimes be needed as extra measure for fresh water supply.

2.3.4. Others

Besides the water boards that supply their users, many other users make use of or depend on the fresh water in the VZM. Other utilisation groups are the shipping industry, recreation (swimming, sailing, else), fishing, sport fishing and living environment.

The most important user group is nature. The VZM is an important location for birds to rest and breed. To prevent flooding of the nest due to water level management, target levels are installed that follow a decline in water level during the breeding season. This can be observed in Figure 2.3. The water quality largely influences the ecosystem of the VZM. Many researches are available on this topic, but for the scope of this thesis (water quantity), this topic is not considered in much detail. Cyanobacteria and chloride concentration largely influence the species that can be found in the water and will thereby also influence the (sport) fishing industry. Due to high Cyanobacteria concentrations in the summer period, recreation in terms of swimming is not possible at every location.

Another important user of the VZM is the shipping industry that needs a constant water level. However, for the shipping industry, only the water level is important and not the water quality. For this industry, the water level can range between -0.25 and +0.75 mNAP without causing troubles at bridges or the chance of touching the bottom of the waterway.

2.4. Regulating structures of the Volkerak-Zoommeer

Different structures regulate the water level and shipping for the VZM. These structures can be found in Figure 2.9. To obtain a feeling in the values of the discharges that flow through these structures, a water balance can be found in Table 2.2. At the Volkeraksluizen in the North, there are three shipping locks for commercial shipping, one lock for recreational shipping and four discharge sluices where fresh water from the Hollandsch Diep can enter the VZM. On average the discharge sluices discharge 67.5 m^3/s into the VZM (Nolte et al., 8 July 2020). The discharge sluices work by opening a gate allowing water to flow towards the VZM by gravitation. Software from Rijkswaterstaat determines the amount of water that is needed for the VZM after which the software determines the opening surface that is needed to provide the desired discharge. The discharge sluices are closed when the discharge of the Rhine at Lobith reaches a value higher than 3000 m^3/s to prevent too much sediment flowing into the VZM. When the discharge at Lobith is below 800 m^3/s, the inlet through the Volkerak discharge sluices are also be closed as water is needed to flush the Nieuwe Waterweg from Rotterdam towards the North Sea. In case of strong western winds and relatively low discharges (discharge at Lobith roughly 1000 m^3/s), there is a change of backwards salt intrusion into the Rhine-Meuse Delta. Salt water from the sea can then flow through the Spui and Oude Maas and reach the Haringvliet and the Hollandsch Diep. Rijkswaterstaat West-Nederland Zuid sometimes asks to stop the inlet at the Volkerak when they

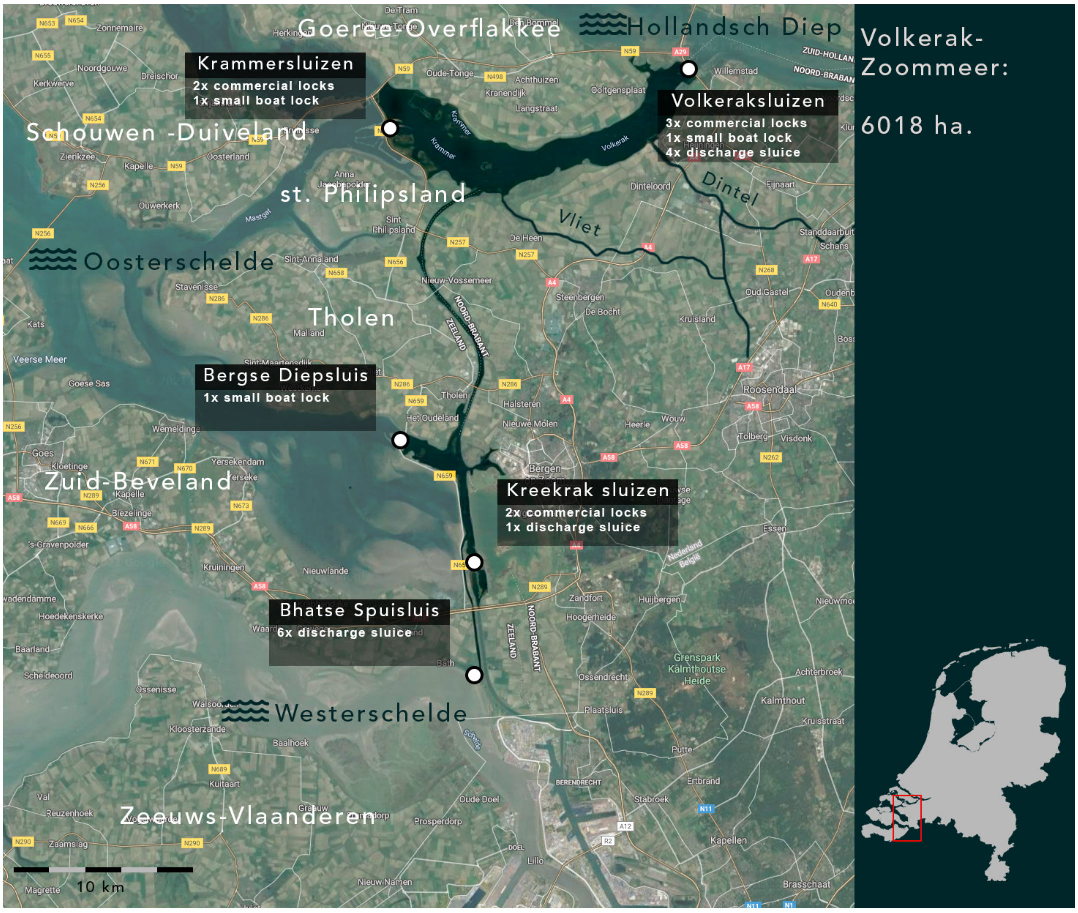


Figure 2.9: Overview of the Volkerak-Zoommeer and the regulating structures

expect this process to occur. It is important to prevent backward salinization as multiple drinking water inlets are located at the Hollandsch Diep and the Haringvliet.

The Krammersluizen are located west of the Krammer and have as main function to allow a connection for (commercial) ships to the Oosterschelde. It consist of two locks for commercial shipping and two locks for recreational shipping. As the Oosterschelde consists of seawater, a system has been developed to separate the salt from the fresh water in the VZM. This is based on the difference between salt and fresh water: salt water has a higher density than fresh water and will therefore be at the bottom of the locks (Waternoodsmuseum, n.d.).

A new system, using small air bubbles is planned to be implemented in the Krammersluizen by 2025 (Boeters and Kielen, n.d.). The new system will use a wall of small air bubbles to separate the sea water from the fresh water in the locks. After the implementation, only a small portion of the fresh water is then needed to flush the locks. The current separation system requires heavy maintenance and a lot of energy. The new system is expected to reduce the energy consumption by 50% and the time for a ship to pass the lock by sixteen minutes. The renovation works will also allow better water quality management of the Oosterschelde. Here, Blue Mussels are harvested in water farms close to the Krammersluizen. A too high fresh water supply from the VZM into the Oosterschelde will harm these mussels. The Krammersluizen can be used as discharge sluices in times the water level in the VZM needs to be lowered after an incident that led to above normal water levels. When the locks are used for this measure, they are closed for shipping.

The Bergse Diepsluis is located south of Tholen and connects the Zoommeer with the Oosterschelde. It is a small lock that is only used for recreational shipping. The interaction between seawater and fresh water is not significant for the VZM (Waternoodsmuseum, n.d.).

In the south of the VZM, the Bathse Spuisluis and the Kreekraksluizen are located. Just before the connection of Zuid-Beveland and Brabant, the VZM splits into two canals. One canal leads to the Bathse Spuisluis; Bathse Spuikanaal. The other canal leads into the Kreekraksluizen.

Table 2.2: Water balance of the VZM for 2017. Complemented with data from Deltares (Vergroesen, 2020)

	Water supply $[millionm^3/j]$	Water supply $[m^3/s]$
Precipitation	53.0	1.68
Dintel	365.5	11.59
Vliet	60.7	1.92
Volkerak Inlet	513.4	16.28

	Water release $[millionm^3/j]$	Water release $[m^3/s]$
Evaporation	40.3	1.28
Bathse Spuisluis	768	24.35
Krammersluizen	278.2	8.82
Kreekraksluizen	73.9	2.34

Pumping stations		
Goeree-Overflakkee	*30.5*	*0.97*
Tholen	*26.7*	*0.85*
Sint Philipsland	-	
PAN-polders	*13.1*	*0.42*
Reigersbergsche polder	-	

Inlets		
Goeree-Overflakkee	*10.5*	*0.33*
Tholen	*27.2*	*0.86*
Sint Philipsland	*5.1*	*0.16*
PAN-polders	*6.5*	*0.21*
Reigersbergsche polder	*2.9*	*0.09*

Lekverlies		
Volkerak	*47.3*	*1.50*
Krammer	*18.9*	*0.60*
Bathse Spuisluis	*2.2*	*0.07*
Bergse Diepsluis	*3.2*	*0.10*

Schutverlies		
Volkerak	*76*	*2.41*

Total	**1210.5**	

Total	**1212.6**	

Rest term (leakage/seepage)	2.1	0.07

Total	**0**	

Total	**0**	

The Kreekraksluizen connect the VZM to the Schelde-Rijnverbinding, a canal that flows directly into the harbour of Antwerp. The Kreekraksluizen consist of two big shipping locks. As the chloride concentration in the Schelde-Rijnverbinding is not controlled and relatively high, the Kreekrakgemaal was constructed as part of the lock system. This pumping station creates a fresh water bubble on the southern side of the Kreekraksluizen to prevent the water from the Schelde-Rijnverbinding that has a higher chloride concentration entering the locks and thereby the VZM.

The Bathse Spuisluis is the main discharge sluice in the VZM. For Rijkswaterstaat, this structure is the regulator of the VZM. Water from the VZM is discharged through the Bathse Spuikanaal towards the Bathse Spuisluis. Here, six discharge sluices are constructed that allow flushing of water into the Westerschelde by means of gravity. When all the six discharge locks are in use, the system is able to discharge up to 130 m^3/s as a daily average. As only gravity is used as a mechanism to release water from the VZM into the Westerschelde, flushing is only possible during low-tide. The value of 130 m^3/s is therefore a daily average. This structure is mostly vulnerable to climate change. Sea level rise will shorten the period the Bathse Spuisluis is able to discharge towards the Westerschelde as the water level at low tide is higher. According to research by Deltares (Nolte et al., 2020), the Bathse Spuisluis is able to cope with sea level rise until 2100.

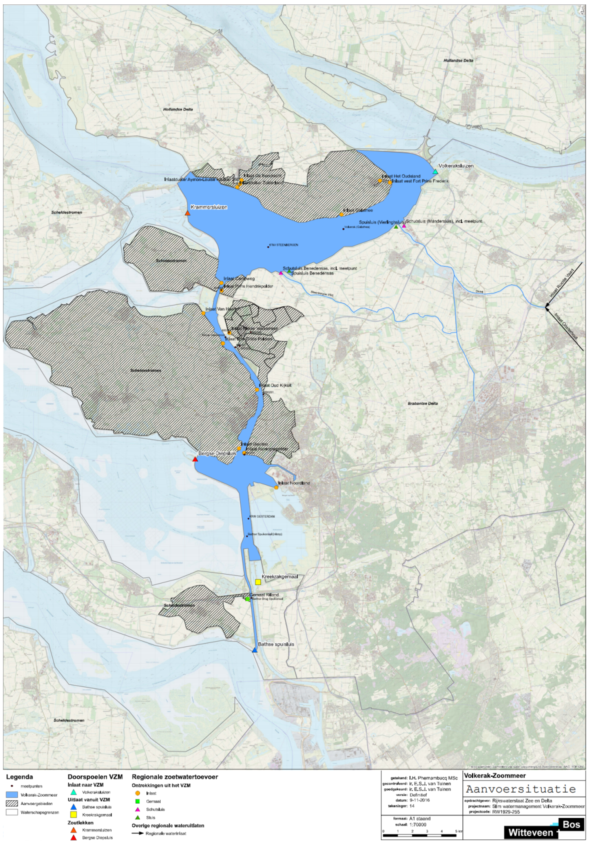


Figure 2.10: Polders that take in water from the VZM as defined by Witteveen & Bos (Tuinen van et al., 2016). See Appendix A.3 for enlarged version of this map.

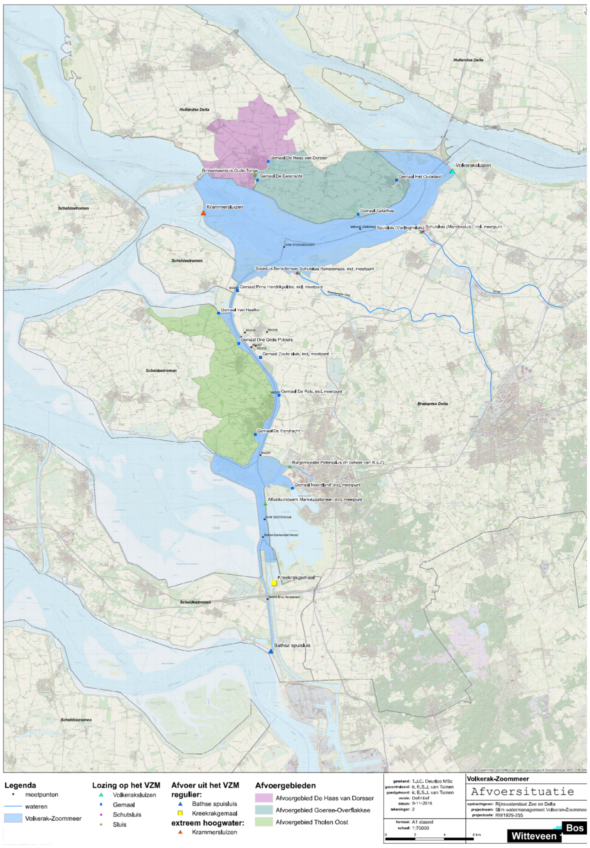


Figure 2.11: Polders that discharge into the VZM as defined by Witteveen & Bos (Tuinen van et al., 2016). See Appendix A.3 for enlarged version of this map.

Two rivers, the Dintel and the Steenbergsche Vliet flow from Noord-Brabant into the lake. Both rivers are part of the system of WSBD and are usually in open connection with the VZM. During dry periods, water from the VZM flows in opposite direction stream upwards, depending on the water level in the lake. At Dinteloord and Benedensas, where the Dintel and the Vliet respectively enter the VZM, a shipping lock and a closing structure are located. This provides WSBD to close the connection between the rivers and the VZM. This measure can be used when the VZM is used as a temporarily water storage area and the water level is significantly higher or during a period of drought. For example, during the summer of 2018, WSBD closed the connection between the Vliet and the VZM to generate more flow in the Dintel to flush the system as the retention time of the water in the system was too high.

In Figures 2.10 and 2.11, the polders that depend on fresh water supply from the VZM are marked. In Appendix A.3, larger versions of these maps are available.

In Goeree-Overflakkee, managed by WSHD, only a small part of the island is supplied by the VZM and a slightly larger part discharges into the VZM. Various pumping stations and inlets regulate the in and outlet of fresh water between the polders and the VZM. In Table 2.3 details of the different regulating structures for WSHD can be found.

Table 2.3: Details of the inlets for WSHD

Inlet	**Type**	**Water Level VZM**	**Summer water level polder**	**Dependent on Water Level VZM?**
Het Oudeland	Weir and pumping station	-0.10 till +0.15 m NAP	-0.80 m NAP	yes
Galathee	Weir and pumping station	-0.10 till +0.15 m NAP	0.00 m NAP	yes
Oude Tonge	Culvert Zuiderland and Aymon-Louise; weir and pumping Eendracht	-0.10 till +0.15 m NAP	-0.10 till +0.15 m NAP	yes

For WSSS, St. Philipsland, Tholen and the Reigenbergse Polder depend on a fresh water supply from the VZM. However, only a part of Tholen discharges fresh water into the VZM. The rest of the service area discharge surplus water into the Oosterschelde. In Table 2.4, an overview of the different pumping stations and inlets is provided.

Table 2.4: Details of the inlets for WSSS

Inlet	**Type**	**Water Level VZM**	**Summer water level polder**	**Dependent on water level VZM?**
Campweg	Weir with threshold at -0.18 m NAP including propeller	-0.10 till +0.15 m NAP	-0.25 m NAP	yes
Van Haaften	Culvert	-0.10 till +0.15 m NAP	- 0.40 m NAP	yes
Drie Grote Polders	Weir with unknown threshold	-0.10 till +0.15 m NAP	-1.90 m NAP	unknown
Oud kijkuit	Weir with threshold at -1.15m NAP	-0.10 till +0.15 m NAP	-1.50 m NAP	no
Deurloo	Weir with threshold at -1.20 m NAP	-0.10 till +0.15 m NAP	-1.40 m NAP	no

As mentioned in 2.3.3, WSBD only has three polders that take in water from the VZM, the so-called PAN-polders. As depicted by Figure 2.11, no area of WSBD discharges directly into the VZM. However, a large part of the system of WSBD is based on releasing water via the rivers Dintel and Vliet, so in the end, water from almost the entire WSBD area is released into the VZM. The infrastructure that is directly connected to the VZM can be found in Table 2.5.

Table 2.5: Details of the inlets for WSBD

Inlet	Type	Water Level VZM	Summer water level polder	Dependent on Water Level VZM?
Prins Hendrikpolder	Weir with unknown threshold; pumping station Prins Hendrikpolder	-0.10 till +0.15 m NAP	0.00 m NAP	yes
Auvergnepolder	Weir with unknown threshold; pumping station De Pals	-0.10 till +0.15 m NAP	-0.80 m NAP	yes
Polder Nieuw-Vossemeer	Weir with unknown threshold; pumping station Zoute Sluis	-0.10 till +0.15 m NAP	-1.10 m NAP	yes

2.5. Managing challenges of the Volkerak-Zoommeer

After the construction of the Philipsdam and the Osterdam, the VZM gradually became a fresh water lake with an almost constant water level and chloride concentration. The change from being an estuary with tidal dynamics to a fresh water lake started in 1987. Since then, three different stages in the development of the new ecosystem can be distinguished, with corresponding observations and impact for the water system in the VZM:

- 1987 – 1990: Colonization by fresh water species and slow degradation of the seawater species. During this period, the water became really clear, in spite of the high nutrients concentration, it reached a transparency of up to 3.2 m.
- 1990 – 1996: Increase in fish population and decrease in transparency. From 1994, Cyanobacteria were observed in the system.
- Since 1996: Increased cloudiness of the water in the system. Next to that, due to an increase in nutrients (e.g. phosphate), the Cyanobacteria are increasing during the summer time (Tosserams and Platteeuw, 2000).

As previously mentioned, the chloride concentration can imply an important water quality issue. There are certain thresholds of chloride concentration allowed for the production of drinking water, industry water and water for agricultural purposes. The VZM is prone to salinization due to its environment. It is enclosed by estuaries with high chloride concentrations as well as groundwater with high chloride concentrations. Furthermore, in the deeper part of the Krammer, water with a higher chloride concentration is still trapped. The maximum chloride concentration in the VZM is set at 450 mg/L as the water from the VZM is only used for agricultural purposes. The chloride threshold must only be taken into account during the agricultural growing season from 15th of March until the 15th of September. In addition to the stationary chloride concentration measurements, moving measurements are performed, the so-called TSO measurements. These monthly measurements follow a certain trajectory in the Volkerak and in the Zoommeer and measure the parameters chloride concentration, water temperature, oxygen concentration and turbidity over the depth. In Appendix A.2, examples are provided for both trajectories in the Volkerak and in the Zoommeer for February 2021 and August 2020. From these measurements, the deeper parts with a higher chloride concentration can be clearly observed. Another difference that can be observed is the the higher chloride concentration during the summer time.

The Cyanobacteria are one of the main concerns in the VZM. This is mostly due to the nutrients that originate from the use of fertilizers by farmers. Part of the fertilizers end up in the ditches and canals that are located next to the agricultural fields. From there, the water is discharged into the VZM as part of the flushing of the water system by the water authorities. In the VZM, these nutrients accumulate and Cyanobacteria are able to grow. Cyanobacteria can cause illness to people that take in water that contain significant concentration of Cyanobacteria. For the local ecology, Cyanobacteria fields are harmful as they take away the sunlight, the major source for photosynthesis. As a consequence, the local water flora and fauna dies. Resulting into odor nuisance in areas neighboring 'contaminated' water bodies. Research showed that it is not possible to manage the VZM purely on flushing the system to prevent Cyanobacteria growth. The wind is the dominant factor in the movement of these floating Cyanobacteria fields.

The combination of the Cyanobacteria and the chloride concentration make the VZM a difficult area to manage. Therefore, there are different discussions going on whether it is useful to change the VZM into a salt water lake (Courant, 9 November 2019). The idea is that a salt-water environment creates a difficult surrounding for Cyanobacteria to live in. As a result, the water quality in terms of Cyanobacteria pollution would increase. Local parties hope that this would lead to more recreation in the VZM. The farmers however, are afraid that the increase of chloride concentrations will cause salinization and that there won't be a sufficient fresh water supply to fight the salt intruding the regional water system. Higher salt concentrations in the soil can cause two types of stresses in the plant. First, due to a deficit of water, osmotic stress occurs in the plant, resulting in water molecules flowing to the places with the highest salt concentrations, which is in the soil. Therefore, it is much more difficult for the roots to extract the water from the soil. Second, sodium is poisonous to plants as it prevents various proteins from working properly and thereby disrupting important processes occurring in the plant, including photosynthesis (van 't Hoog, n.d.).

2.6. Climate change in the Netherlands

According to the climate scenarios of the Koninklijk Nederlands Meteorologisch Instituut (English: Royal Dutch Meteorological Institute) (KNMI), the Netherlands will experience higher temperatures, a rising sea level, more precipitation during the winter season, more intense rainfall and dry summers in the future due to climate change (NKWK, n.d.). Based on the Intergovernmental Panel on Climate Change (IPCC) reports of 2013, that investigates the effects of climate change worldwide, the KNMI translated this into four scenarios in the Netherlands. The scenarios are combinations of two values of the worldwide temperature : moderate (G) and warm (W) and change in air circulation: low value (L) and high value (H). Resulting in the four scenarios GH, GL, WH and WL. Together, these four scenarios form the expected range in which future climate change will propagate in the Netherlands. The climate scenarios do not just provide anthropogenic climate change, but also include natural variation (e.g. daily temperature variation). The natural variations are due to the interaction between the atmosphere, land, ice and oceans. As a result, the average temperature will not increase every year, but variations will occur (Attema et al., 2014). With an increasing length of the period for which the average is calculated, the smaller the influence of the natural variations will be. All scenarios predict that the average temperature will increase, resulting in warmer summer periods and mild winter periods. The average precipitation in the winter will increase as well as will the rainfall intensity. In the summer, the intensity of extreme precipitation events will increase. Furthermore, the sea level will rise as well as the rate of sea level rise. Finally, there will be more incoming solar radiation at the surface. In fall 2021, the KNMI expects to publish the Klimaatsignaal '21. This thesis will therefore use the KNMI '14 climate scenarios. In Figure 2.12, the KNMI climate scenarios overview is presented.

In 2018, the Netherlands experienced one of the most severe droughts (Leunissen, 2020, KNMI, 2020). Scientist expect that dry and extremely warm summers will be more frequent (Bresser et al., 2005). Due to climate change, spring tends to be wetter and summer drier. Research by Buras et al. (Buras et al., 2020) shows that a warmer and wetter spring may increase the drought period in the summer. The idea is that plants grow more in a warmer and wetter spring, extracting more ground water, resulting in a drier summer. A research performed for the Ministry of Infrastructure and Water found out that the economic damage for the 2018 drought was between 900 and 1.650 million euros. The biggest economic losses were in the agricultural and shipping sector (Rijkswaterstaat, 2019).

The delta scenarios are a combination of the climate scenarios and the socio-economic developments that are expected in the Netherlands as part of the *Deltaprogramma*. This programme aims to: (1) protect the Netherlands against floods, (2) assure sufficient fresh water supply and (3) assure climate-resilient spatial planning. The Delta scenarios provide an insight in the manifestation of the different scenarios and the implications for water management in the Netherlands in 2015 and 2085

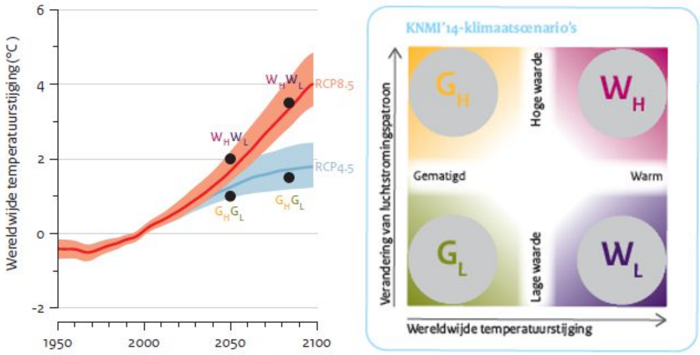


Figure 2.12: The KNMI climatescenarios and their expected temperature increase (Attema et al., 2014)

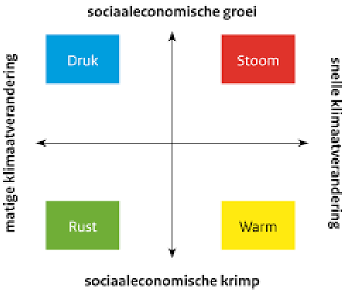


Figure 2.13: The Deltascenarios used in the Deltaplan (Bruggemann et al., 2013).

(Bruggemann et al., 2013). The base for the Deltaplan are four different delta scenarios that are presented in Figure 2.13. On the x-axis, the degree of climate change is provided and on the y-axis, the socio-economic situation is presented. The four scenarios (*Druk, Stoom, Warm and Rust*) are a combination of the socio-economic situation and the degree of climate change (Bruggemann et al., 2013).

2.7. Drought mitigation experiment in the Volkerak-Zoommeer: Praktijkproef Droogte

In fall 2020, Rijkswaterstaat and the water boards WSSS, WSBD and WSHD performed an experiment called the *Praktijkproef Droogte* in the VZM. The aim of the experiment was to get insight into the dynamics of the water level of the VZM when the water level was heightened and the supply was stopped. The idea is that when the discharges in the Rhine and Meuse are too low, the water level in the Hollands Diep may be too low to supply the VZM with sufficient fresh water or that all water is needed to flush towards the Nieuwe Waterweg and intake of fresh water into the VZM is not allowed. The idea of the experiment is to temporarily heighten the water level in the VZM and monitor how long it will take before the water level is back to normal. Furthermore, the chloride concentration is monitored at different locations to evaluate the influence of this measure on the chloride concentration in the VZM. The averaged water level at the VZM is allowed to fluctuate between the water levels that are set within the water agreement (as mentioned in Section 2.2).

Table 2.6: Overview of the start and end points of the three experiments

	Time	Remarks
Experiment 1a	1 September 2020 12:30 - 8 September 2020 11:00	Stopped due to maintenance cyclus at Volkerak inlet
Experiment 1b	11 September 2020 09:20 - 17 September 2020 12:00	Repetition of Experiment 1a
Experiment 2	4 November 2020 11:30 - 4 January 2021 02:00	Experiment ended on 10 December 2020 20:00. Chloride concentrations were back to normal on 4 January 2020 02:00.

The experiment consisted of two parts. In the first part, the water level at the VZM was heightened to +0.15 mNAP, in the second part the inlet at the Volkerak was closed and normal flushing operation was maintained in releasing water at Bath into the Westerschelde during low tide (with one gate opened). During the experiment, two times the outlet at Bath was not used in the normal operation cycle by flushing during a low tide, but a cycle was skipped. Furthermore, the inlet at the Volkerak was accidentally opened during a maintenance cycle, resulting in the organisers deciding to stop the experiment and restart. As a result the first experiment was performed twice, resulting in a part 1a and 1b. The data was stored as it already gave good insights into the behaviour of the water level of the

VZM. During experiment 1b, the outlet operation at Bath was missed once, which was recovered by using an extra gate during the next low tide to reduce the disturbance.

During both experiments in the first part of the experiment, the water level dropped within six days from +0.15 m NAP to -0.10 m NAP. On average, the rate of the lowering of the water level was three to four centimetres per day. It takes three to four days to set up the water level to the initial value of +0.15 m NAP when starting at -0.10 m NAP. During the experiment, higher chloride concentrations were measured at the different measuring locations along the lake.

The aim of the second part of the experiment was to get insight into the evolution of chloride concentrations in the VZM. After the water level was heightened, both the inlet at the Volkerak and the outlet at Bath were closed and the water level propagation and the chloride concentration were monitored. Due to the precipitation that occurred in the area and the higher discharges of the river Dintel and Vliet, the water level at the VZM was almost higher than the + 0.15 m NAP as the water level at the VZM did not drop significantly. Therefore, it was decided to let water out at Bath during seven low-tide moments and the water level dropped to 0.0 m NAP and the experiment continued. After a few days, the organisers decided to stop the experiment as further lowering of the water level was not expected due to precipitation. Hereafter, the normal flushing operation was put into action (inlet at Volkerak and outlet at Bath with one gate) until the chloride concentration at the Bathse Brug was below 450 mg/L. In Table 2.1, the details of the different experiments can be found. In 5.5, the prototype of the tool is validated with the results of the experiments.

During experiment two, the chloride concentration was higher at every measuring station. However, it took some time to observe this change at the different stations as the chloride concentration increased mostly at the bottom of the system. The stationary measuring points are not located on this depth. Only moving chloride measurements could provide these insights. During this part of the experiment, the water level was more stagnant due to the lack of the flushing operation. This increased the stratification within the system, leading to higher chloride concentration at the bottom of the system (Nolte et al., 8 July 2020).

3

What is drought?

This chapter will look into the literature background on drought to provide insight in what drought is and how it manifests itself. There are four different types of droughts: meteorologic, agricultural, hydrologic and socio-economic droughts. Drought can be monitored through drought indicators and indices. They provide insights into the start, end and severity of a drought event by numerical values. Within the context of this thesis, the aim is to define the right drought indicators and indices that are suitable to be implemented in monitoring drought events in the VZM. For Rijkswaterstaat as manager of the VZM, the SPEI and the discharge of the Rhine at Lobith are important indicators, operating at a smaller scale, soil moisture and groundwater level are also of interest to define drought for the water boards, beside the indicators that are already in use.

There does not exist an universally accepted definition of drought (Tate and Gustard, 2000). Generally defined, drought is a deficiency of precipitation over a longer period of time, compared to the precipitation that was expected. As a result, it is not able to meet the demands of human activities and the environment (Hayes et al., 2011). Droughts occur in almost all regions of the world, covering almost all climatic zones (Huang et al., 2016, Mishra and Singh, 2010). Wilhite et al. (Wilhite, 2000) states that drought is a normal feature of climate and its recurrence is inevitable. However, due to the many different definitions on its characteristics within the scientific and policy community, there is not much progress on drought management in most parts of the world. The scientific literature still consist of many definitions depending of the region of interest and the study the individual researcher performed.

The Oxford English Dictionary defines drought as (1) ”the condition or quality of being dry; dryness, aridity, lack of moisture” and (2) ”Dryness of the weather or climate; lack of rain” (Dictionary, 2011). This description somewhat suggests that there are links between dryness and aridity and between weather and climate and thereby causes more confusion than explanation. The Dutch *Van Dale* defines drought as ”a period without precipitation” (Dale, 2020). This implies that when there is some precipitation, there is no drought. When looking at the World Meteorological Organization (WMO), they define drought as: (1) ”prolonged absence or marked deficiency of precipitation” and (2) ”period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance”. In contrast to the Oxford English Dictionary, the other two link drought with precipitation. However, they neglect the importance of evaporation, transpiration and lateral inflows of water for a certain region. Furthermore, no definition is provided on the time aspect of drought (duration, start and end). Palmer et al. (Palmer, 1965) states that drought ”is an interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply”. Thereby combining the duration of the dry period and the considered region within the definition, as identified by Mawdsley et al. (Mawdsley et al., 1994) as essential aspects of water deficiency (Lloyd-Hughes, 2014).

Research showed that among all the natural hazards, droughts rank the first in terms of amount of people impacted, as well they are the costliest in terms of money (Mehran et al., 2015). The problem is that droughts are the least understood natural hazards that currently affect populations worldwide (Wilhite, 2000). Compared to other natural hazards, droughts are the most difficult to define. One of the main problems is that the beginning and the end of a drought are difficult to indicate. The effects slowly accumulate over a considerable period of time and they may remain for a certain period after the drought event has ended. Drought events consist of many complex factors that interact with the environment, making it difficult to observe. Moreover, as there is no universally accepted definition of drought, more confusion is added whether a drought event taking place or not. The consequences of a drought can only be observed after a certain time, making it difficult to recognize. A drought period can be interrupted by short wet periods, but that does not necessarily leads to the drought period being over. Drought definitions should therefore take into account thresholds to determine the severity and determine the beginning and the end of a drought event. Lastly, the impact by drought events are largely spread over areas larger than the impacts from other natural hazards. Whereas other hazards (e.g. floods and fires) result in structural damage, droughts seldom do.

3.1. Drought definitions and types

Drought definitions can be either conceptual and operational definitions. Conceptual definitions are formulated in general terms and try to understand and explain what drought is. The overall function is to understand drought and establish a drought policy. They define the boundaries of the drought definition. As they are not specific, they are unable to define the beginning and the end of a drought event. They do include the concept of intensity and duration of a drought. Operational definitions are case specific and try to describe the the beginning, end and degree of severity of a drought (Quiring, 2009a). Key elements in operational definitions are the precise characteristics and thresholds that can define the beginning, end and degree of severity of a drought. Operation definitions are the base of drought early warning systems. This will help policymakers and stakeholders to get an insight in the severity of a drought event and to respond with the right measures at the right moment. This is only possible when the drought event can be monitored.

In 1985, Wilhite et al. (Wilhite and Glantz, 1985) discovered that at that time, more than 150 different drought definitions existed. All these definitions originated from differences in regions, needs and disciplinary approaches, taking into account different physical, biological and socioeconomic factors. It is therefore that there is confusion on what exactly is the definition as drought (Glantz and Katz, 1977). The main point of interest of drought is the impact it has. Wilhite et al. (Wilhite, 2000) therefore states that ”definitions should be region and impact or application specific in order to be used in an operational mode by decision makers”. Based on their findings, Wilhite et al. (Wilhite and Glantz, 1985) they categorized all the definitions into four groups of drought types.

1. Meteorological drought
2. Agricultural drought
3. Hydrological drought
4. Socioeconomic drought

The first three approaches see drought as a physical phenomenon, whereas socioeconomic drought can be measured in supply and demand throughout a whole socioeconomic system. In the recent years, a debate started on introducing a fifth definition: ecological drought as the other definitions do not fully take into account the ecological dimensions of drought and are viewed through a human-centric lens (Crausbay et al., 2017). In 3.1, the different types of droughts types and the observations are schematized in order of duration. In Figure 3.2, the propagation in time is clearly visualized. Here, the lag between the different types can be clearly observed.

3.1.1. Meteorological drought

Meteorological drought is defined as a shortage of precipitation over a period of time (Quiring, 2009b). It must be considered region specific as atmospheric conditions result in highly variable precipitation deficiencies from region to region (NDMC, 2018). Some meteorological drought definitions focus on the length of time since the last rainfall event, while others identify periods of drought based on the number

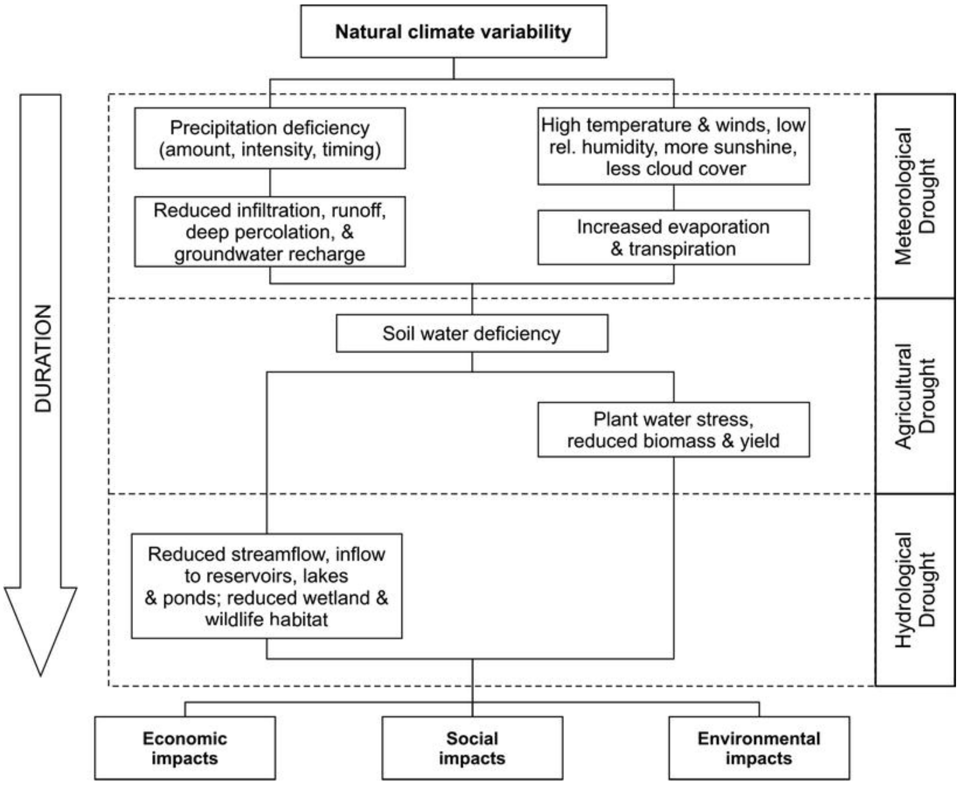


Figure 3.1: Propagation in time and observations of the different conceptual drought types (Wilhite, 2000)

of days with precipitation less than a specific threshold. This depends on the climate of a certain region. For regions with a rain and a dry season, a definition based on the number of days without precipitation is unrealistic. While for regions with a year-round precipitation regime, defining meteorological drought based on the days with precipitation less than a specified threshold is more appropriate. The time period over which drought is defined is also of interest. For example, in areas that are persistently dry, an evaluation period of three rain seasons must be regarded in order to recognize droughts. Whereas for regions with a year-round precipitation regime, this period is much shorter (Olukayode Oladipo, 1985).

3.1.2. Agricultural drought

The effects of drought on agriculture are defined within agricultural drought. It sets in due to soil moisture stress that leads to significant decline in crop yields. Where meteorological drought is an indication of deficiency in precipitation, agricultural drought is the physical manifestation of meteorological drought. One of the factors that make agricultural drought difficult to assess is that the impact only appears once the crops are harvested, possibly a few months after the symptoms of agricultural drought begin to appear. Another aspect that makes agricultural drought difficult to assess is that soil moisture data are not available at the same scale as precipitation data. They require field measurements, agrometeorological models or soil moisture estimates using microwave remote sensing (Boken et al., 2005).

The impact of drought are crop specific as different growing stages of the crop are weather-sensitive. An operational definition of agricultural drought should therefore take into account the variable susceptibility of crops at different stages of crop development. Agricultural planning can often reduce the impact of drought on crops (Wilhite, 2000).

3.1.3. Hydrological drought

An hydrological drought develops when the meteorological drought is prolonged and precipitation deficit causes shortage in surface and/or subsurface water supply. Hydrological droughts are out of phase or lag in time compared to meteorologic drought as it takes time before precipitation deficiencies are detected in the hydrological storage systems (Wilhite, 2000).

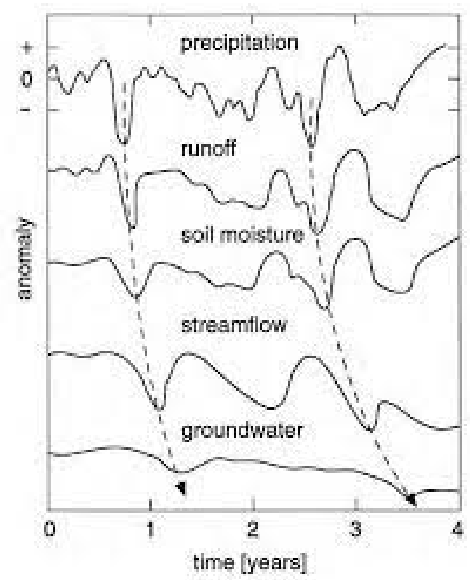


Figure 3.2: Propagation of drought in time. The lag in the system can be clearly observed as the drought propagates through the different stages.

3.1.4. Socioeconomic drought

According to Guo et al. (Guo et al., 2019), "Socioeconomic drought refers to whether the water supply can can meet the demand of various water-use sectors and their economic benefits" (Wilhite and Glantz, 1985, Palmer, 1965). It is expected that due to climate change, changing the amount and seasonality of precipitation, and population growth, leading to more water demand for agriculture and industry, more stress will occur on water supply. Next to that, other factors such as contamination of water supplies leads to more water scarcity. Socioeconomic droughts are thereby becoming a serious threat for different parts of the world (Mehran et al., 2015).

3.1.5. Ecological drought

Ecological drought is a new definition that is slowly being introduced in the research on droughts. The other drought definitions look into the physical phenomenon of drought and the socioeconomic impact. However, no definition describes the impact drought has on environmental services (Redmond, 2002). With the current population growth and climate change, the pressure on ecological water supply increases and thereby alters ecosystems in a way that they are increasingly vulnerable to drought. As a result, human communities suffer from the loss of ecosystem services. Therefore, ecological drought is defined as "a deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedback in natural and/or human systems" (Crausbay et al., 2017).

3.2. Drought, aridity, desertification and water scarcity: what are the differences?

There are different concepts to describe a region to have a water deficit: drought, aridity, desertification and water scarcity. The difference between these concepts depends on the time-scale and the anthropogenic influence.

Aridity

Aridity, a long-term climatic phenomenon, evokes images of dry and barren lands, such as deserts and rock hills, with little vegetation and sparse natural surface-water bodies for most people. Next to that, aridity also occurs in cold climates, such as Antarctica, which is largely considered to be a polar desert (Maliva and Missimer, 2012). The difference between drought and aridity is small. Aridity is a climatic feature of low precipitation that is permanent for a certain region, whereas drought is a temporary period of low precipitation in a certain region (Wilhite, 2000). To determine whether a climate is dry depends on the amount of precipitation and PET. Additional factors affecting aridity are temperature and the annual timing of precipitation. In arid regions, the PET rate on land may exceeds the actual evaporation rates. The main causes of aridity are large-scale, persistent atmospheric and oceanic circulations patterns or regional geography and topography (Thompson et al., 1975).

Water scarcity

In their study, Van Loon et Al. (Van Loon and Van Lanen, 2013) defined water scarcity as ”the over exploitation of water resources when demand for water is higher than water availability”. In their definition, they focus on the impact of human activities on the hydrological system. When comparing to drought, water scarcity is a man-made phenomenon while drought is regarded as a natural phenomenon. The fundamental difference between water scarcity and drought is in how water management can influence both phenomena. In the case of water scarcity, good management can prevent over exploitation of the available water resources. For drought, good management can only adapt to climate variability (Van Loon and Van Lanen, 2013). Synonyms for water scarcity used in other literature are *water shortage* or *water stress* (Taylor et al., 2009).

Desertification

Desertification is the longer term equivalent of water scarcity, as it has anthropogenic causes (Van Loon and Van Lanen, 2013). Desertification often occurs in (semi-) arid regions. Generally speaking, during desertification, the land loses its biological productivity due to a combination of natural processes (climate change) and anthropogenic influence. As a result, only bare land remains. In Europe, some countries are increasingly affected by desertification. Generally speaking, these countries are concentrated in southern Europe, such as Italy, Spain, Portugal and Greece.

3.3. Observing and evaluating drought

Droughts can be evaluated in terms of intensity, duration and spatial coverage. With intensity, the degree of precipitation deficit is regarded. For the duration, the beginning and the end of the drought has to be indicated. The spatial coverage discusses the geographical extent in which the drought period has impacted the region. Other characteristics of interest are: frequency, magnitude, predictability, rate of onset and timing (Zargar et al., 2011). To evaluate these terms, drought indicators and indices are needed. Application of indicators and indices allows to come up with operational definitions of the drought. As operational definitions are able to identify the beginning, severity and the end of a period of drought.

The differences between drought indicators and indices is clearly defined by Svoboda et al. (Svoboda, Fuchs, et al., 2016): ”drought indicators are variables or parameters used to describe drought conditions. Examples include precipitation, temperature, stream flow, groundwater and reservoir levels, soil moisture and snow pack. Indices are typically computed numerical representations of drought severity, assessed using climatic or hydro-meteorological inputs including the indicators listed above”. The drought indices are thereby quantitative measures to observe drought levels that use indicators as variables. The advantage of using indices is that they can simplify the complexity of drought and be used as a communication tool for the different users. Monitoring indices provide insight in in the severity, location, timing and duration of drought events. An important driver in indices is the threshold that is used in the definitions of the different indices, especially in the severity. A threshold for the severity, the difference of an index compared to the average value, can indicate the beginning, ending and the region impacted by drought. Currently, most thresholds are usually set arbitrarily. Wilhite et a. (Wilhite, 2000) suggests that they should be linked to impact. Within the scientific literature, more than 150 drought indices have been defined (Niemeyer et al., 2008, Zargar et al., 2011).

Drought indices are divided over three categories; meteorological, agricultural and hydrological. Niemeyer et al. (Niemeyer et al., 2008) suggest that three more categories should be regarded, being: comprehensive, combined and remote-sensing based. The latter three suggest and describe by what method or source the index was formed. Comprehensive indices are based on the combination of meteorological, agricultural and hydrological indicators. Combined indices are based on the combination of existing drought indicators and indices which are combined into a single measure. Remote-sensing indices are, as the name suggests, based on data from remote sensing.

In the Netherlands, only precipitation deficit is regarded as a drought indicator. In the master thesis of R. Weijers (Weijers, 2020), a research was performed for Rijkswaterstaat and the water board of Vallei and Veluwe in anticipating drought management. During the research, different drought indicators and indices were selected and analysed to take into account for anticipating drought management: SPI-1 & SPI-3, soil moisture, stream discharge, groundwater levels, NDVI and NVI. Based on the scope of this research, and the trade-off between needed information to calculate different indices, the following drought indicators will be further evaluated:

- Precipitation
- Precipitation deficit
- Groundwater levels
- Soil moisture
- Stream discharge
- Standardized Precipitation Index (SPI) introduced by McKee et al. (McKee et al., 1993)
- Standardized Precipitation and Evaporation Index (SPEI)

3.3.1. Precipitation

Precipitation is the main driver in drought monitoring. The KNMI has multiple precipitation stations located throughout the Netherlands of which a part automatically register precipitation and another part is monitored by hobbyists. This enables the KNMI to have a big network of precipitation stations in order to get a good overview of the precipitation activity and the local differences between precipitation events. Precipitation is measured in millimetres precipitation per day.

3.3.2. Precipitation deficit

Precipitation deficit is the difference between precipitation and evaporation per day, given in millimetres. The evaporation measured is the reference evaporation measured by Makkink's Method (Makkink, 1957). In the Netherlands, the KNMI starts monitoring the precipitation deficit on April 1st until September 30th. Every year, the precipitation deficit is reset on April 1st. The idea of resetting the precipitation deficit is that in the winter period, almost no evaporation occurs inside the plants (transpiration), so calculating the precipitation deficit for this period is of less importance.

3.3.3. Groundwater levels

Groundwater levels are commonly measured throughout the Netherlands by the waterboards. The fluctuation of the groundwater table can indicate the severity of the drought. Groundwater levels are monitored based on their level compared to the NAP and can be obtained through the websites of the waterboards as well as through the DINOloket, which is the platform for all data that is related to the ground. The groundwater tables do depend on the soil type. For peat areas, it is important that the ground water tables are sufficiently high enough to prevent oxidation. For the higher sandy soils in the Netherlands, the ground water table can be a good indicator as these areas mostly depend on precipitation as fresh water supply. During a drought period, the groundwater table will lower quickly. In the areas surrounding the VZM, the groundwater table can also indicate the drought. Furthermore, it can be applied to monitor whether salinization occurs through the groundwater when the ground water quality is evaluated. This is important as groundwater is also used for irrigation. A too high chloride concentration is not good for the crops.

3.3.4. Soil Moisture

Soil moisture drought is one of the four main drought types. It is therefore of interest to observe and monitor the soil moisture in the area as a drought indicator. The soil moisture is the water that is available between the pores of the soil particles above the ground water table. Below the groundwater table, the soil is fully saturated, while above the ground water table, the soil is unsaturated. The type of soil strongly influences the soil moisture content and the fluctuation of the groundwater table. For example, clay consist of smaller particles than sand. The pores are therefore smaller and the groundwater table will fluctuate less. The capillary rise is stronger with smaller pores and after a period of water extraction of higher transpiration, the capillary rise will lift the water up. For sandy soils, the pores are bigger, reducing the capillary rise. In 3.1, the equation for the soil moisture is given. θ is the soil moisture content [%], V_w is the volume of the saturated pores [m^3] and V_t is the total volume of the soil [m^3].

$$\theta = \frac{V_w}{V_t} * 100\% \tag{3.1}$$

The problem for soil moisture is that currently there are not sufficient monitoring mechanisms available that could easily and remotely monitor soil moisture in the area of interest. Soil moisture is normally monitored using probes. New methods consist of using satellite data, such as Sentinel-1 that is able to determine the soil moisture.

3.3.5. Stream discharge

An important indicator for hydrological drought is the stream discharge. An example are the news articles during the 2018 drought about reduced shipping capacity in the Rhine river due to low water levels. To observe a drought in stream discharge, one has to set thresholds based on historical data. When the discharge is below the threshold for a longer period, one could say that in terms of river discharge, there is a drought. An important factor that is also secured in legislation, is that an minimum discharge is required in the rivers in order to maintain a ecological condition in the rivers and streams.

The rivers Rhine and Meuse are the main fresh water suppliers of the Netherlands next to precipitation. When the discharge is below certain thresholds, the *Verdringinsreeks* comes into action. This is scheme that provide legislational reasoning for water division between the main groups that demand water.

3.3.6. Standardized precipitation index (SPI)

SPI is an index introduced by McKee et al. (McKee et al., 1993) that is able to identify precipitation deficiency by explicitly specifying time scales. Research by Chang et al. (Chang and Kleopa, 1991) shows that precipitation is the main variable that needs to be considered for determining the on- and offset, intensity and duration of a drought event. By using different time scales, the impact of drought on the availability of the different water resources, can be reflected. As depicted by Figure 3.2, the different drought types have different timescales in which the drought event manifests itself. For example, hydrological drought is only reflected by longer-term precipitation anomalies.

The SPI is based on long-term precipitation data of which it is preferable to have at least a data set with monthly precipitation values for at least 20-30 years, with 50-60 years (or more) is preferred (Guttman, 1998). This data is then fitted to a gamma distribution, which is then transformed into a normal distribution. As a result, the mean SPI for the location and period is thereby equal to zero. Positive SPI values indicate that the mean precipitation of that period is higher tan the median precipitation and negative SPI values indicate that the mean precipitation of that period is lower than the median precipitation (see Table 3.1). As the method standardizes the precipitation data, it is able to represent wetter and drier climates in the same way.

Table 3.1: SPI values

SPI value	Description
>2.0	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-0.99 to 0.99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
<-2	extremely dry

For the SPI, different common timescales are being evaluated, being: 1-, 3-, 6-, 12-, 24- and 36-monthly periods. The longer the period of evaluation, the larger the extent of a drought event can be examined. For a SPI-1 evaluation, meaning the evaluation period is the summation of precipitation during one month, meteorological drought can be monitored. Agricultural, or soil moisture drought, can be evaluated with an SPI-3, or a three month evaluation period. For example, the SPI for July takes into account the summation of the precipitation for the months May, June and July. For hydrological drought, SPI-12 or SPI-24 are evaluated (Organization, 2012).

The advantages of SPI are:

1. As the SPI is normalized, different climate types can be evaluated in the same way.
2. Shorter timescales can be used as an indicator/early warning of a drought event.
3. SPI can be computed for multiple timescales

the disadvantages of SPI are:

1. SPI is not suitable for the analysis of climate change. This is due to the fact that temperature is not taken into account.
2. The only parameter is precipitation.

3.3.7. Standardized precipitation and evaporation index (SPEI)

Different studies provided insights that it is important to consider the influence of temperature in drought observation. During 2003, extreme temperature anomalies caused drought stress throughout central Europe as high temperatures led to increased evaporation rates (Rebetez et al., 2006). Other studies provide proof that higher than average temperature events reinforce drought stress (Vicente-Serrano et al., 2010). Evaporation and transpiration can be accounted for up to 80% of the precipitation Abramopoulos et al., 1988. It is therefore important to consider the influence of temperature in the drought indicators and indices (Vicente-Serrano et al., 2010). Especially, when focusing on climate change as temperature is expected to rise in the coming decades (Pachauri et al., 2014).

SPEI is a drought index that is based on precipitation and Potential Evaporation (PET). The biggest difference with SPI is thereby including the temperature aspect that manifest itself in the PET. Potential evaporation is the amount of water that could be transferred to the atmosphere under ideal conditions of soil moisture and vegetation (**thornthwaite1948approach**). As for SPI, SPEI is able to identify the onset and offset of the drought event and the severity. Moreover, it can be applied to different timescales and thereby assess different drought types.

The PET that is generally used in the Netherlands is based on Makking's method (Hiemstra and Sluiter, 2011). For this method, the incoming shortwave radiation and the mean daily temperature are requires to determine the reference evaporation (Makkink, 1957).

As with the calculation of SPI, SPEI also generates monthly sums, but than based on the difference between precipitation and evaporation as presented in equation 3.2. This data is then fitted to a probability density function, in this case a GEV-fit and then transformed into a normal distribution in order let the mean SPEI be equal to zero. In that way, the difference of a period of interest can then be compared to the mean SPEI of the total dataset. Also for the SPEI, a longer dataset is preferred as with the SPI.

$$D_i = P_i - PET_i \tag{3.2}$$

3.4. Extreme value analysis for discharge measurements

The purpose of frequency analysis to analyse past records of (hydrological) variables to estimate future occurrence probabilities. An important factor for the water supply of the VZM is the discharge of the Rhine at Lobith. In the current regulations, it is stated that when the discharge at Lobith is below 800 m^3/s, all the available water must be used to flush through the Nieuwe-Waterweg in order to provide sufficient pressure against the intrusion of seawater from the North Sea.

In order to define the return periods of discharges below 800 m^3/s, an extreme value analysis will be performed. The data used for this analysis consist of measured daily average discharge values starting in 1901 measured by Rijkswaterstaat. For the analysis, the available data will be used for the period 1901 till 2019.

3.4.1. Theory of Extreme Value Distributions

Currently, two types of extreme value distributions are used to find the correct distributions for maxima and minima. The two types considered are: Generalized Extreme Value (GEV) distribution as proposed by Jenkinson (Jenkinson, 1969) and the Generalized Pareto Distribution (GPD) proposed by Pickands (Pickands III et al., 1975). The GEV distribution contains three standard extreme values distributions, Fréchet, Gumbel and Weibull, while the GPD covers exponential, Pareto and uniform distributions.

The extreme value distribution focuses on the statistical behavior of M_n, where M_n represent the maximum value of measured data during time n:

$$M_n = max(X_1, X_2, ..., X_n) \tag{3.3}$$

There are two methods to define the extreme values from the dataset: the Peak Over Threshold (POT) where a certain threshold is set and all values higher than this threshold are used in the extreme value analysis or the block maxima. The latter is based on the maximum value that occurs within a certain block/time period. Examples of blocks are weeks, months and years. Depending on the used method to determine the maximum values, the distribution used to evaluate the extreme values are the GPD or the GEV distribution respectively.

The behaviour of the tails of the original PDF of the extreme value distribution converges to types I, II or III GEV distribution. The GEV distribution takes three parameters into account: μ is the location parameter, σ the scale parameter and ξ the shape parameter. These parameters can be defined by using the maximum likelihood estimator. This estimator maximizes the likelihood function to fit the distribution best to the data.

The GEV distribution is described by:

$$G(z) = exp\left(-\left(1 + \xi\left(\frac{z-\mu}{\sigma}\right)^{\frac{-1}{\xi}}\right)\right) \tag{3.4}$$

The shape parameter ξ defines the three different extreme value distributions as follows:

$\xi \rightarrow 0$: Gumbel (type I) distribution
$\xi > 0$: Fréchet (type II) distribution
$\xi < 0$: Reverse Weibull (type III) distribution

3.4.2. Return Levels

The return levels associated with the extreme levels can easily be calculated. Let z_p be the return level associated with the return period 1/p. Then, the value of z_p is expected to be exceeded once every 1/p years on average. This is described by:

$$z_p = G^{-1}(1-p) = \begin{cases} \mu - \frac{\sigma}{\xi}(1-(-ln(1-p))^{-\xi}), & if \xi \neq 0 \\ \mu - \sigma ln(-ln(1-p)), & if \xi = 0 \end{cases} \tag{3.5}$$

4

Drought indicators and indices quantified for the VZM

In this chapter, the different drought indicators and indices that were suggested in Chapter 3, will be quantified for the application to the VZM. This chapter is split into two parts. First the river discharges, with emphasis on the Rhine, are evaluated. Secondly, the precipitation based indicators and indices are evaluated. For the drought indicators and indices, a distinction is made in the scale at which the indicators and indices are evaluated. The river discharges for the rhine, precipitation deficit, SPI and SPEI are at a larger scale than ground water levels and soil moisture content. The latter two are more of interest for the water boards than Rijkswaterstaat as Rijkswaterstaat does not have the resources to manage these factors.

4.1. River discharge analysis

A dataset of daily average measured discharges was available from Rijkswaterstaat for the period 1901 till Spring 2020. It was decided to leave out the values for 2020 in order to have 119 years of yearly data available. To analyse the discharge values, an Emperical Cummulative Distribution Function (ECDF) plot was generated (see Figures 4.1 and 4.2). This plot includes all measured daily values of the discharge of the Rhine. It can be observed that the 50% of the daily discharge occurred at 2000 m^3/s. The most important value for the VZM is a discharge of 800 m^3/s as the inlet at the Volkerak must be closed when the discharge is below this level. In Figure 4.1, the left tail is therefore of interest. From the plot, it can be observed that of the probability of a discharge was below 800 m^3/s is P<0.009 or 0.9%. While for a discharge of 1000 m^3/s, P<4.89%. As the ECDF curve is only based on empirical values, the tails stop at the lowest and the highest values. In 4.1.2, an extreme value analysis will be presented to see how extreme low values will occur.

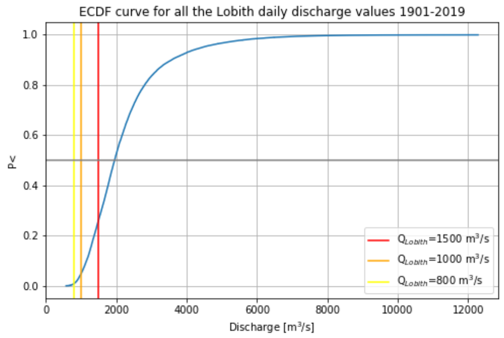


Figure 4.1: ECDF curve for measured average daily discharge at Lobith between 1901 and 2019.

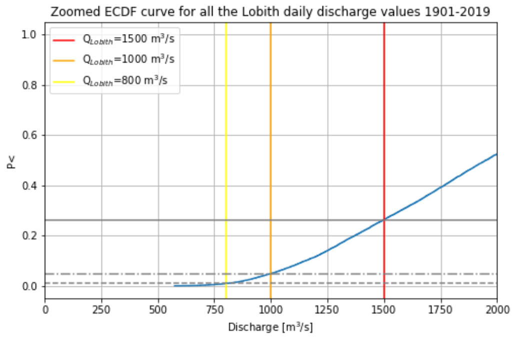


Figure 4.2: Zoomed left tail of ECDF curve for measured average daily discharge at Lobith between 1901 and 2019.

4.1.1. Amount of days with discharge below certain threshold

The duration of a period with discharges at Lobith below 800 m^3/s is one of the main drivers to determine how long the VZM cannot depend on a fresh water supply. With the available discharge data, the duration was determined for which the discharge at Lobith was below a certain threshold.

To avoid single day events being measured, a threshold for a minimum duration of a dry period was set at seven days. As a result, only periods longer than seven days that have a measured average discharge below 800 m^3/s, are taken into consideration. The years were then again manually checked to see whether two events were not separated by one or two days with a discharge above the threshold. This analysis showed that for 1949 and 2018 this indeed occurred. From data analysis, it turned out that most low flows at Lobith occurred during autumn, after the growing season has ended. For that reason, the data was split up to check the amount of days the discharge during the growing season is below the value of 800 m^3/s. For the VZM, it was considered to only observe dry periods during the growing season as the water demand is the highest and the chloride concentration must be taken into account. Moreover, this period corresponds with the precipitation deficit and the target levels with a lowering trend are in place during this period. When we look again to the amount of days with a discharge below the threshold of 800 m^3/s, then only in 1947 and 1949 the discharge at Lobith is below 800 m^3/s for 16 and 31 days respectively (see Figure 4.3 for summer data and Figure 4.6 for yearly data).

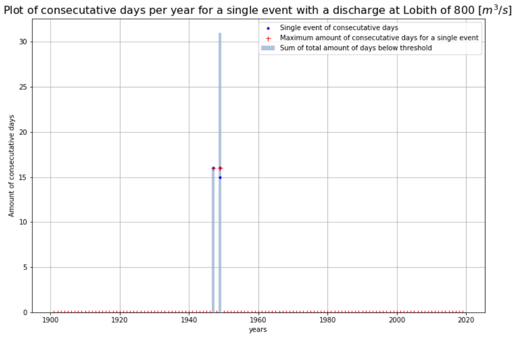


Figure 4.3: Plot of amount of events with number of days with discharge below threshold of $800 m^3/s$ for summer data.

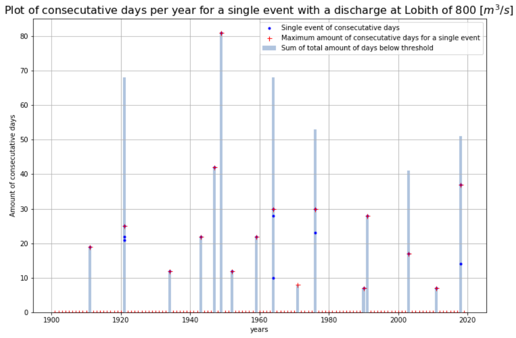
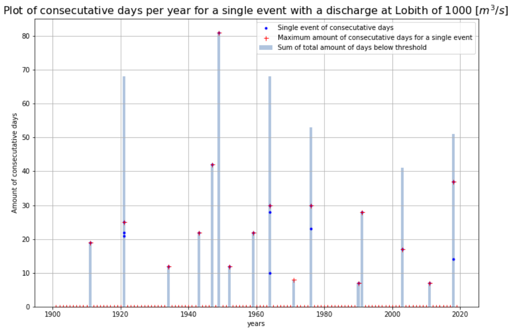


Figure 4.4: Plot of amount of events with number of days with discharge below threshold of $800 m^3/s$ for yearly data.

Next, the amount of dry days with a discharge below 1000 m^3/s is regarded. This threshold is of interest because the discharge is significantly low and with high tide and western winds, backwards infiltration of sea water in the the Rhine Meuse Estuary can occur. The plots for the summer period (left) and the yearly data (right) can be found in Figures 4.5 and 4.6. As with the plots for the threshold of 800 m^3/s, one can clearly observe the differences in length and amount of the dry periods between the summer and yearly data. Often, the low discharges in the Rhine occurs during Fall period. During Fall, the snow in the Alps has already melted.



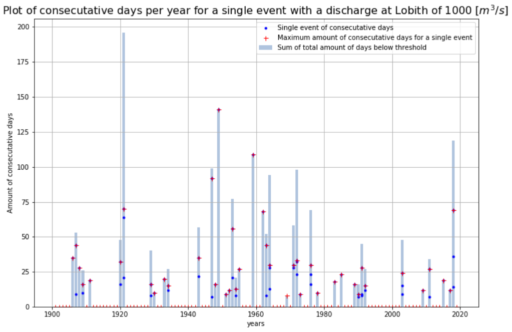


Figure 4.5: Overview of the length and amount of days when Q_{Lobith}<1000 m^3/s in period May 1st till September 30th.

Figure 4.6: Overview of the length and amount of the discharge at Lobith was below 1000 m^3/s for the whole year

4.1.2. Return period for low discharges

Based on the GEV methodology that was discussed in Section 3.4, the plot in Figure 4.7 was obtained. In this plot, the modelled return period and levels for extreme low discharges can be found for return periods up to 1/1000 years. This is plot is based on the minimum discharges per year that was measured at Lobith between 1901 and 2019. The minus sign accounts for the fact that here, we are dealing with minimum values instead of maxima of which the method is more often applied for. So, a value of -800 m^3/s is the same as 800 m^3/s. From the plot, it can be observed that the return period for a discharge below 800 m^3/s is 7.65 years. This indicates that the probability for this discharge is $1/p = 1/7.65 = 0.131$. This analysis is not able to take into account the duration of the period the discharge is below a certain threshold.

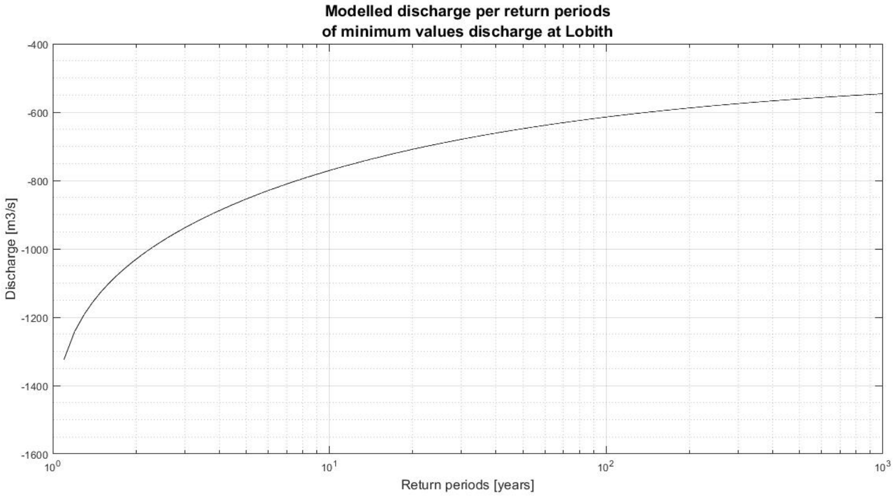


Figure 4.7: Modelled discharge per return period based on daily minimum discharges at Lobith measured between 1901 and 2019

The distance between Lobith and the Volkeraksluizen is roughly 135 kilometres. Assuming a velocity of the water of 1 m/s, the moment this moment this low water level reaches the Volkeraksluizen is roughly 37 hours. As mentioned in Section 2.7, it takes three to four days to raise the water level in the VZM from -0.15 m NAP to +0.10 m NAP. This is more than the 37 hours it takes for a certain discharge to ”travel” the distance between Lobith and the Volkeraksluizen at the Hollandsch Diep. A multiple day discharge prediction therefore necessary to predict the discharge at Lobith more in advance. Rijkswaterstaat has its own system that is able to predict the discharge 15 days in advance.

The difference between the water level of the VZM and the Hollandsch Diep determines the potential discharge that could flow to the VZM as the inlet is driven by gravity. The water level at the Hollandsch Diep partly depends on the discharges of the Rhine and Meuse rivers as it is an open connection.

Moreover, there is a tidal influence as there is an open connection to the North Sea via the Nieuwe Waterweg and the Nieuwe Maas and Oude Maas. Finally, the Haringvliet surge barrier can be opened and closed to allow passage for fish from the North Sea towards the Rhine. Since 2018, some doors are slightly opened in the barrier during high tide to allow passage for fish. This is only applied when the discharge at the Rhine is higher than 1700 m^3/s.

4.2. Precipitation based drought indicators

This section will look into the precipitation based drought indicators and indices. The main data that is needed are precipitation (and evaporation) data. In the Netherlands, weather measurements are performed by the KNMI. The KNMI has multiple weather stations located throughout the Netherlands. Next to that, the KNMI relies on hobbyist that monitor precipitation. Multiple KNMI weather stations are located in proximity of the VZM: Gilze-Rijen (35km), Vlissingen (45 km), Woensdrecht (10 km), Westdorpe (35 km). The availability of the data sets from these weather stations can be found in Table 4.1. Based on the lengths of the data sets, especially taking into account the calculations for the SPI and SPEI, it was decided to use the KNMI data from Vlissingen.

Table 4.1: KNMI weather stations availability of data sets for precipitation and evaporation near the Volkerak-Zoommeer

Name Station	Distance [km]	Start precipitation measurement	Start evaporation measurement
Gilze-Rijen	35	01-10-1976	03-04-1987
Vlissingen	45	01-01-1957	01-01-1964
Woensdrecht	10	01-02-2018	-
Westdorpe	35	23-06-1993	25-06-1991

4.2.1. Precipitation Deficit

Based on the precipitation and evaporation data from the station in Vlissingen, the precipitation deficit could be calculated for every single year. The precipitation deficit is the sum of the daily difference between the precipitation and the potential evaporation. An upward line indicates that the deficit increases (i.e. the potential evaporation is higher than the precipitation). In Figure 4.8, the precipitation deficit for the summer of 2018 is plotted in blue (April 1st till September 30th) as well as the median which is indicated with by the black line ass well as the 50% and 95% interval. For the summer of 2018 (which was a really dry summer), it can be clearly observed that April was quite wet and the deficit remained under the median. From the start of May, the the deficit slowly increases until the start of June from which the deficit follows almost straight line. This indicates that almost no rain occurs in the period between the start of June until the end of July. From the precipitation data that was used as input for this graph, this could also be observed.

4.2.2. SPI

As mentioned in 3.3.6, it is beneficial to present the SPI in different monthly summations to observe the different types of drought (e.g. 1-, 3-, 6-, 12- and 25- monthly summations). In Figure 4.9 the different monthly summations are plotted. It can be clearly observed that 2018 started with more than average precipitation. The SPI-1 is the first one to drop, quickly followed by the SPI-3 in the summer of 2018. The longer intervals follow slowly. The offset between the different SPI calculations can be clearly observed. The SPI calculations with a longer interval are being ”compensated” in the summer by still taking into account the higher SPI values in the beginning of 2018. Slowly, the summer of 2018 is incorporated in the calculations and the SPI values for the longer calculation intervals drop. Only the SPI-24 remains close to zero, but drops significantly in Spring 2019 and keeps decreasing until Spring 2020. One can clearly observe the length of which most SPI values are below zero when the summer periods of 2017 and 2018 are observed. In 2017, the period of which the SPI value (except from the SPI-24) were below zero is much smaller than for the summer 2018 period. For some SPI types, the SPI is still below zero in 2020,

For the water supply to the water users of the VZM, the meteorological and agricultural drought are the most important to observe. Of which the meteorological drought can be indicated the easiest as the SPI-01 and SPI-03 are used for this. Especially the SPI-01 is promising to be taken into account

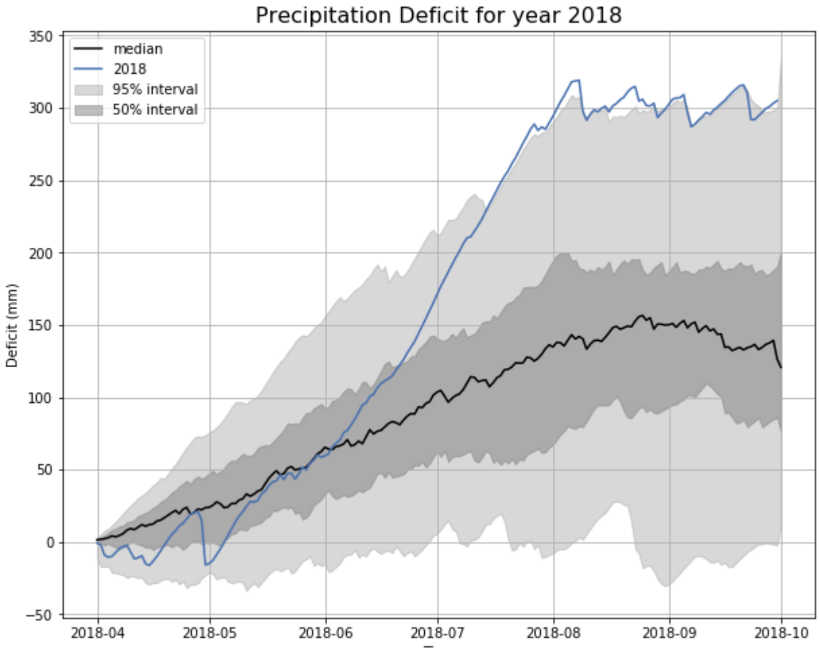


Figure 4.8: Plot of the precipitation deficit for 2018 with the 50% and 95% interval

as a drought index as it does not look too much back in time. When for example the SPI-06 indicates values below zero, this means that the process started already six months ago. This is too late to adapt for. Compared to the SPI-03, the SPI-01 already differs two months, which is quite substantial for water management purposes. In Appendix A.4, the SPI-1 and SPI-3 plots for the period 1964-2019 are presented.

The higher SPI values can be used to observe whether the manifestation of the drought continues after the summer period. This can be of interest for the waterboards in combination with the ground water levels. For Rijkswaterstaat this means that when the higher SPI types show longer manifestation of values below zero, the waterboards would probably require more water to restore groundwater levels or fight salinization in the ground water.

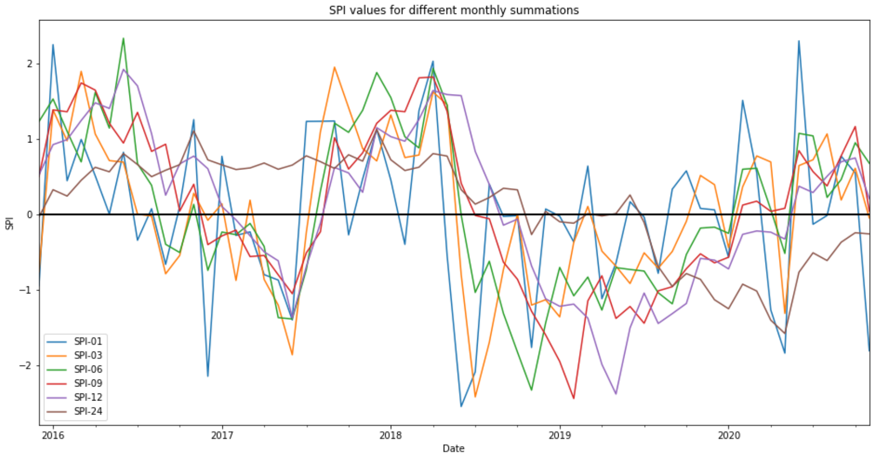


Figure 4.9: Overview of the propagation of different SPI monthly summations with the summer 2018 drought centered.

Another method to present the SPI values is by using a continuous 30-day summation of the past 30 days. Using this interval would increase the insights in the development of the SPI. With the method plotted in Figure 4.9, data is only provided once per month. As a result, only after one month, the new SPI value is available. The idea is that a rolling 30 day SPI calculation gives better insights into the development of the index. In Figure 4.10 both the SPI-01 and the 30 days rolling SPI is plotted. From the plot it can be observed that both calculations do correspond in the location of all peaks. However, due to the calculation of only monthly values or the rolling 30 days, the standardization reference differs, resulting in some slight differences in the peaks at some locations. A clear example for the benefit of the rolling 30 days SPI calculation can be found in the period 2018-01 and 2018-07. Here, halfway during the month, the 30 days rolling SPI value drastically changes direction. The change in the SPI-01 value can only be observed after one month, which delays the time for the water manager of the VZM to adequately responds to the change when necessary.

It was researched to what extent it was possible to reduce the interval over which the SPI was calculated. When adding a seven days rolling SPI calculation as plotted in Figure 4.11, it can be observed that there are more extreme peaks, especially in the negative values. In the 40 years of reference years, on average, there was always precipitation for the weekly periods. A week without precipitation immediately shoots to the tail of the distribution that is used to standardize the distribution and define the SPI value.

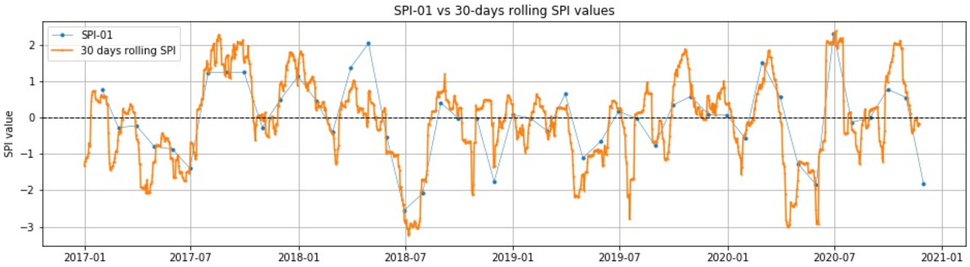


Figure 4.10: SPI-01 vs. 30 days rolling SPI value for the period 2017 - 2020.

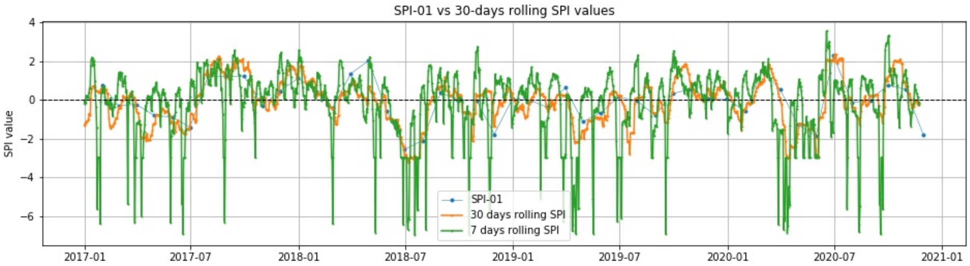


Figure 4.11: SPI-01 vs. 30 days and 7 days rolling SPI value for the period 2017 - 2020.

4.2.3. SPEI

In Figure 4.12, the SPEI-01 values and the 30 days rolling SPEI values are plotted. As with the SPI, there are some differences in the order of magnitude of the peaks, but the location of the peaks is the same. This can be assigned to the difference in reference as the reference window of the rolling calculation moves, while the monthly SPEI is the same. Furhtermore, in the rolling interval, only 30 days are evaluated, while some months also consist of 28 or 31 days.

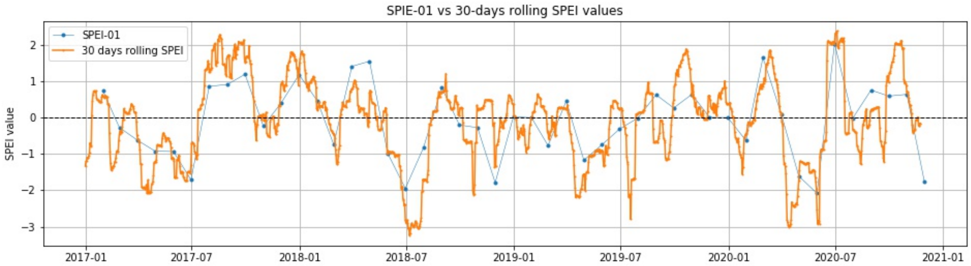


Figure 4.12: SPI-01 vs. 30 days and 7 days rolling SPI value for the period 2017 - 2020.

In Figure 4.13 the different SPI and SPEI values for different length are compared for the past five years to see whether there are big differences between both indices. For the longer monthly summations (9-, 12- and 24-monthly summations), the differences between the SPI and SPEI are getting bigger. A general observation is that the SPEI is lower than the SPI in almost any situation, except from a few spikes. For the 1- and 3-month periods, the SPI and the SPEI show clear similarities in the location of the peaks as well as the severity.

A general note for both indices is that due to the normalization of the data to let the median values correspond to zero, the influence of climate change are taken into the median. When the precipitation deficit increases every year, the histogram of all the yearly data will slowly change. By normalizing the histogram, the median value will slowly move towards to the higher precipitation deficit values. The same needs to be taken into account for the precipitation data. When due to climate change, periods will become dryer or wetter, this will be incorporated in the normalization. When both the SPI and SPEI are evaluated in 2050 for example, the reference values from the normalization have changed. Assuming temperature has increased, resulting in a higher evaporation rate and thereby a higher precipitation deficit. When the same precipitation and evaporation values as in 2020, lower SPEI values will be calculated as the mean SPEI has increased, as the mean SPEI is set to zero in the normalization. The same influence will take place with precipitation values and thereby also in the SPI and SPEI calculations. Therefore, one could consider to stop values being added to the reference period and only calculate the SPEI (and SPI) with a reference period that stopped at 2020, thereby not incorporating the effects of climate change. As a result, the index will indicate more drought.

The advantage of the SPEI over the precipitation deficit is that it is not reset every year when the growing season starts. Long-term drought is therefore better to observe. Already in 4.13, one can observe that the drought of 2018 manifests itself in 2019 too. This is not possible to observe, when one considers the precipitation deficit graphs for 2018 and 2019.

For a short term drought indicator, precipitation deficit is perhaps easier to observe than the SPEI as the SPEI needs monthly summarized data. Unless, the rolling SPEI is considered. The precipitation deficit is monitored daily by the KNMI and also presented for the Netherlands in a map. The disadvantage is that it is not normalized. The severity is mapped in terms of total millimetres precipitation deficit. As the potential evaporation tends to be higher than the precipitation in the summer time, the current way in presenting the precipitation deficit is somewhat misleading. The advantage of the SPEI here is the normalization that occurs. One can clearly indicate that when the SPEI is below zero, this could indicate a drought is building up.

The 30-day rolling SPEI calculation and the precipitation deficit are both available for daily values, Which is an advantage over the monthly SPEI calculation. When implementing the SPEI-01 index, it does provide a value that can be up to more than three weeks old. The 30-day rolling SPEI calculation and the precipitation deficit can provide calculations that can indicate a trend more clearly as actual precipitation and evaporation data can immediately be implemented and observed in the calculations to get insights in manifestation of a drought event.

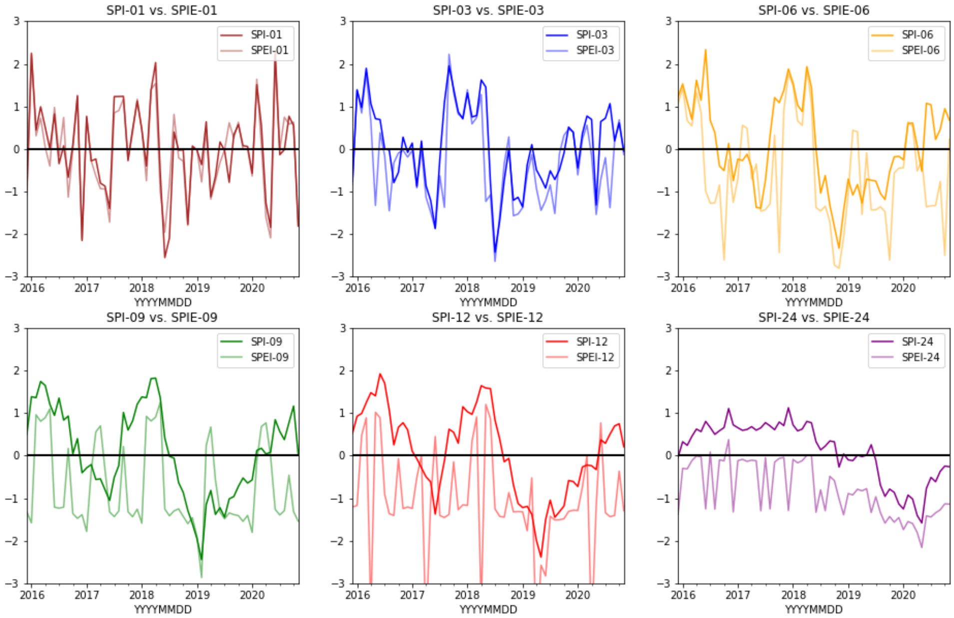


Figure 4.13: Comparison of SPI and SPEI values for different month types over the last 5 years for precipitation and evaporation data from KNMI station Vlissingen.

4.2.4. Groundwater levels

Groundwater levels greatly differ between different locations in the areas of the water users of the VZM. Local situations need to be taken into account as farmers have different preferences regarding the groundwater tables. The groundwater tables are (in)directly managed by managing the water levels in the ditches next to the fields. The waterboards have target level decisions in which the water levels in the ditches are set in a constitutional framework. The waterboards need to care for maintaining these levels.

From the available open source maps with local ground water levels, the development of the ground water levels is monitored.

A good example is the monitoring method of Waterschap Brabantse Delta uses. This monitoring method has five color codes that are listed below. A map of the management area of the waterboard shows the color for every measurement point and provides an easy overview of the values of the water levels in the area compared to the different thresholds.

- Red: the groundwater level is lower than the level that occurs once every ten years for the same period of the year.
- Orange: The groundwater level is lower than the level that occurs once every five years for the same period of the year.
- Green: De groundwater level is normal for the same period of the year.
- Light blue: The groundwater level is higher than the level that occurs once every five years for the same period of the year.
- Dark blue: the groundwater level is higher than the level that occurs once every ten years for the same period of the year

For Rijkswaterstaat, the exact groundwater tables per local management area are not needed as drought indicator. The level of detail is too big for managing the water level of the VZM. The water boards will indicate when they need more water as they are in contact with the land owners (especially the farmers) and responsible for maintaining the water levels in the local system. The monitoring of the groundwater levels of the Waterschap Brabantse Delta is a good example of how to easily provide insight in the groundwater levels by using different color codes.

4.2.5. Soil Moisture

Soil moisture is an important feature to take into account drought monitoring on a local scale. Especially to analyse green drought (agriculture and environmental), a soil moisture deficit can clearly help into monitoring the development of drought impact. Many of the polders that depend on a fresh water supply are used as agricultural lands. Soil moisture monitoring is therefore a tool that can provide clear insights for farmers or nature organisations in the severity of a potential drought event due to soil moisture deficit.

5

Decision Support System

This chapter provides insight into a Decision Support System (DSS) that was created for the VZM. Moreover, results of this tool will be presented for different climate and delta scenarios. The aim of the tool is to obtain better insights in the development of the water level of the VZM after certain management decisions on short-term and long-term scenarios. The decision tree will be shortly introduced where after the functionalities of the DSS are introduced. Next, emphasis is put into the assumptions and simplifications that had to be made. Examples are taking into account lock operations, sea level rise and the water demand of the polders. The results from the DSS are then validated with the results from the practical experiment drought to see whether the dynamics of the system are reproduced correctly. It turned out that the lowering of the water level is represented good, while initiating heightening of the water level is not represented well. Finally, the long-term impact of the climate and delta scenarios are evaluated for 2050 and 2085. The delta scenarios ”Stoom” and ”Rust” were used to determine the lowering rate of the water level.

5.1. Aim of the Decision Support System

The aim of the DSS is to provide insights in the influence of water management measures and decisions taken by the operators of the VZM on the water level. For Rijkswaterstaat, the wish is to see what influence decisions can have on short-term notice (e.g. two weeks) but also to work out future scenarios based on the different climate and delta scenarios calculated for 2050 or 2085. The main focus lies on drought scenarios. However, the tool can also be applied in normal operations.

5.1.1. Short-term insights

For short-term insight, the main client of the tool is the Hydro Meteo Centrum (HMC) of Rijkswaterstaat. The HMC manages the VZM and operates the inlets at the Volkerak and discharge sluices at Bath. It acts as the operational water level manager of the VZM. The current software they use only provides insight in the amount of water they need to take in at the Volkerak. The VZM is operated to maintain the same water level. So, the amount of water that leaves the lake at Bath needs to be taken in at the Volkerak. The software advises the level at which the gates of the inlets need to be set in order to maintain the same water level. Manually, the operators are able to alter the settings of the gates that the system prescribes to heighten or lower the water level in the system. The system does not provide insights in what the water level will do in a couple of days. Therefore, the main goal of the tool is to give insights in the short-term effects of the choices the operators make.

5.1.2. Long-term insights

Another aspect of the tool is to see the impact on the long-term scale for the policy makers of Rijkswaterstaat, ministry and the water boards that are occupied with long-term planning of the VZM. Therefore, insights in the effect of climate change on operational water management of the VZM need to be discovered. This can be accomplished by incorporating the climate and delta scenarios on the existing data that is available of for the VZM. In doing so, it is possible to see whether creating a water buffer at the VZM can be used as a drought mitigation measure and as well as the influences on normal operation of the VZM. These insights could help to argue (new) policies regarding the VZM.

5.2. Decision tree

In the initial stage of the development of the DSS, a decision tree was created to form the base of order of decisions that need to be taken into account. For Rijkswaterstaat, the main objective for the VZM is to maintain the water level within the different target level boundaries of the VZM that are set in the water agreement. Secondly, Rijkswaterstaat should aim to maintain a chloride concentration in the VZM during the growing season that is below 450 mg/L. For the water users of the VZM, it is desirable to also give insights into the development of Cyanobacteria fields in the VZM, but as research proved, it is not possible to manage these fields with the flushing operation. The decision tree is based on these managing aspects of the VZM. The tree provides insights into the boundary conditions that are needed to manage the points of interest and their development during a period of drought.

For the scope of this research, only the water level is further examined. For the chloride concentration, only an advice is provided. The chloride concentration was further examined, but turned out too complex for the scope of this research. For Cyanobacteria, only a warning is provided as less information is available on their development within the system and a nutrients balance is missing.

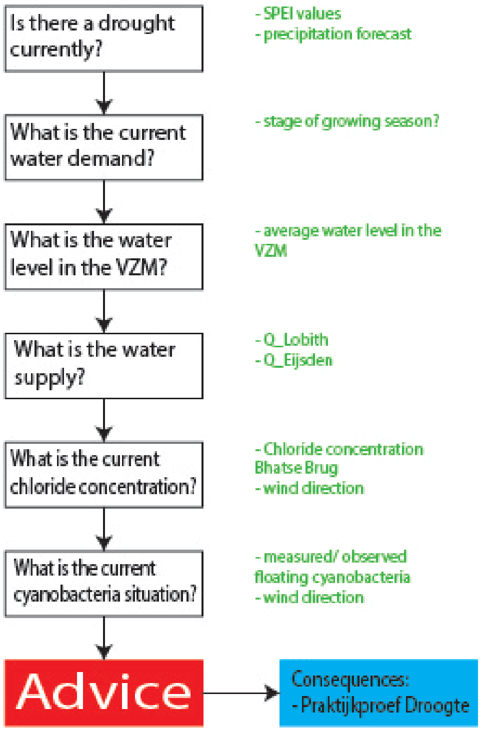


Figure 5.1: The decision tree with the questions of interest and the input arguments that should be considerd to answer the question.

In Figure 5.1, the initial decision tree is presented. As observed in the figure, the questions and their needed input data are shown in green. These questions create an insight into the boundary conditions for the DSS. With the data and the boundary conditions an advice is generated for water level management. The current drought situation can be observed through the actual SPEI values and the precipitation forecast. Based on the period of year and the stage of the growing season, together with knowledge about the crops, an insight can be provided in the water demand towards the different polders. The current water level of the VZM is the main factor that determines the possibility to supply water to the water users of the VZM. The possibility to increase the water level depends on the discharge at Lobith and Eijsden as these values determine whether the inlet at the Volkerak must be closed or can be opened. To provide insights into the chloride concentration and development, the chloride concentration at the measuring point at Bathse Brug must be evaluated. From the interviews, it was suggested that the wind is a determining factor in the releasing of salt water from the deep parts of the Volkerak. Research by Deltares on the results of the practical trial drought showed that wind is not the unique driving factor (Nolte et al., 8 July 2020). Therefore, only a warning is provided based on the wind direction and force. The observed floating Cyanobacteria fields and the wind direction provide insights in the direction this fields can flow and where they can cause nuisance.

The questions and the needed parameters from the decision tree were then combined into a conceptual model that is presented in Figure 5.2. Next to the input arguments that are needed to answer the questions from the decision tree, new arguments were added. These include the climate and deltascenarios for 2050 and 2085 and the initial input arguments were categorized into:

1. Current meteorological input arguments
2. Current hydrological input arguments
3. Climate and delta scenarios for 2050 and 2085
4. Threshold values

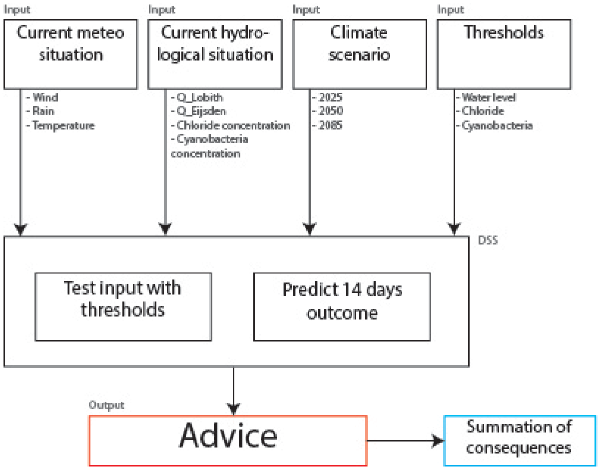


Figure 5.2: Conceptual model of the DSS

The idea of the tool is that all aspects that are mentioned in 5.2 are combined and an advice is provided and the consequences of different management options are listed. In the DSS, the input arguments are compared to the threshold values to provide an insight in the situation.

5.3. Decision Support System functionalities

The DSS is created in Excel and consist of two parts. The first part is the dashboard in which the users can give different input arguments, read an advice based on basic input arguments and apply this advice in the operational part. The impact on the average water level of the VZM can then be observed in a graph. The second part consists of all the calculations that are on a separate tab in the excel file. Most of the calculations are clustered in different tables. This makes it easy for other people to observe the information and change different values when necessary. Excel was chosen as the platform for this prototype as it can easily be used and shared and Rijkswaterstaat computers are not equipped with programming tools such as Python or Matlab. In Figure 5.3, the dashboard of the prototype of the DSS can be found. The various steps are clearly visible. This example shows a long-term evaluation. Therefore, the inputs for the precipitation, evaporation and the discharge of the Dintel and the Vliet are blocked out.

5.3.1. Input

The following input arguments, including a small explanation, are taken into account:

1. Date: this influences the target levels as mentioned in the target level decisions.
2. Discharge at Lobith: is of interest as this is the main driver of fresh water supply to the VZM
3. Wind direction: influences the movement of Cyanobacteria fields and can release high chloride concentrations from deep parts.
4. Wind force: influences the movement of Cyanobacteria fields and can release high chloride concentrations from deep parts
5. Chloride concentration in the VZM: must be below certain value in order to be used as fresh water supply for agricultural use.
6. Initial water level VZM: starting point of the water level at the VZM.
7. Surface VZM: different values of total area of the VZM are considered in different researches.
8. Water demand: can be set to either 0.1 or 0.3 L/s/ha to calculate the discharge used by the polders.
9. Extra surface that benefits from fresh water supply from the VZM: to include extra surface area that can benefit by a fresh water supply from the VZM in the future.
10. Possibility of extra water supply in Moerdijk: a new fresh water supply is built by WSBD at Moerdijk to take in extra water that will eventually end up in the VZM.
11. Delta and climate scenario: possibility to choose different delta and climate scenario.
12. Year of delta and climate scenario: the year of the desired delta and climate scenario.
13. Precipitation: total daily precipitation in millimetres.
14. Evaporation: total daily evaporation in millimetres
15. Discharge Dintel and Vliet: the average discharges of the Dintel and the Vliet.

5.3.2. Output

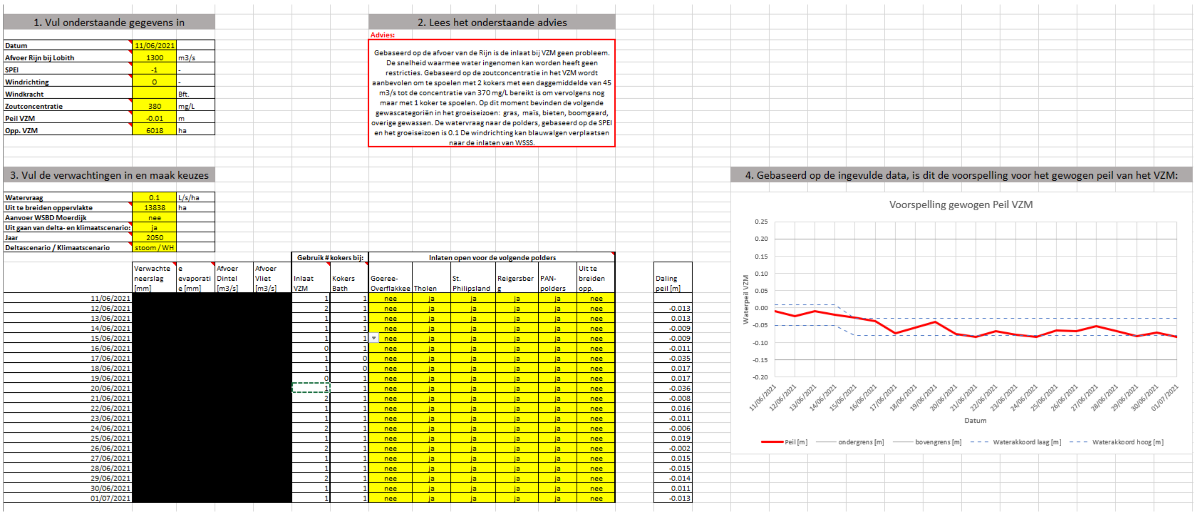
The output of the prototype consist of an advice based on the input arguments and a graph with the gradient of the calculated water level at the VZM. These provide insights in the management choices of the operators for the next day, as all values are averaged to daily discharges in m^3/s. So the decisions that are made on day one, result in a change of water level for day two.

5.4. Assumptions and simplifications

5.4.1. Water demand polders

From the interviews, it turned out that the water managers use two values to determine the water demand of the polders: 0.1 L/s/ha in normal situations and 0.3 L/s/ha during periods of drought. Moreover, it was indicated that the regional systems are designed to cope with a water supply of 0.5 L/s/ha, but this number can only be achieved with sufficient water level on the VZM. During a period of drought, extra water is needed to flush the systems and provide water for irrigation.

Before applying these values in the tool, it is necessary to check whether a value of 0.3 L/s/ha is a sufficient water supply during a period of drought. Therefore, for the summer of 2018, the precipitation deficit was determined. The water supply was then converted into precipitation values and incorporated into the precipitation deficit. Six scenarios were evaluated: water supply of 0.1, 0.3 or 0.5 L/s/ha for every day, or a water supply of 0.1, 0.3 or 0.5 L/s/ha for every day there was no precipitation. The value of 0.5 L/s/ha was evaluated to see what the influence would be in the scenario when the system is at design capacity. The precipitation deficit calculated with the irrigation is defined by:



1. Vul onderstaande gegevens in

Datum	11/06/2021	
Afvoer Rijn bij Lobith	1300	m3/s
SPEI	-1	-
Windrichting	0	-
Windkracht		Bft.
Zoutconcentratie	380	mg/L
Peil VZM	-0.01	m
Opp. VZM	6018	ha

2. Lees het onderstaande advies

Advies:

Gebaseerd op de afvoer van de Rijn is de inlaat bij VZM geen probleem. De snelheid waarmee water ingenomen kan worden heeft geen restricties. Gebaseerd op de zoutconcentratie in het VZM wordt aanbevolen om te spoelen met 2 kokers met een daggemiddelde van 45 m3/s tot de concentratie van 370 mg/L bereikt is om vervolgens nog maar met 1 koker te spoelen. Op dit moment bevinden de volgende gewascategoriën in het groeiseizoen: gras, maïs, bieten, boomgaard, overige gewassen. De watervraag naar de polders, gebaseerd op de SPEI en het groeiseizoen is 0.1 De windrichting kan blauwalgen verplaatsen naar de inlaten van WSSS.

3. Vul de verwachtingen in en maak keuzes

Watervraag	0.1	L/s/ha
Uit te breiden oppervlakte	13838	ha
Aanvoer WSBD Moerdijk	nee	
Uit gaan van delta- en klimaatscenario:	ja	
Jaar	2050	
Deltascenario / Klimaatscenario	stoom / WH	

					Gebruik # kokers bij:		Inlaten open voor de volgende polders						
	Verwachte neerslag [mm]	e evaporati e [mm]	Afvoer Dintel [m3/s]	Afvoer Vliet [m3/s]	Inlaat VZM	Kokers Bath	Goeree-Overflakkee	Tholen	St. Philipsland	Reigersberg	PAN-polders	Uit te breiden opp.	Daling peil [m]
11/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	
12/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	2	1	nee	ja	ja	ja	ja	nee	-0.013
13/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	0.013
14/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	-0.009
15/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	-0.009
16/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	0	1	nee	ja	ja	ja	ja	nee	-0.011
17/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	0	nee	ja	ja	ja	ja	nee	-0.035
18/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	0	nee	ja	ja	ja	ja	nee	0.017
19/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	0	1	nee	ja	ja	ja	ja	nee	0.017
20/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	-0.036
21/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	2	1	nee	ja	ja	ja	ja	nee	-0.008
22/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	0.016
23/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	-0.011
24/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	2	1	nee	ja	ja	ja	ja	nee	-0.006
25/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	0.019
26/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	2	1	nee	ja	ja	ja	ja	nee	-0.002
27/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	0.015
28/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	-0.015
29/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	2	1	nee	ja	ja	ja	ja	nee	-0.014
30/06/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	0.011
01/07/2021	[redacted]	[redacted]	[redacted]	[redacted]	1	1	nee	ja	ja	ja	ja	nee	-0.013

4. Gebaseerd op de ingevulde data, is dit de voorspelling voor het gewogen peil van het VZM:

Figure 5.3: The Dashboard of the prototype DSS

$$precipitationdeficit(t) = precipitationdeficit(t-1) + E(t) - (P(t) + I(t))[mm] \tag{5.1}$$

Here $I(t)$ is the amount of millimetres irrigation based on 0.1, 0.3 or 0.5 L/s/ha. In Figure 5.4, the different scenarios are plotted. It can be observed that a supply of 0.3 L/s/ha already reduces the precipitation deficit considerably. The case where 0.3 L/s/ha is added on days with no precipitation is more likely to occur than adding fresh water everyday. Excess rainfall in the polders that is not able to infiltrate needs to be released into the VZM to prevent the potential water levels to rise too high and agricultural land to become too wet. In the worst case, flooding of the canals can occur. From the interviews, it became clear that in the polders, there is a small trade-off between water shortage and excess water. In order to prevent excess water, one could assume that it is not desirable to supply with 0.3 L/s/ha on days with rain. Another observation from the graph is that with a supply of 0.5 L/s/ha, the precipitation deficit would be negative for the whole summer period. Indicating there is more water available than would potentially evaporate. When translating this to a plot of land, this would mean that all the pores of the soil are fully filled with water. Excess water can only drain over land. So the soil is above field capacity. Due to seasonality, precipitation deficit always occurs as evaporation rates during the summer are higher than during the winter.

In Table 5.1, the water demand needed for the different polders in m^3/s is provided for the scenarios of 0.1, 0.3 and 0.5 L/s/ha. An important note is that the water level at the VZM should be sufficiently higher than the threshold levels of the inlets to allow a sufficient discharge.

Table 5.1: Defined water demand for the polders based on different scenarios

	Surface [ha]	Water demand based on 0.1 L/s/ha [m^3/s]	Water demand based on 0.3 L/s/ha [m^3/s]	Water demand based on 0.5 L/s/ha [m^3/s]
Goeree-Overflakke	3443	0.34	1.03	1.72
Tholen	10754	1.08	3.23	5.38
St. Philipsland	1930	0.19	0.58	0.97
Reigersbergsche polder	1248	0.12	0.37	1.35
PAN-polders	2700	0.27	0.81	6.92

There are plans to create a fresh water supply to Schouwen-Duiveland by a connection from the VZM. To investigate the influences of the water demand of this area, the area of Schouwen-Duiveland that could benefit from a fresh water supply has been defined. Therefore, Schouwen-Duiveland was divided into four areas. The most western part has a higher elevation and is therefore not suitable. To the right, the second area has a surface of 8558 ha, the third has a surface of 4366 hectares and

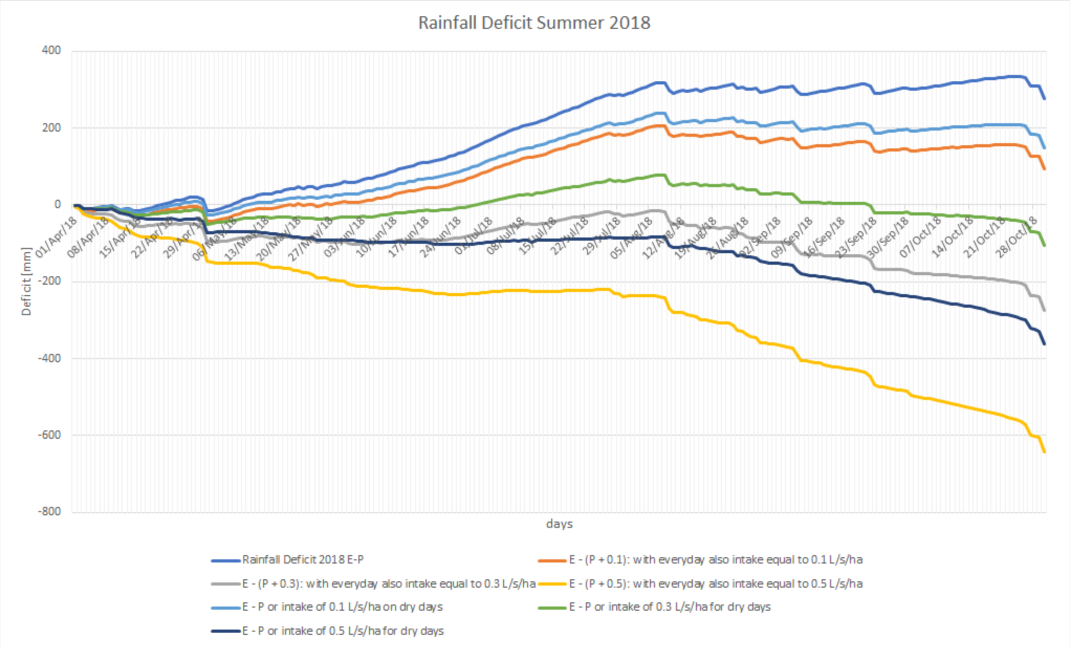


Figure 5.4: precipitation deficit 2018 and the influence of different water supply scenarios.

the most eastern area has a surface of 5280 hectares. Combined, these three areas cover 13838 hectares when all areas are suitable for fresh water supply from the VZM. In Appendix A.6, the maps for the different areas are provided. However, in the middle of Schouwen-Duivenland, a *kreekrug* is located. This is a higher elevated area aging back from the time this land was part of the estuary, before dykes were built and Schouwen-Duiveland became one island. In the *kreekrug* storage of fresh water is possible through groundwater infiltration to provide some fresh ground water during a period of drought. However, sufficient fresh water pressure must remain in order to prevent salinization of the *kreekrug*. In February 2021 research by Witteveen & Bos (Spielmann and Dekens, 2021) showed that a supply from the Krammer will not provide the desired water quality. The Eendracht or the Haringvliet will be better sources, but it all depend on the costs of such a system, which is expected to turn out high.

5.4.2. Growing season

The growing season of different crop types is of interest to determine the water demand by the different polders. In the DSS, this is only taken into account in the advice part to indicate to the operators which crop type is in its growing season. No further calculations are used in this version of the prototype. The different crops that are evaluated are grass, potatoes, corn, beet, orchard, onion and others. These are the same crop types as the ones that are evaluated in the Water Demand Forecasting Tool, a new software that can determine the water demand for the water boards at local scale. It is a software that takes into account numerous input arguments to determine the water demand at a high resolution. As this tool is currently under consideration to be implemented by the water boards WSHD, WSSS and WSBD, it was decided to not take into account more detailed information about the growing season. The final goal of the DSS would be that the growing season and the meteorological input arguments are combined to generate a water demand for the polders. This Water Demand Forecasting Tool could just provide that information.

5.4.3. Sea level rise

The influence of sea level rise mainly manifests itself in the amount of water that can be flushed at Bath into the Westerschelde. With a higher sea level, the available time in which the water level in the VZM is higher than the Westerschelde is shorter. In earlier research into the climate resilience of the VZM, researchers from Deltares indicate that the current maximum discharge at Bath of 135 m^3/s will reduce to 100 m^3/s when the sea level rises 50 centimetres. This can be reduced to a maximum discharge of 70 m^3/s when sea level rises to 100 centimetres relative to 2017 (Nolte et al., 2020). Based on this number, a linear relation was assumed to define the maximum available discharge at Bath according to equation 5.2. Where $Q_{Bath,max}$ is the maximum available daily discharge that can be used in Bath when all the tubes are available and h is the sea level rise in centimetres.

$$Q_{Bath,max} = -32.5 * h + 166.67 \tag{5.2}$$

The above mentioned assumption does not take into account wind direction and force. A western storm will push water into the Westerschelde, and thus heighten the water level, reducing the time available to flush water from the VZM into the Westerschelde. In the delta and climate scenarios, the predicted sea level rise (in centimetres) is presented for every scenario and used in the calculations of the DSS.

5.4.4. Precipitation and evaporation

The precipitation and evaporation data that is used as an input argument in the DSS is different for the short-term and long-term use of the DSS. For the short-term use, precipitation and evaporation data is manually inserted. Precipitation forecasts are available at a 14-day term. Evaporation forecast are not largely available. Different studies suggest to use artificial neural networks to forecast evaporation. One issue is the computation of evaporation. In the Netherlands, the KNMI uses Makkink reference evaporation, while suggested artificial neural network forecasts use Penmann evaporation (Allawi et al., 2019).

For evaluation of the long-term impact on the management of the VZM, the DSS uses 2017 precipitation and evaporation as base for the delta en climate scenarios. In these scenarios percentages of change are provided per scenario for the years 2050 and 2085. Based on the input date, the DSS automatically defines the corresponding period in 2017 and calculates the new precipitation and evaporation values for the scenario. This means that the precipitation and evaporation pattern of 2017 is used in all scenarios but the severity changes per scenario.

5.4.5. Discharge Dintel and Vliet

The discharge of the two rivers Dintel and Vliet are considered in two different ways within the DSS. For the short-term insights, one has to put in the expected discharges for both rivers. Rijkswaterstaat and WSBD have a model that does predict the discharges for a few days in advance.

For the long-term insights, the measured daily average discharges of 2018 are considered in the DSS. Depending on the period of interest, the corresponding discharges are provided. To implement the delta and climate scenarios, percentages of change are applied per scenario. This is based on research from Deltares (Nolte et al., 2020). They only found percentages of change for seasons for 2050 and 2085. No other data is available on how the discharge of the Dintel and the Vliet are expected to change due to the delta and climate scenarios. It is important to stress that the base flow of 2018 is considered, while for precipitation and evaporation data, 2017 is the base year. As a consequence, precipitation-discharge relationships do not occur. Another important factor to consider is that during a period of drought, WSBD sometimes closes the connection from the Vliet towards the VZM in order to flush more water through the Dintel. As a result, the retention time within the system is shorter, reducing the impact of Cyanobacteria. This measure is not implemented within the DSS as the total discharge from both rivers still flows into the VZM, which is used to calculate the water balance.

5.4.6. Lock operations

Different big shipping locks connect the VZM with other water bodies. In their operations, fresh water is lost or supplied to the VZM. For the analysis of the fresh water supply and/or losses in their operations, data from the 2018 drought period was obtained from Rijkswaterstaat for the Volkeraksluizen, Kreekraksluizen and the Krammersluizen. Only the Bergse Diepsluis has no available measured data while for the other locks measurements are available per lock chamber. The Kreekraksluizen, Krammersluizen and Bergse Diepsluis lose fresh water in their lock operations. The Volkeraksluizen supply the VZM with extra fresh water. In the DSS, monthly averages are taken into account. These can be found in Table 5.2. From the table, it can be observed that for the Krammersluizen, the discharge in the winter season is three times higher than during the summer growing season (1 April - 30 September). These locks will undergo a refurbishment which will be finished in 2025. The current system to divide fresh and salt water will be improved and it is expected that an average of 29 m^3/s fresh water is needed to prevent sea water intrusion in the VZM. However, due to the growing season of the blue mussel which is harvested in the Oosterschelde, the fresh water must supply into this sea water environment must be as low as possible. Therefore, as less as possible fresh water may be used in the lock operations. A new system consisting of small air bubbles will be implemented and help to reduce the salt intrusion into the VZM due to lock operations (Wijsman, 2020).

Table 5.2: Discharges to and from the VZM due to lock operations. Negative values indicate fresh water is lost in the lock operation and positive values indicate fresh water supply towards the VZM due to lock operations.

	Kreekraksluizen $[m^3/s]$	**Krammersluizen** $[m^3/s]$	**Volkeraksluizen** $[m^3/s]$	**Bergse Diepsluis** $[m^3/s]$	**Som Q** $[m^3/s]$
January	-2.00	-29.00	2.00	-1.00	-30.00
February	-2.00	-29.00	2.00	-1.00	-30.00
March	-2.00	-29.00	2.00	-1.00	-30.00
April	-1.26	-9.22	2.04	-1.00	-9.44
May	-1.19	-9.27	2.42	-1.00	-9.04
June	-2.71	-9.60	2.55	-1.00	-10.75
July	-3.25	-9.66	1.73	-1.00	-12.18
August	-3.86	-9.45	1.40	-1.00	-12.91
September	-4.70	-9.08	1.85	-1.00	-12.93
October	-4.74	-9.00	1.80	-1.00	-12.94
November	-2.00	-29.00	2.00	-1.00	-30.00
December	-2.00	-29.00	2.00	-1.00	-30.00

5.4.7. Entry volume

The main driver for the water supply of the VZM is the amount of water that enters at the Volkeraksluizen through the discharge sluices. The availability depends on the discharge of the Rhine as discussed in Chapter 4. When the discharge of the Rhine at Lobith is below 800 m^3/s, the inlet of the VZM must be closed. When the discharge is higher than 3000 m^3/s, the inlet is also closed to prevent a high amount of sediment entering the VZM. Within the DSS, these values are taken into account. There are situations in which it is preferred that the intake of water into the VZM is slower that normal. For example, when the discharge at the Rhine is lower and there is a western wind/storm. This could increase the salinization of the Nieuwe Maas as water from the North Sea intrudes into the Oude Maas and enters the Haringvliet and Hollandsch Diep via Spui or Dordtse Kil. To prevent this, Rijkswaterstaat could ask to reduce the inlet of water into the VZM to provide sufficient flow against this intrusion. Therefore, in the tool, a warning is implemented that when a discharge is below 1200 m^3/s, the speed at which water is let into the VZM must be communicated with *Rijkswaterstaat district West-Nederland Zuid*.

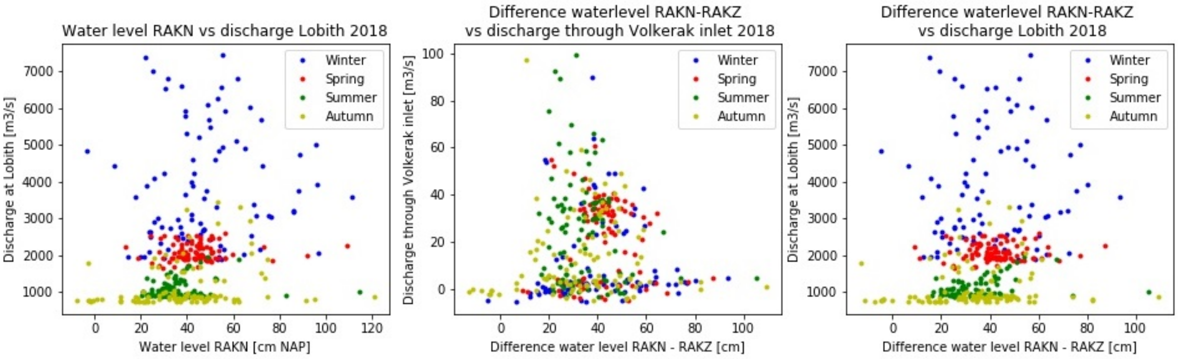


Figure 5.5: Analysis into the supply factors of the VZM per season

The inlet of the VZM works by inlet gates that can be set at a certain height. Currently, the software of Rijkswaterstaat calculates the total volume that is needed to maintain the same water level within the system, taking into account flushing operation at Bath, precipitation and the discharges of the rivers Dintel and Vliet. Based on these numbers, the discharge through the inlet is calculated and presented in numbers and percentages of opened gate. Unfortunately, there are no measurements available for percentage of opening of the gates and only an estimation of the total daily discharge per gate is provided. Of the four gates, only two gates had measurements for more years. The measurements of the other two just started in 2020. To see whether there are relations between the discharge at Lobith, the water level at the Hollandsch Diep (RAKN), the water level at the VZM (RAKZ) and the discharge through the inlet, different plots were made. These plots can be observed in 5.5. The aim was to see whether these relations could improve the approximation of possible supply towards the VZM. In the plot in Figure 5.5, only the data for 2018 is plotted. Step one was to see whether there was a relation between the discharge at Lobith and the water level at the Hollandsch Diep (RAKN). No clear relation can be observed. The spread for the winter period is quite large while the spread for the spring and summer are more clustered. Autumn has again a bigger spread. The reason that no relation can be observed can be accounted to the tidal influence and opening and closing of the Haringvliet surge barrier. The data presented in the plots only shows the average daily water level. The second step looked into a possible relation between the water level difference over the inlet at the Volkeraksluizen (RAKN-RAKZ) and the discharge through the inlet structure. It is important to note that only two out of four inlets had working measurements. Rijkswaterstaat internally organised that when the inlets were put into action, the two inlets with working measurements were used first. However, from the measurements it cannot be observed whether three or four inlets were put into action. From the second plot in Figure 5.5, significant spreads can be observed for all seasons. In the third plot, the difference in water level over the inlet structure (RAKN-RAKZ) and the discharge at Lobith is plotted. In the spring and summer period the data points are more clustered while the winter period shows a significant spread as well as the autumn period, although smaller. From the three plots, no clear relation can be obtained to link the amount of discharge through the inlet with either the discharge at Lobith or the available difference of water level over the inlet. Different reasons account for this:

- Manual operation of the inlet at the Volkeraksluizen: the inlet of the VZM is manually set to certain heights based on the advice of the software of Rijkswaterstaat. The operators can choose to heighten or lower the amount and percentage of opened gates to heighten or lower the water level of the VZM.
- Flushing of the VZM and lowering the chloride concentration starts only in February. After the growing season, water is only let into the VZM to maintain the water level according to the target level decision. From February on, more water is let in to flush the system and lower the chloride concentration for the start of the growing season.
- The Rhine discharge largely fluctuates during winter times.
- *Kierbesluit Haringvliet*: Since 2018, Rijkswaterstaat opens the Haringvlietsluizen a bit to give space for fish species like salmon to enter the Haringvliet from the North Sea and swim up the Rhine. This occurs during high tide. This influences the water level at the Hollandsch Diep. The gates are closed if the discharge of the Rhine at Lobith is below 1700 m^3/s.

5.4.8. Wind direction and force

The wind direction and force play a role in terms of chloride concentration and Cyanobacteria fields. The main goal of the DSS is to assess the influence of management of the water quantity in the VZM. The DSS does provide advice on these two water quality parameters, but the influence is not modelled. The current chloride concentration is the base for the advice on the amount of outlets that need to be used at Bath. This is based on the guidelines provided in (Herman Haas et al., 2017). Moreover, it is assumed that the wind direction and force are one of the triggers of releasing higher chloride concentration from the deeper parts of the system. Within the DSS only a warning is provided as salt concentrations are not modelled within the DSS. Wind is also the main driver for the floating Cyanobacteria fields that occur on the VZM during the Summer. Research proved that it is impossible to flush the Cyanobacteria fields by creating a flow in the system using the in and outlet points. The influence of the wind is bigger than the influence of a flow in the system (Verspagen et al., 2005). Within the DSS, management of Cyanobacteria fields are not taken into account. Only information about the direction the fields can flow to is shared to inform the water managers about the potential thread of taking in Cyanobacteria.

5.5. Validation

In fall 2020, Rijkswaterstaat performed an experiment to monitor how the the water level at the VZM develops due to certain operation (see Chapter 2.7). The results from this experiment can be used to validate the tool. As mentioned, the experiment consisted of two parts. The first part of the experiment was performed twice (part 1a and 1b). This part of the experiment is of interest in the validation of the tool as it looks into the behaviour of the water level at the VZM when the intake is closed and normal flushing operations occur at Bath.

In experiment 1a, the water level dropped from +0.15 m NAP to -0.07 m NAP in six days and 22 hours, which is equal to 3.18 cm/day. The water level of -0.10 m NAP was not reached as the experiment was halted due to an automatic maintenance cycle resulting in opening of the inlet locks. During experiment 1b, the water level took six days and two hours to drop from +0.15 m NAP to -0.10 m NAP, which is equal to 3.94 cm/day. This is slightly faster than experiment 1a. The difference between the two experiments can be assigned to the precipitation that occurred during experiment 1a and a smaller available discharge at Bath (Pans and Nolte, 2021). In Figure 5.6, the measured water level and the projected water level from the DSS are presented.

To simulate the experiments, the weather data (precipitation and evaporation) and discharge measurements for the Dintel and Vliet were collected and used as input. It can be observed that the approximation of lowering the water level is slightly better than heightening the water level. This can be appointed to the fact that the tool makes use of equivalent discharges that it is able to flush at Bath. The value for one channel at Bath is based on the measurements performed over the past years and therefore closer to the actual discharge at Bath. When observing the results, the heightening of the water level of the VZM was less well represented by the tool than lowering the water level. For part 1a an average daily discharge through the inlet of 36 m^3/s was measured, while the tool needs 63 m^3/s and for part 1b an average of 45 m^3/s was measured against 78.75 m^3/s needed by the tool. Another clear observation is the fact that the tool and the measurements are off certain hours. The tool only calculates one value for a day, while the measurements were taken with ten minutes interval.

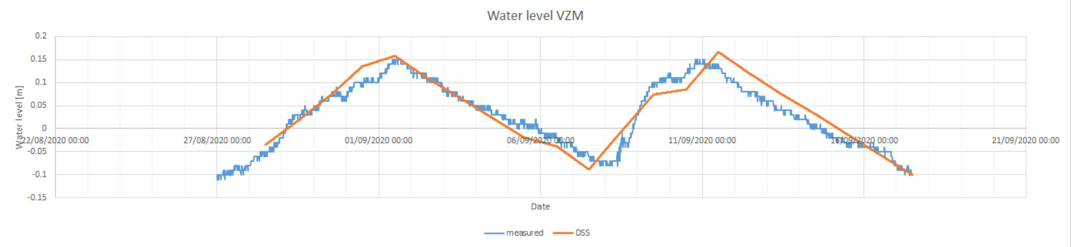


Figure 5.6: Comparison of the measured water level and the projected water level during Praktijkproef 1a and 1b

5.6. Result from different scenarios in the decision support system

To get the best impression of how the tool works and the insights that can be gathered, it is advised to open the tool and look around by using different settings to see the influence on the water level of the VZM. In this section, two scenarios will be evaluated for 2050 and 2085. The scenarios are the delta scenario *Stoom* which is based on the climate scenario WH (higher world wide temperature change and significant change in the circulation process) and the deltascenario *Rust* which is based on the climate scenario GL (moderate increase in temperature change worldwide and minor change in circulation process). In Appendix A.7, the numerical values per scenario are provided. All scenarios start on August 1st. The reduces target levels are not in place after July 15th and low discharge values in the Rhine occur more often during the end of summer or the start of autumn when all snow has melted. Furthermore, in this analysis only the water level change is evaluated as performed during the drought mitigation experiment. So, the initial water level is +0.15 m NAP and it is research how long it takes until a water level of - 0.10 m NAP is reached. For every scenario, three management choices for flushing at Bath are evaluated:

1. No outlet at Bath

2. Use of one discharge channel every two days, which is equal to skipping one low tide every time.
3. Use of one discharge channel every day

For every choice, the difference between 0.1 and 0.3 L/s/ha are evaluated.

5.6.1. 2050

For the delta scenario ”Stoom”, the results can be observed in Table 5.3. From the table it can be observed that no flushing operations at Bath can overcome a period of 24 days when a water supply to the polders of 0.3 L/s/ha is used. When a water supply to the polders of 0.1 L/s/ha is considered, this period can be extended to 45 till 50 days. When a half flushing operation is used; where water is released every second low tide at Bath, the water level decreases faster. The period the VZM can withstand without a fresh water supply from the Hollandsch Diep has decreased to ten days when a water supply to the polders of 0.3 L/s/ha is considered. For the water supply of 0.1 L/s/ha, the duration of this period is 14 days. For normal flushing operations, only six or seven days is the maximum amount the VZM can withstand without a fresh water supply from the Hollandsch Diep. Due to an expected sea level rise of 40 centimetres in this scenario, the discharge of one channel at Bath has been reduced to an average of 18.2 m^3/s.

Table 5.3: Results into the propagation of the water level of the VZM based on climate and delta scenario ”Stoom” for 2050.

No outlet at Bath:	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-1.1	cm/d	-0.5	cm/d
reached -0.10 m NAP after	24	days	45-50	days

1 discharge channel every 2 days	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-2.8	cm/d	-1.9	cm/d
reached -0.10 m NAP after	10	days	14	days

1 discharge channel at Bath	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-4.2	cm/d	-3.7	cm/d
reached -0.10 m NAP after	6	days	7	days

When comparing the scenarios ”Stoom” and ”Rust” for 2050, the most interesting observation is that only when the outlet at Bath is closed, the rate of the lowering of the water level at the VZM is lower for ”Rust” than for ”Stoom” (see Table 5.4). For the other two options, the water level decreases more rapidly during ”Stoom” than in ”Rust”. In ”Rust” the differences between the summer precipitation and the yearly evaporation in 2050 compared to the reference 2017 are small, +1% and + 3% respectively. For ”Stoom” this is -13% and +11%. One would suspect that due to these values, the water level in the VZM would drop faster in ”Stoom”, but this cannot be observed during everyday flushing operation or every second low tide. This can be observed for both the 0.1 and 0.3 L/s/ha water supply cases.

Table 5.4: Results into the propagation of the water level of the VZM based on climate and delta scenario ”Rust” for 2050.

No outlet at Bath:	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-1	cm/d	-0.4	cm/d
reached -0.10 m NAP after	25	days	60-65	days

1 discharge channel every 2 days	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-3.2	cm/d	-2.2	cm/d
reached -0.10 m NAP after	8	days	12	days

1 discharge channel at Bath	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-5.2	cm/d	-4	cm/d
reached -0.10 m NAP after	5	days	7	days

5.6.2. 2085

In Table 5.5, the values for the scenario ”Stoom” in 2085 are presented. When comparing the 2050 and 2085 data, the 2085 scenario shows higher water lowering rates for the options no flushing at Bath or with every second low tide. However, for normal flushing operations, the water level lowers more rapidly in 2050 than 2085. A reason for this is that in the 2017 reference data, an intense rainfall event occurs at the seventh day. On the sixth day the water level has dropped to -0.09 m NAP. As the average rate is considered over the period the water level has dropped from +0.15 m NAP to the first event the water level is below -0.10 m NAP, this rainfall event is taken into account and drastically lowers the lowering rate. The lowering rate in the period from +0.15 m NAP to -0.09 m NAP is 4.8 cm/day for a water supply of 0.3 L/s/ha and 3.7 cm/day for a water supply towards the polders of 0.1 L/s/ha.

Table 5.5: Results into the propagation of the water level of the VZM based on climate and delta scenario ”Stoom” for 2085.

No outlet at Bath:	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-1.3	cm/d	-0.7	cm/d
reached -0.10 m NAP after	20	days	35-40	days

1 discharge channel every 2 days	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-2.9	cm/d	-1.9	cm/d
reached -0.10 m NAP after	9	days	13	days

1 discharge channel at Bath	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-3.8	cm/d	-3.3	cm/d
reached -0.10 m NAP after	7	days	8	days

For the scenario of ”Rust” in 2085, the calculations show that the rate of water level decrease is higher in this scenario for one discharge channel every second low tide or every day for a water supply to the polders of 0.3 L/s/ha. The results can be found in Table 5.6. Compared to 2050, the rate of lowering the water level at the VZM is only lower for the case of normal flushing operations at Bath. This can be assigned to the fact that the tool currently calculates daily water level values. As the time span reduces, the differences get smaller. Now, the calculation only stops after the value of -0.10 m NAP has been reached, without taking into account the exact moment of the day. Especially during such a short period of just five days, a few hours can already make a difference.

Table 5.6: Results into the propagation of the water level of the VZM based on climate and delta scenario ”Rust” for 2085.

No outlet at Bath:	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-1.2	cm/d	-0.6	cm/d
reached -0.10 m NAP after	21	days	40-45	days

1 discharge channel every 2 days	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	3.2	cm/d	-2.5	cm/d
reached -0.10 m NAP after	8	days	11	days

1 discharge channel at Bath	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-5.1	cm/d	-3.9	cm/d
reached -0.10 m NAP after	5	days	7	days

The results mentioned in the tables before look into the water buffer that can be created between -0.10 and +0.15 m NAP. It can be observed that with normal flushing operations only a maximum period of seven days can be bridged. For flushing operations every two days, this is slightly lengthened to a maximum of 14 days. However, research showed that in the past, for the summer period the maximum duration for a period without fresh water supply was 16 days. For yearly data, this was even longer: one event lasted for 82 days, while the second longest event lasted 42 days. This indicates that when flushing operations are desired, a bigger buffer should be created. Only without flushing the system, the measured period of 16 days can be bridged. Results from the practical trial drought show that without flushing, the chloride concentration will slowly increase. Lengthening the period can be achieved by heightening the initial water level or lowering the minimum allowed water level. As lowering the minimum allowed water level reduces the discharge at Bath, this option is not considered within this research. For heightening of the water level, the maximum water level depends on the water level at the Hollandsch Diep. The water flows by gravity into the VZM. Therefore, based on historical water levels, the maximum possible water level should be determined.

For the period 2010-2020, the water level at the Hollandsch Diep (measuring station RAKN), was plotted for when the discharge at Lobith was between 800 and 1000 m^3/s. This can be observed in Figure 5.7. The restriction to only take the water levels at the Hollandsch Diep when the discharge at Lobith is between 800 and 1000 m^3/s was chosen as this is the final stage at which the water level at the VZM could be heightened. Data from the discharge at Lobith show that during the summer period, fluctuations in the discharge are small.

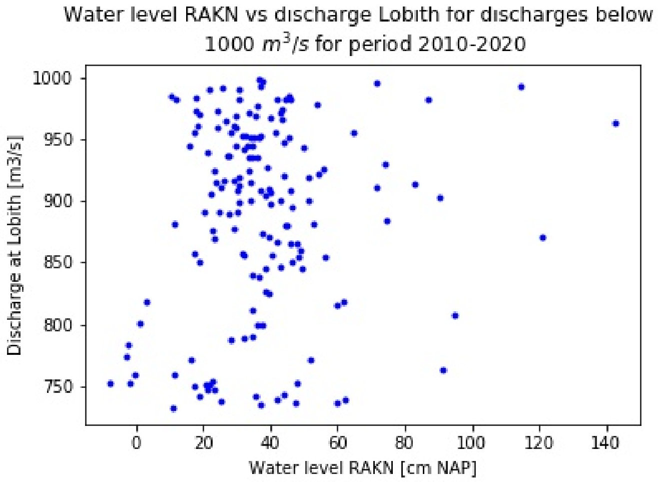


Figure 5.7: Plot of water level at Hollandsch Diep (measuring point RAKN) and the measured discharge at Lobith for discharge values between 800 and 1000 m^3/s for the period 2010-2020.

From the graph in Figure 5.7, it can be observed that most of the measured water level values at RAKN can be found between +0.20 and + 0.50 m NAP. Above +0.50 m NAP, only a few data points can be observed. It is important to stress that these values are average daily values. The water level at the Hollandsch Diep is under tidal influence. On average, the amplitude is between 10 and 15 centimetres. As water flows from the Hollandsch Diep into the VZM by gravity, the water level of the VZM cannot become higher than at the Hollandsch Diep. Furthermore, the rate of the inflow depends on the difference of water levels over the inlet at the Volkeraksluizen. The tidal influence can increase and decrease the inflow thereby slightly. The wind only slightly influences the water level at the Hollandsch Diep. When wind velocities are high and the coming from the west, the influence is bigger. However, at this point, the chance of backwards salinization is increasing, which could result in closure of the inlet at the Volkerak. Taking the above mentioned points into account, the maximum water level of +0.50 m NAP is considered as the maximum water level that can be used as initial water level at the VZM. This water level does not take into account the open connection with the Dintel and the Vliet in the evaluation of the period without a fresh water supply. A small 'back of the envelope' calculation was performed on the economic feasibility of a solution where these open connections were closed of and pumping stations were installed (see Appendix A.9). This showed that it is not economic feasible to install pumping stations at Dinteloord and Benedensas.

Based on the rate of lowering the water level for the different scenarios and with the different demands to the polders, the required initial water level was determined. In Tables 5.7, 5.8, 5.9 and 5.10 the result for the different scenarios can be found. The output of the tables provide the required initial value that needs to be set in order to bridge the required period without a fresh water supply. When the required initial water level is higher than +0.50 m NAP, the value is left blank as it was determined that higher initial values were not possible.

Table 5.7: Needed initial water level to sustain the desired duration for scenario 2050 Stoom/WH. When the required water level is higher than +0.50 m NAP, the scenario is not considered.

2050 Stoom/WH						
	0.1 L/s/h			0.3 L/s/ha		
Duration	No outlet	1 discharge channel every 2 days	1 discharge channel daily	No outlet	1 discharge channel every 2 days	1 discharge channel daily
5 days	-0.08 m NAP	-0.01 m NAP	+0.09 m NAP	-0.05 m NAP	+0.04 m NAP	+0.11 m NAP
10 days	-0.05 m NAP	+0.09 m NAP	+0.27 m NAP	+0.01 m NAP	+0.18 m NAP	+ 0.32 m NAP
15 days	-0.03 m NAP	+0.19 m NAP	+0.46 m NAP	+0.07 m NAP	+0.32 m NAP	
20 days	0.00 m NAP	+0.28 m NAP		+0.12 m NAP	+0.46 m NAP	
25 days	+0.03 m NAP	+0.38 m NAP		+0.18 m NAP		
30 days	+0.05 m NAP	+0.47 m NAP		+0.23 m NAP		

Table 5.8: Needed initial water level to sustain the desired duration for scenario 2050 Rust/GL. When the required water level is higher than +0.50 m NAP, the scenario is not considered.

2050 Rust/GL						
	0.1 L/s/h			0.3 L/s/ha		
Duration	No outlet	1 discharge channel every 2 days	1 discharge channel daily	No outlet	1 discharge channel every 2 days	1 discharge channel daily
5 days	-0.08 m NAP	+0.01 m NAP	+0.10 m NAP	-0.05 m NAP	+0.06 m NAP	+0.16 m NAP
10 days	-0.06 m NAP	+0.12 m NAP	+0.30 m NAP	+0.00 m NAP	+0.22 m NAP	+0.42 m NAP
15 days	-0.04 m NAP	+0.23 m NAP	+0.50 m NAP	+0.05 m NAP	+0.38 m NAP	
20 days	-0.02 m NAP	+0.34 m NAP		+0.10 m NAP		
25 days	+0.00 m NAP	+0.45 m NAP		+0.15 m NAP		
30 days	+0.02 m NAP			+0.20 m NAP		

Table 5.9: Needed initial water level to sustain the desired duration for scenario 2085 Stoom/WH. When the required water level is higher than +0.50 m NAP, the scenario is not considered.

2085 Stoom/WH						
	0.1 L/s/h			0.3 L/s/ha		
Duration	No outlet	1 discharge channel every 2 days	1 discharge channel daily	No outlet	1 discharge channel every 2 days	1 discharge channel daily
5 days	-0.07 m NAP	-0.01 m NAP	+0.07 m NAP	-0.04 m NAP	+0.05 m NAP	+0.09 m NAP
10 days	-0.03 m NAP	+0.09 m NAP	+0.23 m NAP	+0.03 m NAP	+0.19 m NAP	+ 0.28 m NAP
15 days	0.00 m NAP	+0.19 m NAP	+0.40 m NAP	+0.10 m NAP	+0.34 m NAP	+0.47 m NAP
20 days	+0.04 m NAP	+0.28 m NAP		+0.16 m NAP	+0.48 m NAP	
25 days	+0.08 m NAP	+0.38 m NAP		+0.23 m NAP		
30 days	+0.11 m NAP	+0.47 m NAP		+0.29 m NAP		

In Appendix A.8, more calculations can be found on needed water levels. In the Tables A.5 and A.6, the needed amount of days to overcome a period of 60 days with no water supply are calculated per scenario for the years 2050 and 2085 respectively. This the result of a small tool that was created

Table 5.10: Needed initial water level to sustain the desired duration for scenario 2085 Rust/GL. When the required water level is higher than +0.50 m NAP, the scenario is not considered.

2085 Rust/GL						
	0.1 L/s/h			0.3 L/s/ha		
Duration	No outlet	1 discharge channel every 2 days	1 discharge channel daily	No outlet	1 discharge channel every 2 days	1 discharge channel daily
5 days	-0.05 m NAP	+0.06 m NAP	+0.16 m NAP	-0.08 m NAP	+0.01 m NAP	+0.10 m NAP
10 days	0.00 m NAP	+0.22 m NAP	+0.42 m NAP	-0.06 m NAP	+0.12 m NAP	+0.30 m NAP
15 days	+0.05 m NAP	+0.38 m NAP	+0.68 m NAP	-.0.4 m NAP	+0.23 m NAP	+0.50 m NAP
20 days	+0.10 m NAP	+0.54 m NAP		-0.02m NAP	+0.34 m NAP	
25 days	+0.15 m NAP			0.00 m NAP	+0.42 m NAP	
30 days	+0.20 m NAP			+0.0.2 m NAP		

to calculate the desired initial water level for a desired period. Per scenario, the lowering rate of the water level is presented in cm/d. This rate was determined by the DSS. Based on this lowering rate, the theoretical extra water level to store the amount of water that is needed to overcome a period of 60 days is presented in cm. This is then calculated back to a water level relative to NAP in metres.

5.7. From prototype to implementation

The DSS that is presented in this thesis, still is a prototype. In short, various suggestions will be made that are needed to go from prototype to implementation of the DSS.

First of all, this prototype needs many input arguments that has to put in manually. Examples are: discharge Rhine, Dintel and Vliet, meteorology, water level of the VZM, chloride concentration and determining the water demand. In an ideal situation, for the short-term prediction, it is desirable to have a system that automatically provides the precipitation, evaporation, wind direction and wind force prediction from the KNMI. From the network of Rijkswaterstaat, the measurements of the discharges of the Rhine, Dintel and Vliet should be obtained as well as the actual water level and the chloride concentration at the VZM. This could reduce the chance of errors and increase the operation speed.

An important factor in managing the VZM for Rijkswaterstaat is maintaining a chloride concentration below 450 mg/L during the growing season. After water level management, this is the most important factor. In this prototype, the chloride concentration is only taken into account in the advice part to come up with the amount of locks that need to be used at Bath to release water into the Westerschelde or to warn for rising chloride concentrations from the deeper parts during a western storm. Implementing a prediction for the chloride concentration (with confidence interval) could contribute significantly to the insights this tool provides to the water managers of the VZM. However, the complexity of the chloride balance was too big to take into account for this tool. In different trials, chloride balances were created, but these did not represent the chloride concentration well.

At the moment, different models are being created at different companies to better model the chloride dynamics of the VZM. Implementation of these models could make it possible to observe the impact of different management decisions on the chloride concentration. It could be beneficial to implement a chloride balance after the refurbishment of the Krammersluizen, when the new water separating mechanism is put in place, reducing the salt load towards the lake.

One of the main assumptions that was made during the creation of the tool was a closed water balance. Variousresearches were not able to make a fully closed water balance (Pans and Nolte, 2021). Still, leakage and seepage occurs in the system. This is difficult to quantify, but better insights in these parts of the water balance could increase the predictability of the water level.

6

Discussion, conclusion and recommendations

In this chapter, at first some points of discussion are provided. Next, the answers to the research questions are given in the conclusion. Finally, based on the insights gained during this thesis, recommendations will be given for topics for further research.

6.1. Discussion

The scope of this thesis was to look into the water quantity aspect of creating a temporarily buffer at the VZM. Water quality parameters, chloride concentration and Cyanobacteria were not taken into account in the DSS in detail. Only suggestions and warnings were provided for the user of the DSS. The prototype that is presented in this thesis does not implement the effect of water quantity decisions onto the water quality and vice versa. For example, when the flushing at Bath is stopped, beneficial feedback in terms of a stagnant or increasing water level is observed. In the meantime, the chloride concentration is increased, as insights from the practical trial showed. Currently, only an advice is provided for the amount of discharge channels to be used at Bath, based on the current chloride concentration. The DSS does not provide the user insight how long this amount of discharge channels should be used. Thereby a lot of water could get lost in unnecessarily flushing the system.

An implementation of a graph that represents the chloride concentration would be of great benefit to provide this insight. This could combine the water quantity and quality aspect of water management of the VZM. The impact in management decisions on one of the two factors can be observed in the other. Different attempts were performed to create a relatively simple chloride balance to obtain insights in the development of the chloride concentration. These turned out to be not representative. Therefore, it was decided to leave this out of the DSS.

Implementation of water quality, especially chloride concentration, could also influence the flushing regime at Bath. Now, only three management options are evaluated. These consisted of: normal flushing operations, a flushing operation every second low tide or closing of the outlet at Bath. Combining both water quantity and water quality could result in insights in whether more or less flushing operations are needed. Thereby optimizing the operation. A lower chloride concentration reduces the amount of flushing operations needed and thereby lengthening the period that no fresh water supply from the Hollandsch Diep is needed. A (too) high(er) chloride concentration needs more flushing cycles, thereby reducing the length the VZM can stand without a fresh water supply from the Hollandsch Diep.

Different researches have been performed on the water balance of the VZM. They all concluded that it was not possible to close the water balance completely. The rest term was assigned to leaking structures and seepage. No actual research was performed into quantification of these posts on the water balance. In this tool, a water balance was used to calculate the predicted water level at the VZM. The major assumption that was made is that the water balance was closed, while there still exists a rest term. In Table 2.2 an example of a simple water balance is provided for the VZM for the summer of 2018. The rest term is roughly 12% of the total water balance for this period. For the water balance in the DSS, seepage and leakage were not taken into account. Another part of the water balance that was not taken into account is the water from the polders that is pumped back into the VZM in anticipation of or after a heavy rainfall event. For drought management this is less significant as (almost) no rain occurs. However, for daily operation, it would be beneficial to implement this post next to leakage and seepage to reduce the rest term and optimize water level management even more.

The water demand of the polders in this prototype is based on the input of the operator: 0.1 or 0.3 L/s/ha. This is based on the interviews with the water managers from the water boards. In the tool, it is either 0.1 or 0.3 L/s/ha but in reality, the discharge towards the polders depends on the water level of the VZM and the level of the threshold of the inlet. Another aspect that is related to the water demand towards the polders is how it is implemented in the current prototype. The initial plan was to base the water demand of the polders on the SPEI value and the growing season. However, easy implementation of the SPEI into this prototype was not possible as the code made on another platform. Moreover, the growing season of different crop types do not follow strict dates. For example, potato farmers, stop irrigation roughly one month before harvesting. So there is a difference between the growing season and the irrigation season.

Another point of discussion are the assumptions and simplifications that were made for this prototype as discussed in 5.4. In the validation process, it can be observed that there are differences between the observed water level decline and the decline of the calculated water level using the DSS. One of the main simplification is the timescale. The DSS only calculates the average daily water level, while the measured data from the experiment is in ten minutes intervals. The choice was made to use daily data as the different input arguments that are measured differed between daily values, hourly values or ten minutes intervals.

Moreover, in the suggested prototype, the amount of water that can enter through the inlet is set equal to the amount of water that can be discharged at Bath. For the inlet, the DSS works with equivalent discharge channels at Bath. Sea level rise will reduce the total discharge at Bath per channel in the future. As a result, the modelled discharge into the VZM will also reduce for the same scenarios. The decision was made to make use of this simplification as data on the water level at the Hollandsch Diep and the Volkerak and the discharge through the inlet did not show any relations for the period 2010-2020. This is due to the tidal influence at the Hollandsch Diep, the opening of the Haringvliet surge barrier for fish migration and the manual operation of the VZM. This simplification reduces the ability to regulate the flow into the VZM through the inlet at the Volkeraksluizen. This is in contrast to the current operational software that suggests the amount of gates and the opening level for the gates that is needed to maintain a constant water level at the VZM based on a water balance. The operator can manually adapt the settings to lower or heighten the water level of the VZM.

Another point of interest is that for future forecasts the precipitation pattern is based on data from 2017. This year is used as reference year. The KNMI climate scenarios calculate percentages of change for precipitation and evaporation based on 2017. In the calculations, these percentages are applied to the measured values of 2017. However, for the discharges of the Dintel and Vliet the data is based on 2018. So, firstly, there is no distinction in the different scenarios. Secondly, the precipitation patterns are different for 2017 and 2018. A high precipitation event will not result in higher discharges at the rivers in the future scenarios (precipitation-discharge relation).

Furthermore, this research does not take into account the conflict of the desired water level for WSSS and WSBD during an extreme drought event. WSBD desires a low water level at the VZM in order to flush its system while WSSS desires a high water level to have a sufficient fresh water supply (RHDHV, 2020). Which one is of best interest for the entire VZM is out of scope in this thesis. However, it is important to keep in mind that with an open connection between the Vliet, Dintel and the VZM, a higher water level at the VZM does influence the regional system of WSBD. The ability to flush its own system and reduce Cyanobacteria in its system will be reduced.

A last point of discussion is that the duration for a period with a water supply lower than 800 m^3/s is now based on historical data. Two periods were found. The first is only looking into the period April 1st till September 30th which incorporates the growing season. In this period only in two years the discharge was below the threshold with a maximum duration of 16 days. When looking at yearly data, the longest single event was 63 days. However, this event took place during autumn. Then the chloride concentration must not be taken into account, and on average, precipitation levels are higher than in the summer period. This will not necessary lead to problems for the VZM. In the results both values are taken into consideration but they differ quite a lot.

6.2. Conclusion

The main objective of this research was to gain understanding into the development of the water level of the VZM during a period of drought and to visualize how water management interventions influence the water level of the VZM. The main research question is: *Could (temporarily) heightening of the water level at the Volkerak-Zoommeer be used as a drought mitigation measure for the water users of the Volkerak-Zoommeer?*

To answer the main research question, the research was split into three parts. First a literature study was performed on drought and drought indicators and indices. Next, interviews with the different water boards took place to gain understanding in their system and how they monitor and manage their water system during a drought event. Last, a tool was created to give insight into how management decisions could influence the water level of the VZM during a drought event in different scenarios.

1. **How is drought defined for the water users of the Volkerak-Zoommeer?**

The water boards WSHD, WSSS and WSBD have different drought definitions in their management areas. From the interviews, it turned out that WSHD only speaks of drought when they are not able to maintain the water level in the regional system as defined in the local water level decisions. WSSS is still looking for suitable drought indicators and indices to use. They see great potential in the Water Demand Forecasting Tool that is currently under evaluation. WSBD defines drought when they are unable to supply the water or when they cannot flush the regional system and prevent Cyanobacteria fields. Special emphasis is put on the latter. The water board is really focused on preventing nuisance from Cyanobacteria in its system. They monitor the retention time for different trajectories. Therefore, measurements are performed on the discharge of the streams, Cyanobacteria concentrations and water temperature.

For Rijkswaterstaat, the water level at the VZM and the chloride concentration are the main drought indicators that are currently used.

During the interviews with the different representatives of the water boards, insight was also gathered in how the different water boards manage drought. WSHD and WSSS focus a lot on communication to their users. It proves that short communication lines and clear communication can largely influence how their users deal with different measures the water boards have to take. The water boards indicate that during a period of drought, they are sometimes forced to take in water with a worse quality than required. This is for example to flush the local system and prevent Cyanobacteria formation or higher chloride concentrations due to seepage. Also safety of the local system is important. When water levels are becoming too low, dykes and other structures can dry out. Maintaining a sufficient height in the system in this case more important than water quality.

For the three water boards, drought management is based on the insights and the experience of the operational water managers. WSHD and WSSS do not use many drought indicators and indices. They mention that operational water managers are the main factor in drought management and management is based on their expertise and insights. This is in contrast with WSBD which uses multiple indicators to monitor drought propagation and assign management decisions. WSSS clearly mentioned they are looking for drought indicators to substantiate their decisions towards the local water users and the board of the water board.

Based on the literature review, the insights from the thesis of R. Weijers (Weijers, 2020) and the calculations of the different drought indicators and indices, it is advised for Rijkswaterstaat to take into account a rolling 30-day SPEI. For the water boards, the soil moisture and the groundwater levels are suggested as drought indicators due to the local scale they represent. When the Water Demand Forecasting Tool will be applied, these factors will also be taken into account.

2. What is the water demand of the water users of the Volkerak-Zoommeer while experiencing a period of drought?

From the interviews, it became apparent that two values for the water demand in the polders are being used: 0.1 L/s/ha (which is equal to 0.1 mm/d) during normal situations and 0.3 L/s/ha during dry situations. The regional systems are designed at a maximum supply of 0.5 L/s/ha.

It was tested whether the demand values 0.1 and 0.3 L/s/ha were sufficient as water supply in the summer of 2018. Therefore, the precipitation deficit was calculated and the values of 0.1, 0.3 and 0.5 L/s/ha were taken into account as irrigation. Two versions were regarded: irrigation everyday or irrigation when there was no precipitation. It turned out that the scenarios with a supply of 0.3 L/s/ha on every day, 0.5 L/s/ha every day or 0.5 L/s/ha on dry days lead to negative precipitation deficit values for the whole period. This indicates that in theory, there will be a water surplus as there is more precipitation than evaporation. With a supply of 0.1 L/s/ha, the deficit was still around 200 millimetres. A supply of 0.3 L/s/ha on days with no precipitation reaches a maximum precipitation deficit around 50 millimetres. From this analysis the conclusion can be drawn that a supply of 0.5 L/s/ha leads to water surplus and 0.1 L/s/ha leads to water shortage during a period of drought. In future stages of the development of a tool, the Water Demand Forecasting Tool could provide more exact values in the exact water demand at a regional scale as it takes in many input arguments (e.g. crop type, soil type, growing stage, ground water tables, NDVI etc.) and it will be able to determine the water demand at a high resolution (per land lot).

It is important to stress that this method does not take into account the soil type, crop species and irrigation system. Moreover, a precipitation deficit equal to zero resembles a soil at field capacity. In agriculture, this is not needed as roots will be able to extract water from slightly deeper parts of the soil.

Who are the water users of the Volkerak-Zoommeer?
To narrow down the scope of this research, the water users of the VZM were defined to be the water boards that take in water from the VZM and distribute it in their regional systems. These are the WSHD, WSSS and WSBD. In the scope of this research, only heightening of the water level between -0.10 m NAP and +0.15 m NAP was evaluated with the option to heighten it to +0.50m NAP. Within this range, shipping is not affected. Only when water levels are below -0.25 m NAP or above + 0.75 m NAP the VZM does not provide enough space for shipping. Other utilisation groups are recreation (swimming, sailing, else), fishing, sport fishing and living environment.

3. How much must the water level of the Volkerak-Zoommeer be heightened in order to comply with the water demand of the water users during a period of drought?

The longest continuous period with a discharge at Lobith below 800 m^3/s ever measured was 82 days. However, this occurred outside of the growing season. Within the growing season the longest single period that was measured was only 16 days. Within the current target levels of the VZM, bridging a period of 16 days with flushing operations is not possible. However, when the outlet at Bath is closed, in terms of water quantity, this period can achieved. One must keep in mind that, based on the results of the practical trial drought, the chloride concentration will gradually increase. The maximum period of 82 days, cannot be bridged. From evaluation of the different delta and climate scenarios, it was found that without any flushing operations, a maximum duration of 45 till 65 days could be bridged. This value is largely reduced when the demand to polders is equal to 0.3 L/s/ha (drought). Then the maximum duration will only be 25 days (2050) or 21 days (2085). Flushing operations largely reduce the duration. For normal flushing operations the maximum duration is five till eight days while for half flushing operations, the period is slightly extended to eight till fourteen days, based on the different scenarios considered.

To increase the duration of a period without any fresh water supply, the maximum theoretically possible initial water level was found. Based on data on low discharges for the Rhine at Lobith and the water level at the Hollandsch Diep, a water level of +0.50 m NAP was found to theoretically be possible. As water flows from the Hollandsch Diep to the VZM by gravity, the water level at the VZM cannot be higher. When considering a period of ”only” 16 days, many scenarios are able to bridge this period (as presented in Tables 5.3, 5.4, 5.5 and 5.6). Also, in 2085, many scenarios are able to withstand even a longer period, even with normal flushing operations. For many of the scenarios, the initial water level can even be lower than +0.50m NAP. Considering that improvements are made to prevent leakage in the system and prevent seepage, it is expected that in these extreme scenarios less flushing is needed to lower the chloride concentration.

An important note is that during these calculations, the VZM was considered as a closed system. As the VZM has been assigned as a high water retention area, the lake can handle high water levels. However, there is currently an open connection with the rivers Dintel and Vliet that flow from the management area of WSBD into the VZM. A water level of +0.50 m NAP is currently considered as a high water calamity (Herman Haas et al., 2017). With an open connection, this could induce flooding in the area of WSBD around Breda.

4. Could an implementation of a decision-support system provide better insight to the water managers of the Volkerak-Zoommeer?

The prototype for the DSS that is presented in this research does provide good insights in how different management decisions affect the water level of the VZM. It does, however, not give insights in the effects of water quality in terms of chloride concentration as well as Cyanobacteria. This is the second most important factor on which Rijkswaterstaat has the obligation to manage to the best extent they can, as determined by the water agreement. The advantage of this DSS compared to the current software is that it is easy to operate in Excel, the results can immediately be observed and finally it is possible to analyse many different scenarios, manually and pre-programmed (such as the climate and delta scenarios). As mentioned in the discussion, multiple assumptions and simplifications were applied in creation of the DSS.

Could (temporarily) heightening of the water level at the Volkerak-Zoommeer be used as a drought mitigation measure for the water users of the Volkerak-Zoommeer?

The DSS provides insights in how the water level of the VZM develops according to different water management decisions. It turns out that temporarily heightening of the water level of the VZM can be used as a drought mitigation measure for the water users of the VZM when looking at the water quantity aspect. The extra water level enables Rijkswaterstaat to supply the water users of the VZM with sufficient fresh water supply to overcome a period when no fresh water supply from the Hollandsch Diep is available. Hereby disregarding the open connection and the influences of a higher water level in the local system of WSBD.

The current target levels are set at a maximum water level of +0.15 m NAP and a minimum of -0.10 m NAP. First, it was researched how long it took during different scenarios until the water level of -0.10 m NAP was reached. Only the options with no flushing at Bath were able to bridge a period of 16 days during the growing season. When looking at yearly data, the longest period was 82 days. No scenario was able to overcome this period.

A higher initial water level is only possible when the water level at the Hollandsch Diep is higher that the VZM as water enters the VZM by gravity. From historical data, it became clear that starting with an initial level of +0.50 m NAP could theoretically be possible. This is due to the fact that with discharges between 1000 and 800 m^3/s at Lobith, most measured average daily water levels at the Hollandsch Diep reached up to +0.50 m NAP. This value is way over the +0.15 m NAP that is stated at the water agreement. Currently, this would not be allowed according to the water agreement. Calculations showed that with an initial water level of +0.50 m NAP, almost every scenario for 2050 and 2085 could overcome a period of 16 days without a fresh water supply, including normal flushing operations for almost every scenario. For the period of 82 days, only scenarios without flushing operations are able to bridge these amount of days.

6.3. Recommendations

Based on the insights that were gathered during this research, various recommendations for future research on drought management at the Volkerak-Zoommeer and the implementation of a DSS are presented below.

- An important factor that determines the severity of a drought event is the duration. For the VZM, the duration of the period that the discharge of the Rhine is below 800 m^3/s is the driving factor. In this research, only the maximum historical duration was evaluated. Further research should approach look into the statistics and define what would be the return period of the amount of days the discharge at Lobith is below 800 m^3/s.
- The division between the preferences of the different water boards needs extra attention. Insights show that for WSBD an as low as possible water level at the VZM is beneficial during a period of drought. For WSSS and WSHD, a fresh water buffer at the VZM is beneficial. Research should look into the (financial) benefits of heightening the water level at the VZM as well as the costs for changes at the system or regional systems to cope with higher water levels. This research looked into the theoretical possible initial water level to create a fresh water buffer at the VZM, without considering the influences of the open connection with the rivers Dintel and Vliet.
- As mentioned multiple times in this research, only the water quantity is taken into consideration. More research is needed to obtain sufficient insights in the chloride dynamics and to create a chloride balance. An important aspect of the research should be on whether there are major differences within the system in terms of chloride concentration and what the dynamics in the system are. More measuring stations at multiple locations and depths or more sailing measurements could increase the insights in the development of chloride concentrations within the system. This would also provide the water boards useful information on the water they take in when these measuring stations are located at their inlets. A simulation with Delft3D could provide good model insights to make further predictions of the system. Currently, the operation based on chloride concentration is based on only one measuring point at the Bathse Brug. Historical data show that this measuring station in general measures the highest concentrations. The question rises whether this point is representative for the whole system.
- In order to be able to monitor Cyanobacteria development within the system, a nutrients balance could introduce the first insights in where these Cyanobacteria originate from.
- The water demand of the polders, especially during the growing season, is an important factor to determine the flow towards the polders. In this research, only key figures were applied for normal and drought operations. When the Water Demand Forecasting Tool is live, further research should look into the defined water demand during a period of drought and whether this is equal to the key figures. Furthermore, it should be tested whether with the current structures, this water demand can be met.
- During the *Praktijkproef Droogte*, only the possibility to use normal flushing operations at Bath or stop the flushing entirely were considered. From the tool it turns out that flushing every second low tide does already increase the time it takes before the water level in the VZM reaches the value of -0.10 m NAP. When a chloride concentration is available, further research should look into the effect of this option as a period up to 14 days can be reached instead of seven.
- Due to climate change, it is expected that the average SPEI value will change. As the average SPEI value is normalized to zero, the same precipitation and evaporation data in 2010 and 2050 for the same period could give another SPEI value. Further research should look into whether it is advised to stop the reference period instead of continuously monitoring the SPEI and implement climate change.
- In terms of drought, more research could result in insights on how to temporarily store more water in the regional systems to create local buffers. The different regional systems are designed on flushing while storing water locally becomes more and more interesting with increasing amount of periods of drought due to climate change.

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A

Appendices

A.1. Appendix A: Interview with the different water boards

A.1.1. Waterschap Hollandse Delta (WSHHD) 21-10-2020

Spreker 1: Hydroloog. Houdt zich bezig met automatisering en adviezen op het gebied van hydrologie en het watersysteem. Spreker 2: process engineer Goeree overvlakee: kwalitatief en kwantitatief. In contact met peilbeheerders. Systeemoptimalisatie, onderhoud, aanpassen stuwen.

Introductie tot het beheergebied van WSHD

WSHD beheert Goeree Overflakkee, Voorne Putten, Hoeksewaard, Eilnd van Dordrecht en IJselmonde (zuid Rotterdam). Daarbij is het oost deel van Goeree Overflakkee afhankelijk van water van het VZM. De meeste bemalingsgebieden in Goeree-Overflakkee hebben een gemaal, echter is het in het oost deel ook mogelijk om water uit het Haringvliet in te laten. De belangrijkste inlaten voor het VZM zijn de gemalen Oude Tonge, Gemaal Galathee en Gemaal het Oude Land.

Bemalingsgebied is het land dat door één gemaal wordt gemalen. Op Goeree-Overflakkee niet helemaal waar. Bij het VZM verschillende gemalen:

- 2x in Oude Tongen
- Gemaal Galatee
- Oltgensplaat

Daarna een introductie tot compenserende maatregelen kierbesluit (CMK)

Verschillende inlaten bij het Haringvliet. Met het Kierbesluit komt er zout water in het zoete Haringvliet. Deze maatregel wordt gedaan ter bevordering van de vismigratie. Deze CMK worden gerealiseerd in kader van het kierbesluit. Er is besloten dat zout water tot de lijn Middelharnis – Spui zal komen en sommige inlaten van het waterschap en drinkwaterbedrijf zouden dan in zout water bevinden. Er is afgesproken dat zoet water niet verder gaat komen bij Middelharnis/Spui. Anders moet RWS maatregelen nemen om de opstuwing van zout water tegen te gaan. Daarom zijn er verschillende maatregelen genomen om het zoete water voor deze lijn in te gaan nemen binnendijks te verdelen. Het grote probleem, en daarmee de onzekerheid, is dat van het Kierbesluit helemaal niet bekend is of deze gaat werken.

Ervaringen droogte zomer 2018

In het algemeen, rivierwater kreeg hogere chloride waardes. WSHD stuurt op landbouw 600 mg/L (waterbeheerprogramma 2016-2021). Het oosten van Goeree Overvlakkee is gunstig gelegen. Ondanks weinig neerslag is er voldoende zoet water beschikbaar. Bij Haringvlietzijde moet het peil echt heel echt gedaald zijn, willen zij problemen ervaren om water in te laten. Tijdens droogte staat het WSHD soms voor de keuze: water met slechte kwaliteit (incl. blauwalg) inlaten of geen water inlaten. Dan kan er gekozen worden voor het inlaten van water met blauwalg. Blauwalg is specifiek VZM probleem. Dus dit speelt voornamelijk voor het oosten van Goeree Overflakkee dat dan hinder ondervindt vanwege blauwalg. Dit gebied bestaat voornamelijk uit landbouwgronden. De wereld vergaat dan nog niet want na beregening van water met blauwalg sterft het blauwalg binnen 24 uur. Wel blijft goede communicatie essentieel, want indien dit water ingelaten wordt, moet er goed gecommuniceerd worden met de inwoners dat oppervlaktewateren niet beschikbaar zijn voor zwemmen en het uitlaten van dieren. Een ander belangrijk onderdeel is het in stand houden van de oevers. Daarvoor is de water kwaliteit niet de maatgevende factor maar de waterkwantiteit. Er zit dus dan wel een slechtere water kwaliteit in het systeem.

Wanneer spreken jullie van droogte:
Waterschap blijft een politieke organisatie. Waterschap is daarom ook afhankelijk van media. Dit jaar vanwege het nieuws over droogte in het oosten wel een crisisteam droogte opgezet, maar operationeel heeft WSHD geen last gehad van droogte en konden in alle tijden in de watervraag voorzien. Zelf hebben ze geen echte droogte definitie en is het gebaseerd op ervaring van de peilbeheerders. Vincent: “je zou kunnen zeggen dat wij last hebben van droogte als ze met de reguliere kunstwerken niet meer kunnen voldoen aan het peilbeheer zoals deze is vastgesteld in het peilbesluit”. Beschikt WSHD dan over hoogtelijnen die aangeven dat een peil te laag is? WSHD heeft automatische peilregistratie. Je kan zien dat de peilen naar beneden gaan en dat ze niet meer aan het streefpeil (+/-10cm) kunnen voldoen. Peilbesluit is juridisch document. Dus eigenlijk hebben ze in dat opzicht wel een soort threshold die aan kan geven dat een peil te laag is. Van dit streefpeil mag er dus 10 cm verschillen in de hoogte.

Zijn er als waterschap mogelijkheden om tijdelijk af te zien van dit streefpeil?
Peilbesluit staat vast voor onder reguliere omstandigheden. Mocht hier niet aan voldaan kunnen worden, dan spreekt men van een calamiteit. In geval van droogte is dit diffuser, wateroverlast door een bui van meer dan 20mm is bijvoorbeeld duidelijker. Daarbij kan het peil in een korte tijd snel stijgen en daalt het ook wel weer, droogte is langzamer.

Is er een tijdsbestek waarin het calamiteit beholpen moet worden (voor droogte)?
Een waterschap heeft een inspanningsverplichting. Er wordt dus verwacht dat zij alles op alles zetten om zich aan de afspraken te houden en anders extra maatregelen inzetten, zoals noodpompen etc. Maar soms kun je er niet meer voldoen. Thijs: in reguliere beheer mag je ongeveer 6 weken afwijken tot +/-25cm van het streefpeil. Overmacht bij calamiteiten kun je vergelijken met dijkdoorbraak. Dit zou in droogte ook soms het geval kunnen zijn.

25cm klinkt als een ruime marge, klopt dat?
Dit valt nog wel eens tegen. Voor droogte geldt dat als een peilbeheerder ziet dat een droge periode eraan komt, hij/zij het peil op zou kunnen zetten. In groeiseizoen kan dit toegepast worden. Dit doen ze bijvoorbeeld in het westen van Goeree Overflakkee in de buurt van Ouddorp. Hier is de enige zoetwatervoorziening namelijk de nieuwe inlaat in het Hollands Diep. Bij het gebied dat vanuit het VZM van zoet water wordt voorzien is dit minder nodig, omdat ze hier in de regel eigenlijk altijd wel water in kunnen laten (afhankelijk van de blauwalg situatie).

In de meeting van SWM viel mij op dat WSHD niet meedoet aan de peiloptimalisatie. Waarom?
WSHD doet niet mee met peiloptimalisatie omdat zij makkelijker water in kunnen laten. Goeree Overvlakkee is een afvoer putje, dus alles wat niet verdampt moeten ze eruit pompen. Peilopzet is gunstiger voor WSHD, aangezien dit resulteert in een groter debiet. Maar inlaat capaciteit is niet de beperkende factor

Maakt WSHD ook gebruik van kengetallen om de watervraag te bepalen in het gebied?
WSHD ontwerp aanvoer op 0.5 L/s/ha en afvoer op 2 L/s/ha. Er is geen onderscheid gemaakt in droogte situaties en scenario’s. Het bepalen van de hoeveelheid water dat wordt ingelaten gaat op de expertise van de peilbeheerders. In het algemeen is het meer een verhaal van expertise en gevoel dan gebaseerd op afgewogen keuzes die gebaseerd zijn op cijfers. Peilbeheerder kan wel met agrariërs overleggen/vragen of mensen tijdelijk niet willen beregenen om te zorgen dat in een bepaald peilgebied de vraag niet de aanvoer overstijgt. Er bestaan echter geen juridische hulpmiddelen om agrariërs ertoe

te dwingen om tijdelijk te stoppen met beregenen. Het is in het belang van de agrariërs om samen te werken op dit gebied om problemen in de waterhuishouding van een peilgebied te voorkomen

Nog wat informatie over huidige projecten binnen WSHD
Waterschap wil wel beter de waterbalans in kaart brengen. Op dit moment kunnen ze niet goed de cijfers aantonen voor externe partijen die vragen hebben over de waterbalans etc. Een voorbeeld is de watersprognose tool. Bij inlaten wordt eigenlijk niet gemeten. Van pompen is het al wat makkelijker om te bepalen wat de capaciteit is omdat je de duur kunt vermenigvuldigen met de capaciteit van de pomp. Echter weet je weer niet of een pomp op maximaal vermogen de hele tijd heeft gedraaid en of het nog voldoet aan de specificaties zoals deze geleverd is.

A.1.2. Interview with Waterschap Scheldestromen (WSSS) 26-10-2020

Spreker 3: Coordinerend peilbeheerder van het hele waterschap. Overziet ook de andere peilbeheerders en het geautomatiseerde systeem dat WSSS gebruikt voor peilbeheer.

Kun je wat vertellen over het operationele deel van WSSS?
Van het WSSS is slechts een klein gebied afhankelijk van het zoetwatervoorziening uit het VZM. Wim schat dat dit ongeveer 1/6 is van het totale oppervlakte van het VZM. Dit gebied bevat de eilanden Tholen en St. Philipsland. De rest van het beheergebied is eigenlijk grotendeels afhankelijk van de neerslag die valt en de zoete bellen in het grondwater. Er zijn bij de agrarische sector wel ontwikkelingen gaande aangezien zij wel veel verzoeken en onderzoeken willen om het gebied te vergroten dat voorzien kan worden van zoet oppervlakte water. Wim stelt voor om met de toekomst in het achterhoofd dit ook mee te nemen in de analyse, indien mogelijk. Schouwen-Duiveland heeft een hoogte behoefte aan zoet water. Het bevat lage polders, maar de afstand is eigenlijk te ver. Er zijn plannen om te kijken of Schouwen-Duiveland wel voorzien kan worden via een pijpleiding. Een ander gebied om eventueel van zoet water te voorzien is Zuid-Beveland tot het kanaal Zuid-Beveland. Dit acht Wim nog eventueel reëel. De rest van het beheergebied is afhankelijk van neerslag. Om de zilte kwel te voorkomen, moeten de kweekruggen voldoende zoet gehouden worden. Deze kunnen nog wat meer benut worden, indien er meer inzichten bekend zijn. Er is bijvoorbeeld een kweekrug bij Kapelle. Er zouden op de website van de provincie kaarten beschikbaar moeten zijn om de zoetwater bellen te vinden (zoetwater voorkomens)

Hoe gaat het waterschap om met droogte? / Wat is droogte voor het WSSS?
De laatste winters heeft het WSSS anticiperend op droge periodes bijna nergens het winterpeil aangehouden. Er werd gestuurd op het zomerpeil om zo het grondwater aan te kunnen vullen met alle neerslag. Alleen in de periode dat er gezaaid werd, werd het peil tijdelijk verlaagd zodat de machines het land op konden. Via bestuurders en communicatie in overleg met de boeren werd er afgestemd over deze maatregel. Media en omroep zeeland hebben opgepikt en ook verdeeld. Op deze manier kwam ook de weerstand op deze maatregel beter in beeld en kon het waterschap beter uitleggen waarom ze zich niet aan het winterpeil hielden. Er werd vooral gericht op communicatie vanuit de opzichters die in contact stonden met de boeren. Als agrariërs problemen hadden konden ze zo makkelijk aan de bel trekken. Er was wel echt een kanteling bij de agrariërs te merken en dat zij ook inzagen dat dit de beste maatregelen waren op dit moment om droogte tegen te kunnen gaan.

Dit jaar was de watervoorziening voor het zaaien niet toereikend. Slecht zaaibed kunnen leggen, korte regenperiode ervoor, maar daarna hadden ze nog eigenlijk een goede bui moeten krijgen. De droge wind die voornamelijk in het voorjaar stond, maakte het moeilijker.

Gebruikt WSSS indicatoren etc. om anticiperend peilbeheer toe te passen?
Er wordt voornamelijk gestuurd op ervaring van afgelopen jaren en de eigen inzichten van de peilbeheerders. WSSS werkt niet echt op data in dat opzicht. Het waterschap is nog op zoek naar de juiste tool om aan te tonen dit aan te tonen. OASIS van Hydrologic is veelbelovend. Waterschap is voornamelijk aan het kijken naar aanbod bij gemalen. Met als doel het rekenen aan reactietijd. Wanneer ga je van een neerslagoverschot naar een droge periode. Als je geen aanvoermogelijkheden hebt,

moet je zorgen dat je het zolang mogelijk vast kunt houden, maar je wilt voorkomen dat je aan de verkeerde kant van de grens bent en dat je eigenlijk last hebt van wateroverlast. Het waterschap gebruikt geen droogte indicatoren, Dit gaat op gevoel. Het doel van WSSS is om wel iets in die trant te gaan gebruiken om handvaten te hebben en aan te kunnen tonen aan de bestuurders en de agrariërs dat ze anticiperend maatregelen gaan nemen of dit kunnen gebruiken om aan te tonen waarom speciale maatregelen zijn genomen.

Wat is OASIS?
OASIS: bodemberging en waterstanden -> hoeveel kan er nog gebergd worden. Bodemvocht in de wortelzone. 1000 peilgebieden.

Met welke watervraag houdt WSSS rekening?
0.3 L/s/ha benadert de watervraag goed. Gedeeltelijk om te beregenen en voor st. Philipsland ook door te spoelen. Een gedeelte van het water dat gebruikt wordt om door te spoelen, wordt uiteindelijk beregeningswater. Niet alle gewassen hebben beregeningswater nodig (alleen aardappelen, uien, winterwortelen. Dit is afhankelijk van de financiële middelen en mogelijkheden van de agrariërs. Beregening kost vrij veel geld en dit zijn de gewassen waar het loont om te investeren in beregening installaties.

T.o.v. de andere waterschappen heeft WSSS een hogere chloride-eis in het waterakkoord van 2016 staan. Klopt dit? Indien ja, waarom?
Chloride eis is 450. In water akkoord is 600. Een agrariër stopt niet met beregening als de chloridegehalte opeens 450 mg/L is. Hij kan niet meer stoppen want. De schade door droogte is erger dan de schade die gewassen ervaren door zout. Bij chloride concentraties van 600 mg/L kan de agrariër nog steeds beregenen. Hij zal na de oogst meer kalk moeten toevoegen aan de grond. Daarom stopt WSSS het inlaten van water niet indien het water een concentratie heeft van 450 mg/L.

Hoe zit dit met blauwalgen?
Met blauwalg heeft WSSS heel kort de water inlaat gestopt. Op het gebied van blauwalg is ook de communicatie van belang. Voor WSSS speelt ook dat water ingelaten moet worden om bijvoorbeeld de vissterfte in de sloten voorkomen moet worden. Dus er moet voornamelijk aangegeven worden bij de agrariërs; “We hebben te veel blauwalg en daarom hebben we restricties” Blauwalg is gedeeltelijk toxisch, alleen als het afsterft, is blauwalg toxisch om andere soorten te verdringen. Zolang er geen drijfvlekken zijn kan je blauwalg wel binnen laten. Zolang er doorspoeling in het oppervlaktewater systeem is, hoeven de blauwalgen zichzelf niet te verdringen. Het is dus van belang dat de waterbeheerders voorkomen dat het water stil komt te staan. Landelijk zou wel onderzoek gedaan moeten worden naar de invloed van blauwalg op de gewassen in verband met voedselveiligheid.

Monitort WSSS ook blauwalgen? Zo ja, hoe?
Het waterschap monitort visueel op blauwalgen. Een keer per week gaat er een opzichter langs de verschillende inlaten om te kijken of er drijflagen op het VZM liggen voor de inlaten. Gebaseerd op de uitslagen van zijn/haar observaties wordt er een protocol ingesteld of de inlaten dicht moeten of niet. Blauwalg is moeilijk te meten, bij RWS loopt een onderzoek, gebaseerd op chloriden maar er moeten nog steeds monsters genomen worden. WSSS volgt wel de ontwikkelingen. WSBD heeft ook een automatisch meet punt. Daarentegen bij WSSS alleen maar visueel. Het voordeel voor WSSS is dat de meest voorkomende wind zuid-west is. Daardoor spoelen de drijfvlakken vaak van de inlaten af.

Hoe kan WSSS het gebied sturen?
Tijdens het zoetwaterseizoen wordt er alleen geloosd via het gemaal Eendracht. Het is mogelijk om ook via de andere gemalen (Gemaal Van Haven en Gemaal 3 Grote polders) water te lozen. Echter moet daarvoor het systeem omgegooid worden. Het is niet mogelijk om tegelijkertijd via deze gemalen water in- en uit te laten. Soms moet dus na een heftige regenbui de waterinlaat gestaakt worden. Het duurt ongeveer 14 dagen voordat het systeem weer voldoende zoet is. Dit komt door de zoute kwel. Daarom is het omgooien van het systeem niet heel wenselijk. Van 3 grote polders maar de helft bij Eendracht.

Kijkt WSSS nog naar andere waterkwaliteitsparameters?
WSSS neemt geen andere waterkwaliteitsparameters mee als criteria om water in te laten vanuit het VZM.

In de analyse van RHDHV wordt gesproken over een voorstuwer, wat is dat precies?
Een voorstuwer zuigt het water mee in de stroom en bevindt zich voor de inlaat. Indien de vraag is om meer dan 15 kuub/min moet voorstuwer aan. De voorstuwer kan uiteindelijk helpen tot een debiet van 22 kuub/min. In de analyse van RHDHV is wel te lezen dat de exacte effectiviteit on de maximale werking niet helemaal duidelijk zijn. Gemalen (af te malen) 11 mm/ha/dag

Overige opmerkingen/notities die tijdens het interview naar voren kwamen:

- Het kan een keer interessant zijn om nog te spreken met de hydroloog van WSSS van Tholen, st. philipsland en VZM.
- Bij de vraag naar robuustheidsonderzoek zoals voorgeschreven vanuit het deltaplan, zou ik contact moeten opnemen met een hydroloog. Als ze hier op dit moment al mee bezig zijn. Wim weet dat niet zeker. Misschien zou Luuk mij verder kunnen helpen.
- Op het RMN informatiescherm is een voorbeeld van OASIS te vinden met een landelijke kaart droogte.

Andere scenario's waarvan de spreker zei dat het nog handig kan zijn om in je analyse mee te kunnen nemen:

- Wat kost het voor WSBD om het peil op te zetten? Nu lijkt het namelijk dat WSBD te afhankelijk is van een laag peil op het VZM en misschien zou het met een hoger peil wel haalbaar zijn om beide partijen te voorzien van voldoende water gedurende een droge periode.
- Is het mogelijk om het peil op te zetten aan de inlaatkant van WSBD?
- Kijk ook naar het scenario van weinig aanvoer op de Rijn maar wel met een regenoverschot in de Delta. Dit zal waarschijnlijk niet snel voorkomen, maar is wel mogelijk gezien de klimaatverandering. Is er in dat geval sprake van droogte of niet? Hoe zou daar mee om gegaan moeten worden?

A.1.3. Interview with Waterschap Brabantse Delta (WSBD) 28-10-2020

Spreker 4: Hydroloog die zich ook bezig houdt met beleid en toekomstig onderzoek op gebied van waterveiligheid en droogte. Naast projecten in beheergebied ook projecten in het buitenland. Daarnaast gewerkt bij IHE en RISA.

Systeem uitleg
Dit is al besproken tijdens het werkbezoek aan WSBD.

Wanneer spreekt WSBD van droogte?
Het antwoord op deze vraag moet de spreker mij schuldig blijven. Het beheergebied is te verdelen in twee gebieden: polders in noord-westen en de hoger gelegen vrij afwaterende zandgebieden in het oostelijke deel. De lijn tussen deze twee gebieden komt ongeveer overeen met de lijn Bergen op Zoom naar Waalwijk. Bij droogte dient met onderscheid te maken binnen deze twee gebieden. Voor de zandgebieden stelt WSBD onttrekkingsverboden in. De afvoer kan gemeten worden op een bepaald aantal punten. Voor peilbeheerde gebieden is er water nodig om boezemsysteem door te spoelen t.b.v. blauwalg. En er is water vanuit de boezem nodig om aan de watervraag te kunnen voldoen. Er wordt gesproken van droogte wanneer niet aan de watervraag gedaan kan worden en er geen doorspoeling

gedaan kan worden. Bijv. 2018 en dit jaar, toen heeft WSBD aan RWS gevraagd of de Marksluis tijdelijk (paar uur per dag) in te zetten om te spuien en zo meer water in het gebied te laten stromen. Voor het gebied afhankelijk van het VZM: er is hier water nodig om te kunnen voldoen aan de watervraag en het doorspoel van het gebied. Onder verschillende omstandigheden is dan sprake van droogte.

De boezem is opgedeeld in verschillende trajecten. Deze bevatten kritische verblijftijden om blauwalg te voorkomen. Inlaat Oosterhout wordt open gezet om de verblijftijd te drukken. Verblijftijd is een rekensysteem, volume bepaald bij een soort streefpeil (verhang VZM-Breda). Voor verschillende trajecten zijn de volumes bepaald per bakje. Daarachter draait een operationeel tool: verwachting water temperatuur gebaseerd op lucht temperatuur. Tevens wordt er op zes locaties de blauwalgconcentraties gemeten. In tijden van droogte kan de Dintelsas gesloten worden om meer water over de Dintel af te voeren. In 2018 dermate groot algenprobleem. WSBD heeft een sterk standpunt en dat is dat ze absoluut geen last willen hebben van blauwalgen en dus geen blauwalgen in het systeem willen hebben. Dit is wel anders vergleken met WSSS.

Een anekdote: In 2003 redelijk droge zomer. Boer in westelijke deel water gepompt uit VZM. Daar zat blauwalg in. Controleur van de Albert Heijn heeft het afgekeurd. Dus eigenlijk als we dit samenvatten en dit willen omzetten naar indicatoren, dan maakt WSBD eigenlijk gebruik van 3 indicatoren: verblijftijd, watertemperatuur en afvoer? Droogte indicatoren:

De spreker merkt op dat ze meer willen gaan sturen op debieten, die kun je koppelen aan verblijftijden. Met Roode Vaart zou debieten maatgevend kunnen worden. Daarbij zou debiet dus een hydraulische randvoorwaarde kunnen worden en daarbij een indicator.

Het onderzoek van RHDHV spreekt van een bepaalde water vraag. Klopt deze binnen WSBD?
Nu watervraag vs. Wateraanbod. Nu normaal 0.1 L/s/ha = 1 mm/d. droge omstandigheden ongeveer 0.3 L/s/ha is eigenlijk compensatie van het verdampingstekort. Willen nu meer gevoel krijgen om te kijken hoeveel water ze eigenlijk inlaten. Polder is moeilijker te definiëren. Dus eigenlijk is droogte als je niet meer aan de watervraag kan voldoen. Ander PhD onderzoek IHE nu naar indicatoren/indexen die kunnen toegepast worden voor bijvoorbeeld WSBD. Probleem is dat veel indicatoren en indexen theoretisch zijn en niet heel snel toegepast kunnen worden.

Als ik zo kijk naar het verslag van RHDHV, zou met de inzet van de Roode Vaart er voldoende water beschikbaar zijn om te voldoen aan de watervraag van WSBD? En eventueel een hogere waterstand op het VZM mogelijk zijn?
Er moet verschil gemaakt worden tussen Oosterhout en Amer. Voor de duiker bij Oosterhout is het belangrijk dat het verval over de duiker afhankelijk is van het Markkanaal en de andere inlaatkant van de duiker. Er is een relatie van peil VZM en Markkanaal. De aanvoer in Rode Vaart is onafhankelijk van het waterpeil op het VZM.

Kijken naar historische waarden nu met duiker Oosterhout en Roode Vaart zou je nu wel kunnen voldoen als het hele systeem operationeel in 2020 is om aan de watervraag te kunnen voldoen en doorspoelen. Voor debiet van Oosterhout is er wel uit gegaan van een gemiddeld peil op het VZM in het groeiseizoen, dus dit is wel van invloed op het maximale debiet. Onder reguliere omstandigheden als de Roode Vaart helemaal werkt is WSBD minder afhankelijk van de duiker in Oosterhout maar Klaas-Jan geeft aan dat bij extreme droogte situaties de inzet van de Marksluizen wel nodig moeten zijn.

Is WSBD afhankelijk van chloride gehalten op het VZM?
WSBD heeft drie kleine bemalingsgebieden die rechtstreeks water inlaten van het VZM. Daar wordt door de boeren wel angstvalliger gekeken naar de chloride waardes. Grenswaardes in het waterakkoord zijn voldoende. Deze gebieden worden ook de PAN polders genoemd en zijn ongeveer 4000 ha. Iets minder, misschien 3500 ha.

Soms lijkt in mijn optiek het VZM het afvoerputje van WSBD. Hoe zit dat qua communicatie?
De grote blauwalg ontwikkeling vond plaats op VZM. Vanwege windrichting liggen de blauwalgen vaak

voor de deur van WSBD en door de inlaten te sluiten voorkomen ze dat er geen blauwalg binnenkomt. De blauwalgen die WSBD loost op het VZM is gevoelsmatig heel klein vergeleken met wat er op het VZM ontwikkelt. Er is nu een appgroep met verschillende beheerders waarin men overlegt en informatie verstuurt over de blauwalgen op het VZM. Dit is heel indicatief. Bevat een overlast drempel in en ze kunnen er dan rekening mee houden om eventueel de inlaten te sluiten.

Hoe zit het met de inlaat in de Amer, zijn daar nog problemen met waterinlaat?
Er zijn wel problemen met de waterinlaat vanuit het oosten van Brabant. Dit water bevat nog wel eens bruinrot. Bij Oosterhout, dat ligt in het Wilhelminakanaal dat uit oost-Brabant komt, wordt nog wel eens de inlaat dicht gezet als er een flinke zomers bui heeft plaats gevonden en bruinrot zich bevindt in het Wilhelminakanaal. Laag peil op de Amer vanwege lage maas afvoer nog weinig last van gehad. Bij lage maasafvoer via Rijnwater toch wel weinig problemen.

Is het voor WSBD mogelijk om ook een andere stroom richting te hebben van het water. Bijvoorbeeld inlaat vanuit het VZM?
Er wordt wel degelijk water ingenomen vanuit het VZM. Dit gebeurt voornamelijk wanneer de watertemperatuur laag is en VZM hoge peiltrap heeft in combinatie met een lage afvoer van de vrij waterende afvoer van de beken in de zandgronden. Dat is voornamelijk in de winter. Voor WSBD is dat absoluut geen probleem, maar het probleem doet zich voor wanneer er toenemende water temperaturen zijn en er op het VZM dus blauwalgen ontstaan. WSBD wil absoluut voorkomen dat die ingelaten worden.

A.2. Appendix B: Plots of moving measurements at Volkerak and Zoommeer

The plots in this appendix show the moving measurements of chloride concentration, water temperature, the oxygen concentration and turbidity over the depth. In the map on the bottom of the chart, the trajectory of the moving measurements can be observed. The points in he map correspond to the numbers that can be found in the graphs. For the Volkerak and the Zoommeer, two maps are provided. One for February 2021 and one for August 2021. The measurements are performed by Rijkswaterstaat and can be found at: https://waterberichtgeving.rws.nl/monitoring/tso-metingen/volkerak.

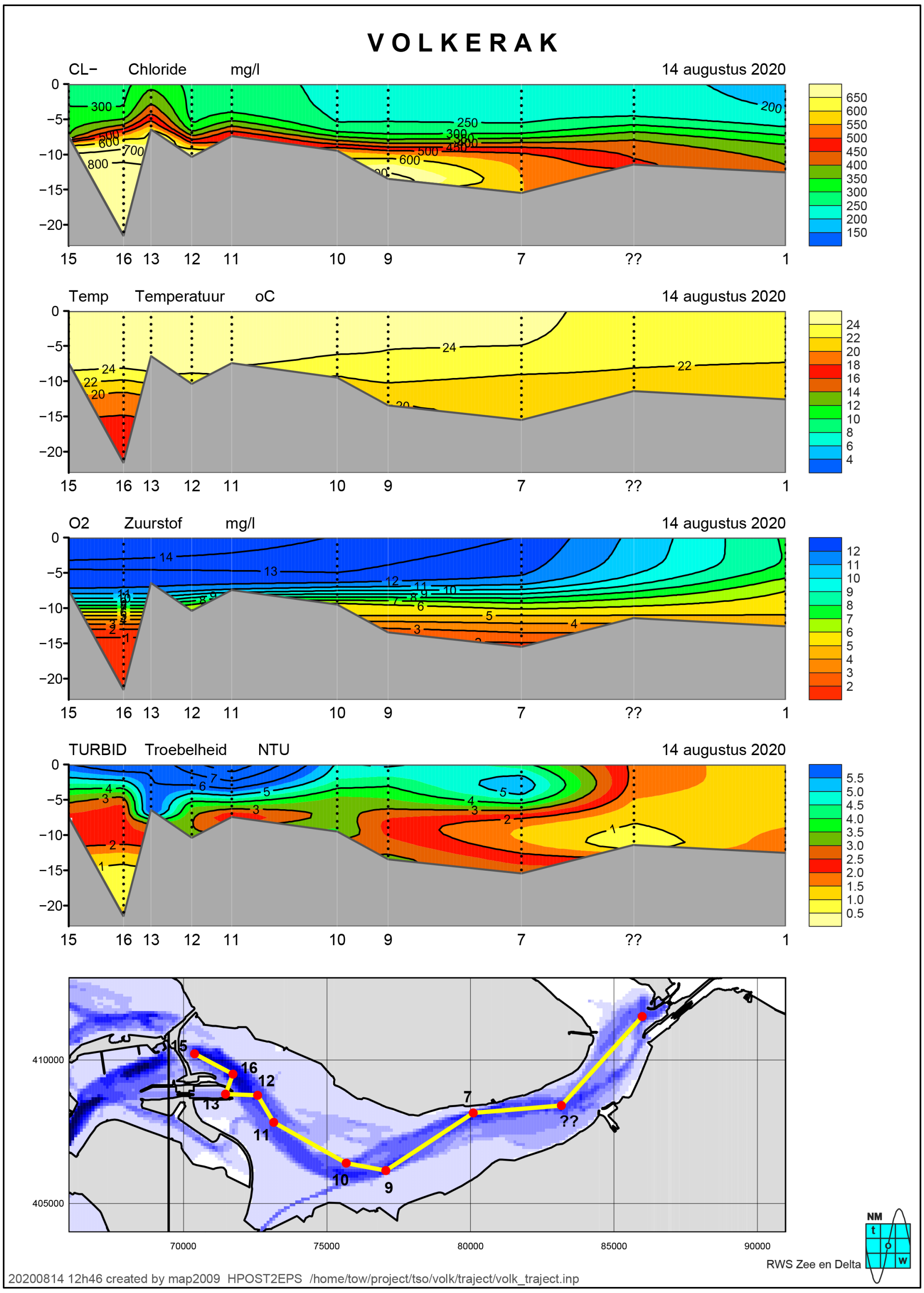


Figure A.1: Moving salt, temperature, oxygen concentration and depth measurement at the Volkerak for August 2020

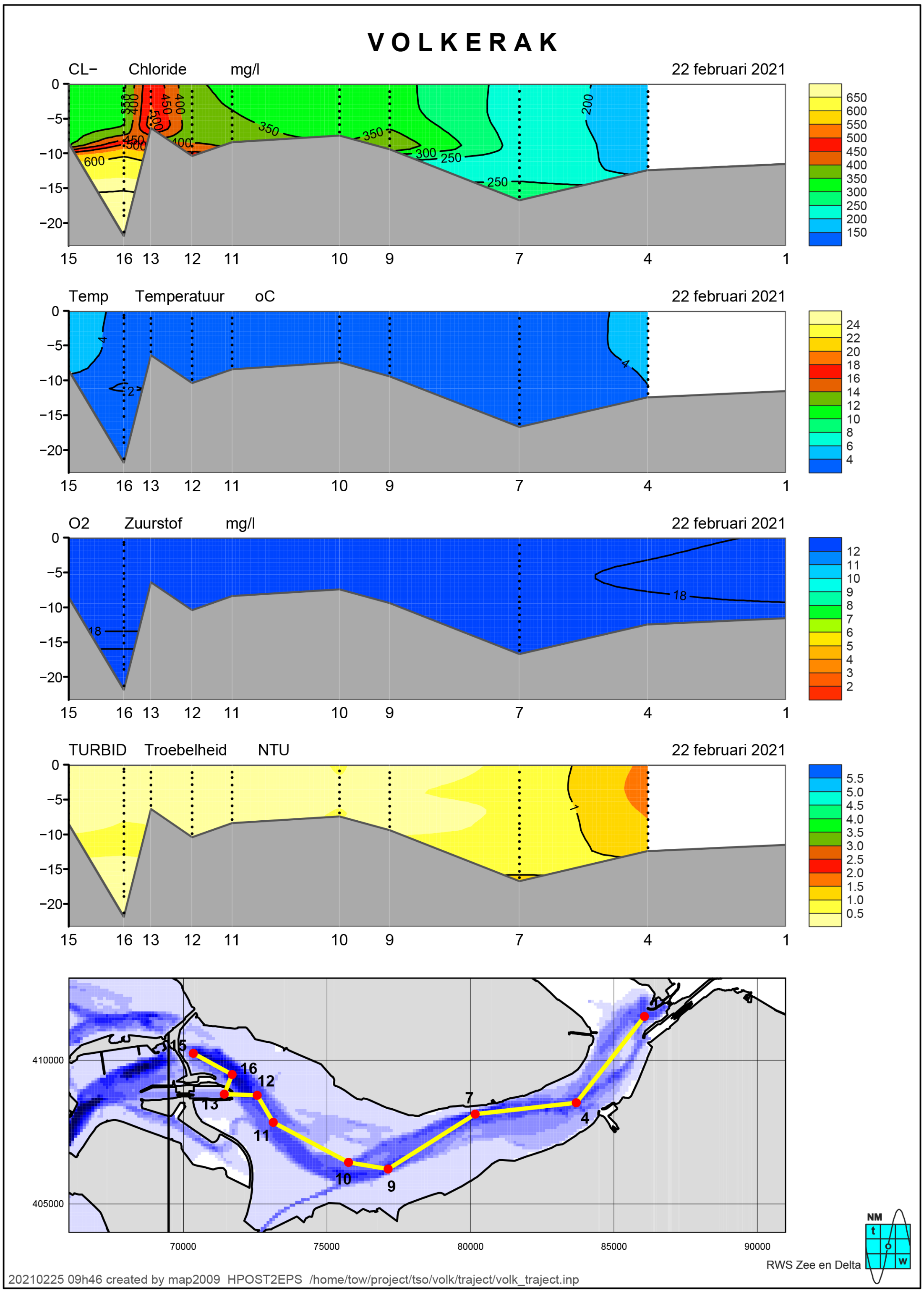


Figure A.2: Moving salt, temperature, oxygen concentration and depth measurement at the Volkerak for February 2021

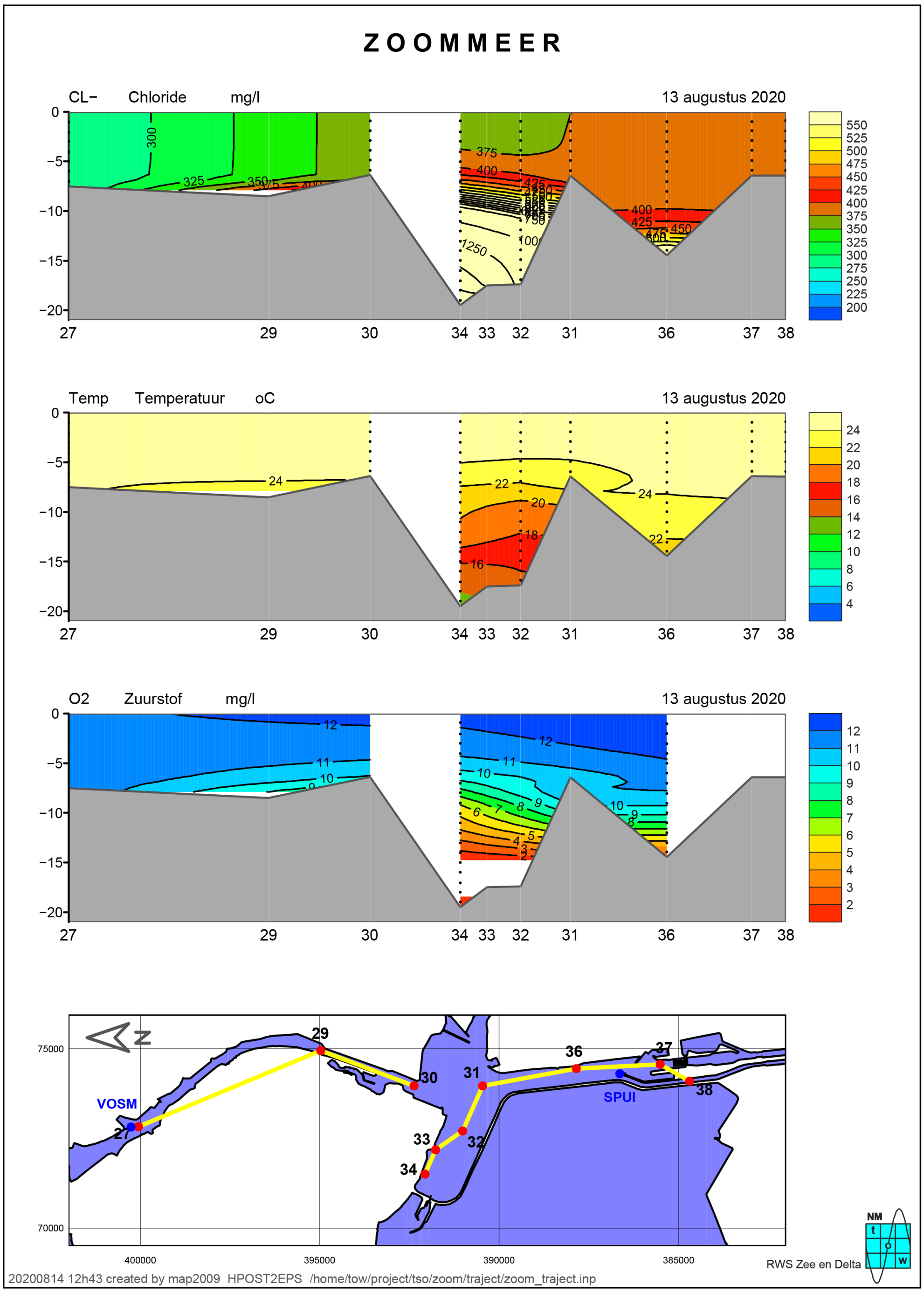
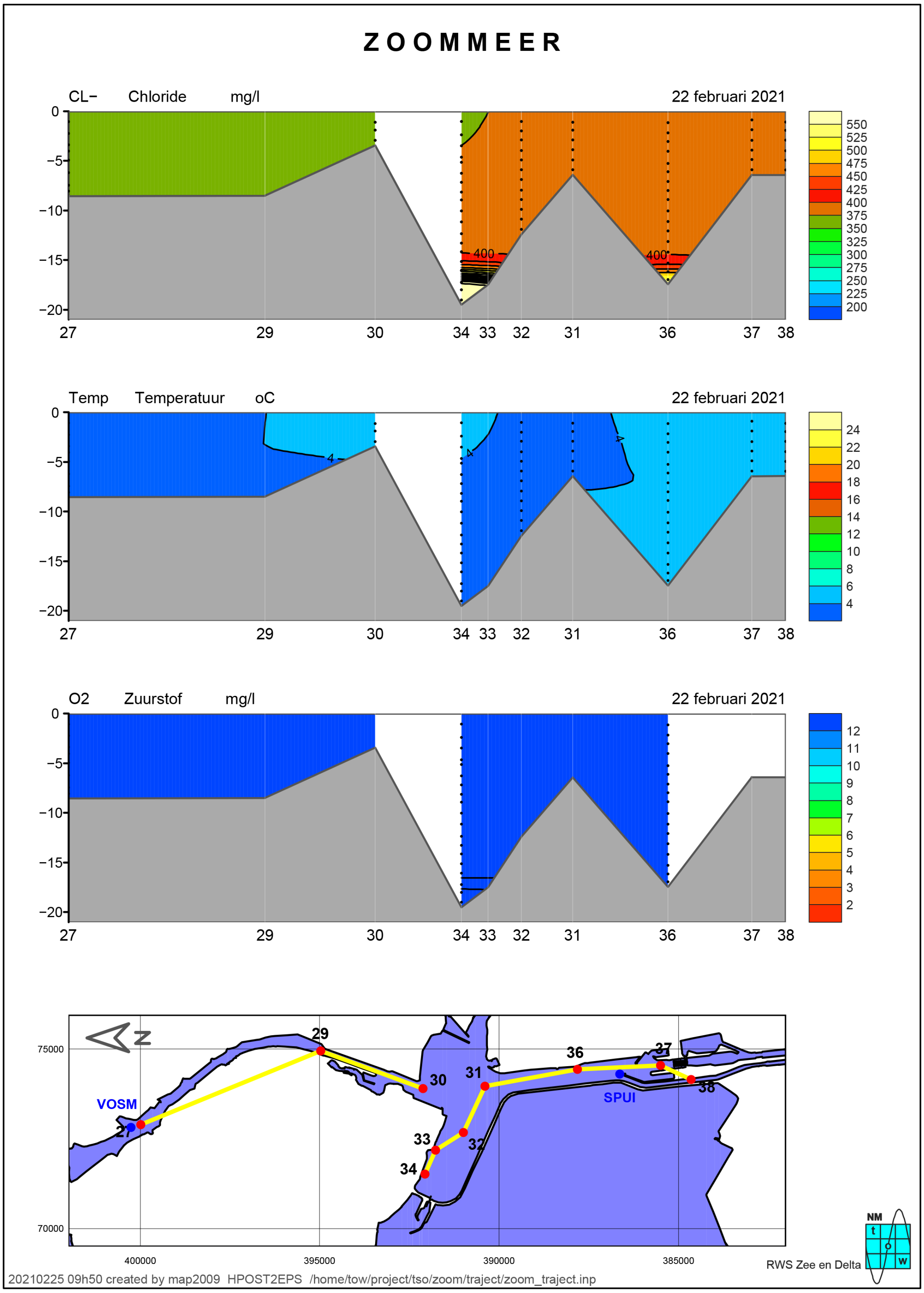


Figure A.3: Moving salt, temperature, oxygen concentration and depth measurement at the Zoommeer for August 2020



20210225 09h50 created by map2009 HPOST2EPS /home/tow/project/tso/zoom/traject/zoom_traject.inp

Figure A.4: Moving salt, temperature, oxygen concentration and depth measurement at the Zoommeer for February 2021

A.3. Appendix C: Maps of service areas of the VZM

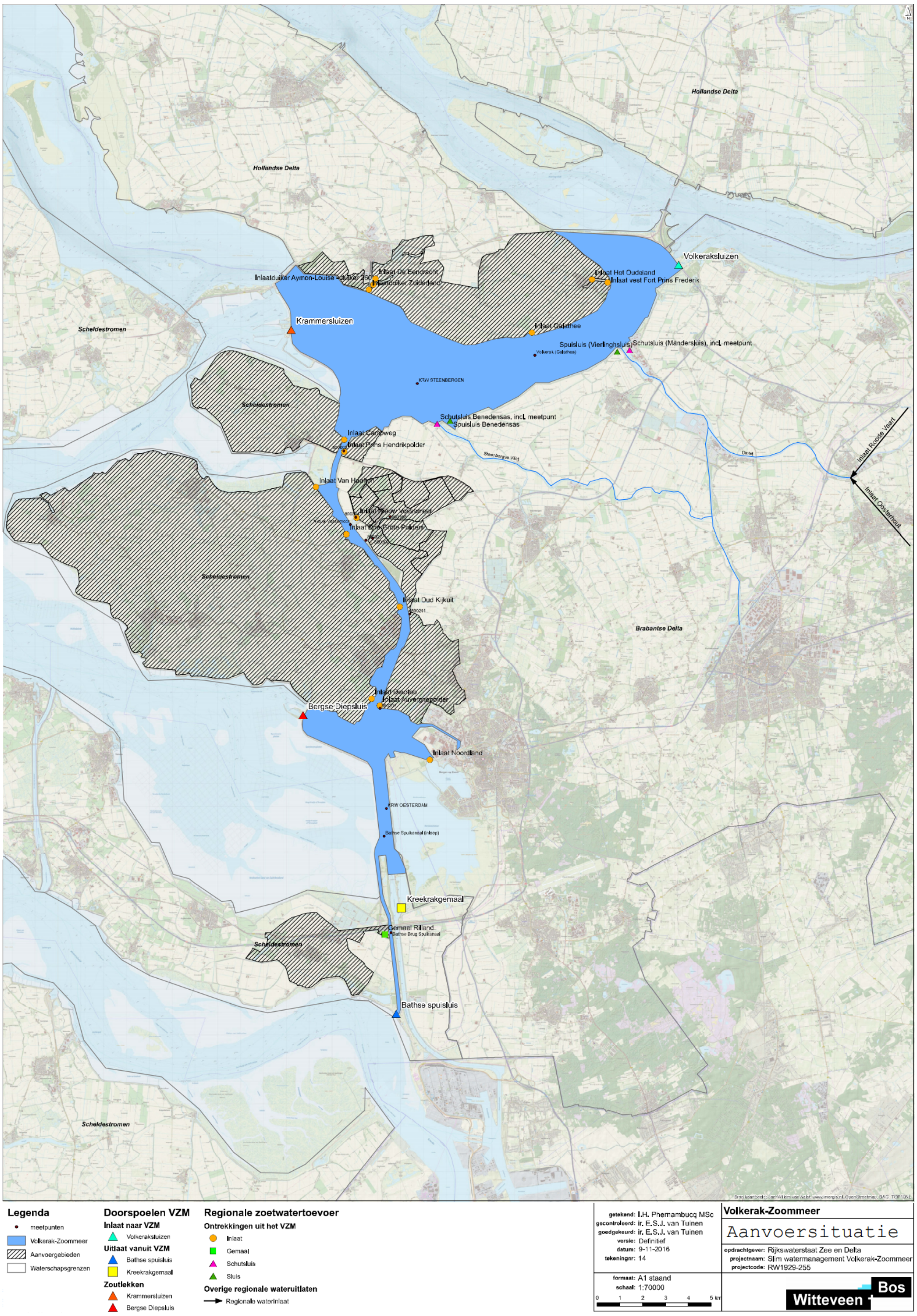


Figure A.5: Polders that take in water from the VZM as defined by Witteveen & Bos (Tuinen van et al., 2016).

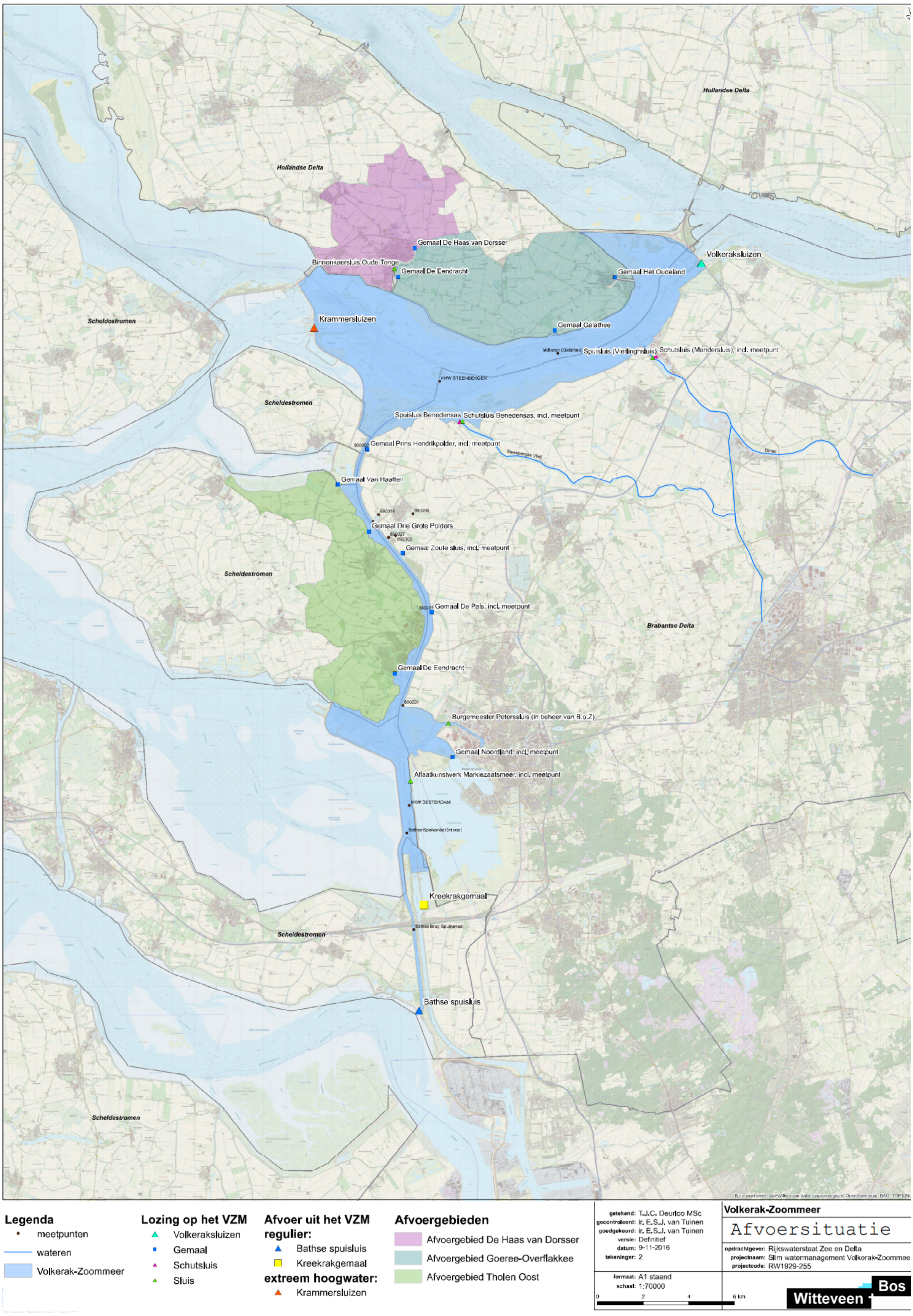
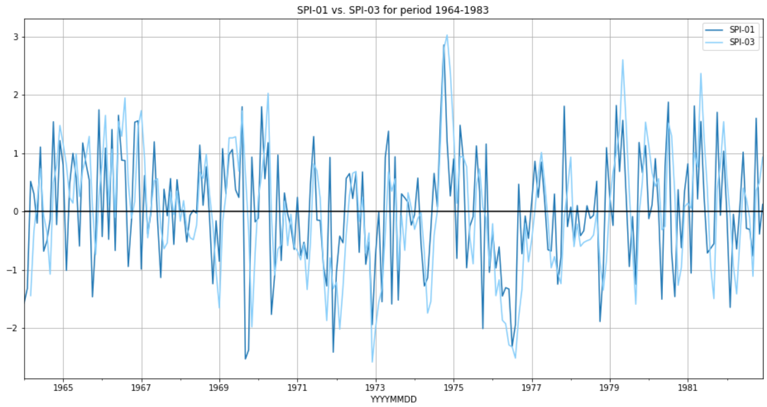
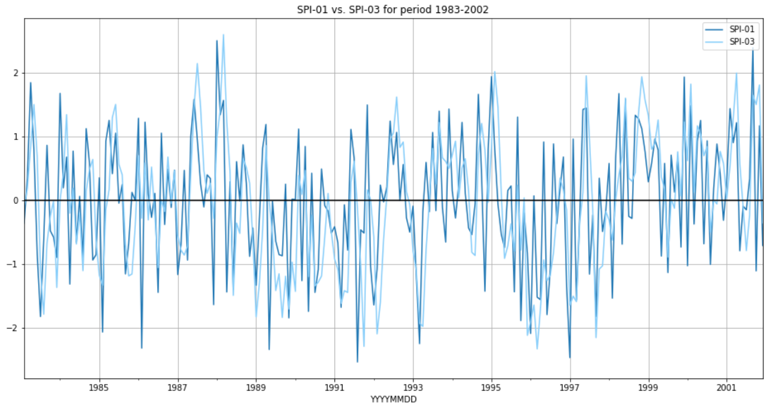


Figure A.6: Polders that discharge into the VZM as defined by Witteveen & Bos (Tuinen van et al., 2016).

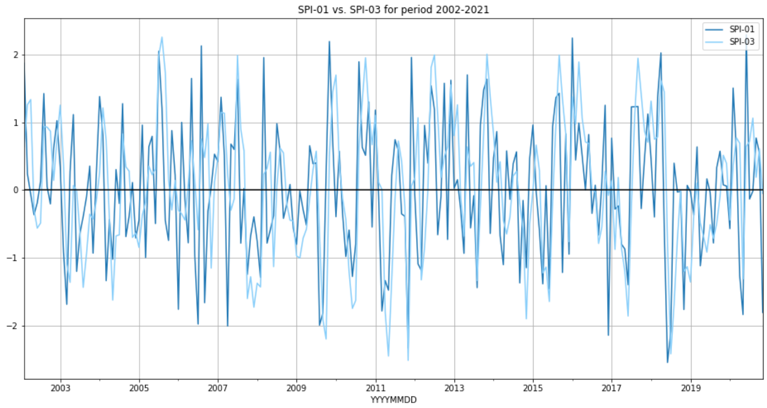
A.4. Appendix D: SPI-1 and SPI-3 plot for period 1964-2020



(a) 1964 - 1983



(b) 1984 - 2002



(c) Lorem ipsum

Figure A.7: The calculated SPI-1 and SPI-3 values for the period 1964-2020 for Vlissingen KNMI weather station.

A.5. Appendix E: Chloride concentrations analysis in the VZM

The plots in this appendix show the chloride concentration measured for the different measuring stations across the VZM, using only the lower measuring points. Figure A.8 combines the four individual plots. It can be observed that this makes it rather difficult to differentiate between the different measuring stations. Therefore, these were split out individually. From these plots, the seasonality of the chloride concentrations is clearly visible. During the growing season, the chloride concentration is lower and mostly below 450 mg Cl/L, while during autumn, the concentration clearly increases until flushing operations start around February.

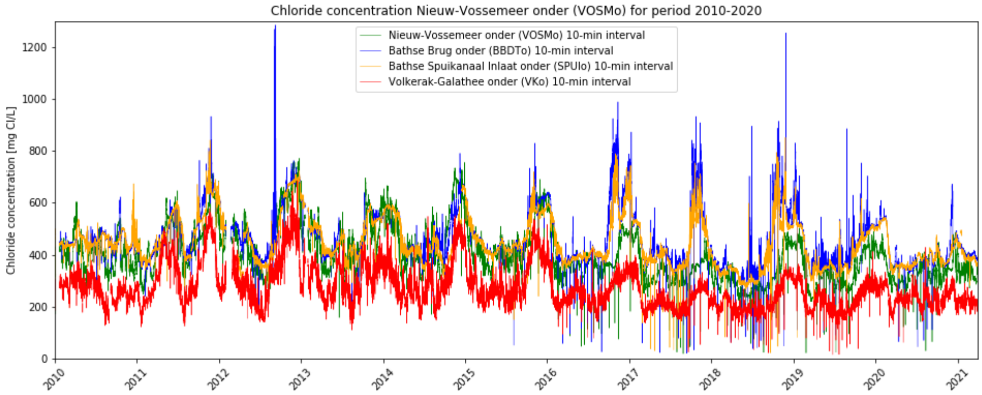


Figure A.8: Measured chloride concentration at the different lower measuring points for the period 2010-2020.

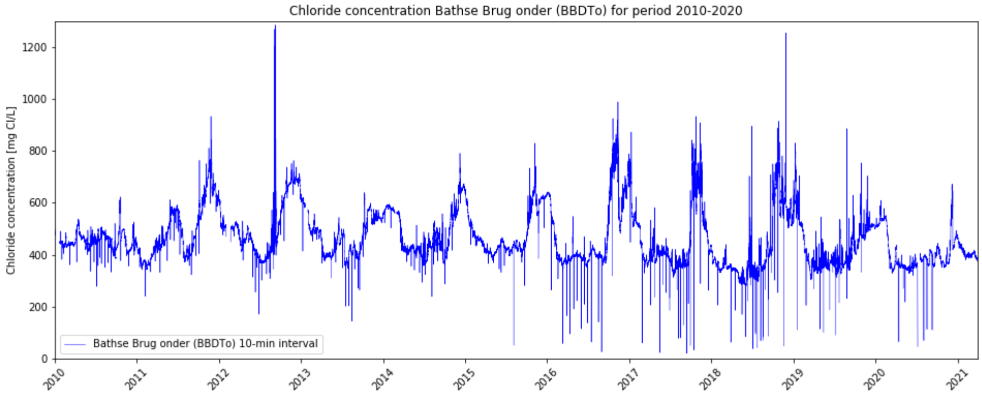


Figure A.9: Measured chloride concentration the lower measuring point at Bathse Brug onder (BBDTo) for the period 2010-2020.

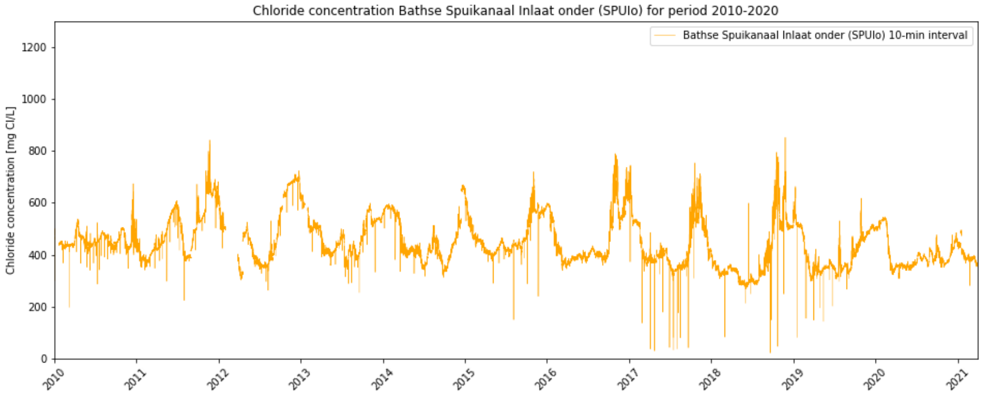


Figure A.10: Measured chloride concentration the lower measuring point at Bathse Spuikanaal Inlaat onder (SPUIo) for the period 2010-2020.

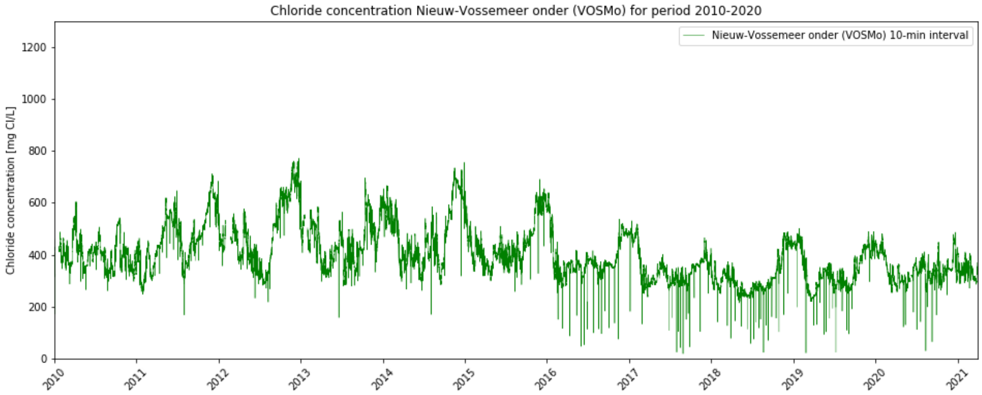


Figure A.11: Measured chloride concentration the lower measuring point at Nieuw-Vossemeer onder (VOSMo) for the period 2010-2020.

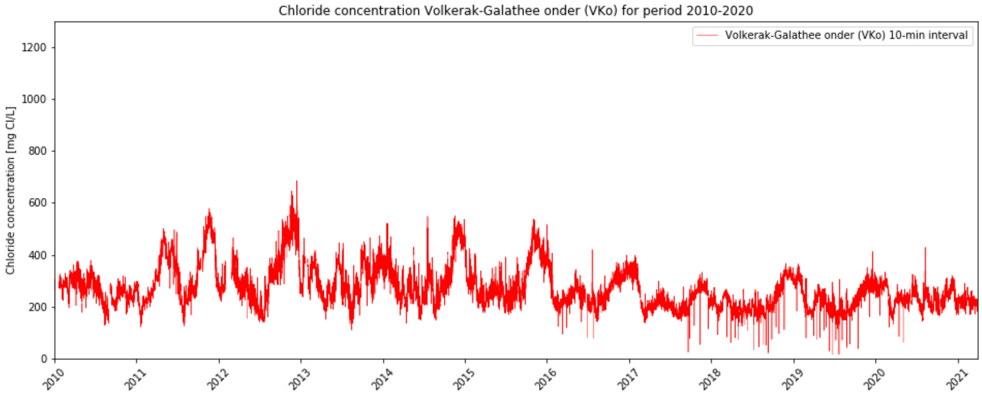
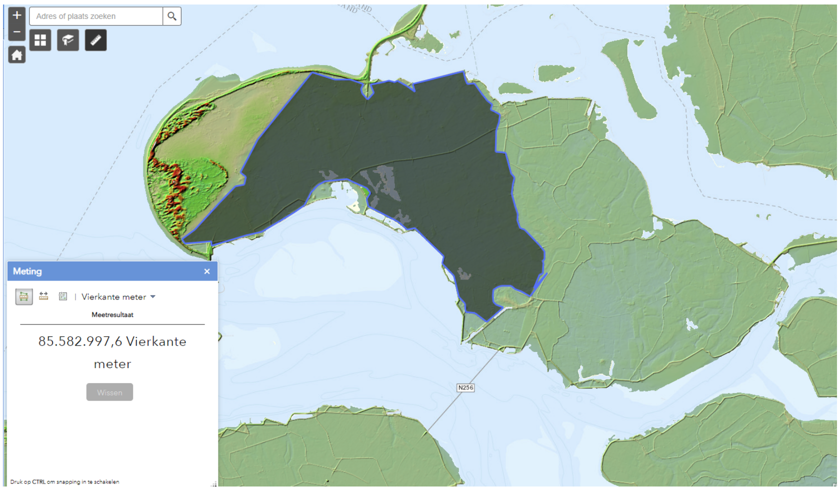


Figure A.12: Measured chloride concentration the lower measuring point at Volkerak-Galathee onder (VKo) for the period 2010-2020.

A.6. Appendix E: Defined areas Schouwen-Duiveland

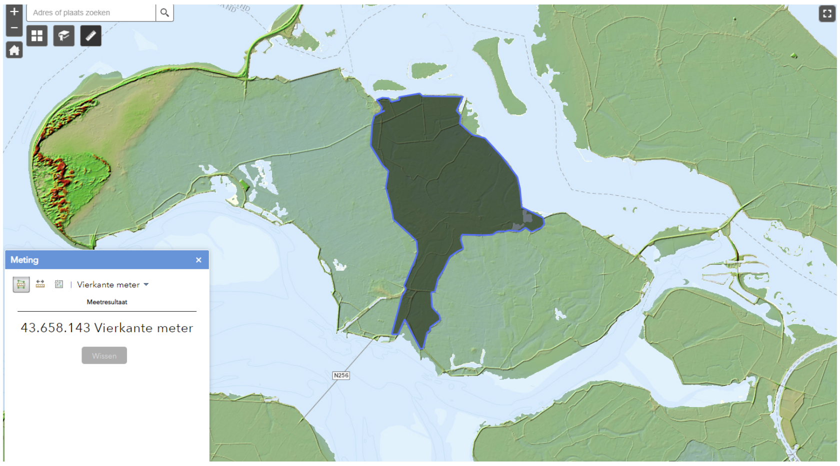


Vierkante meter

Meetresultaat

85.582.997,6 Vierkante meter

(a) Area1

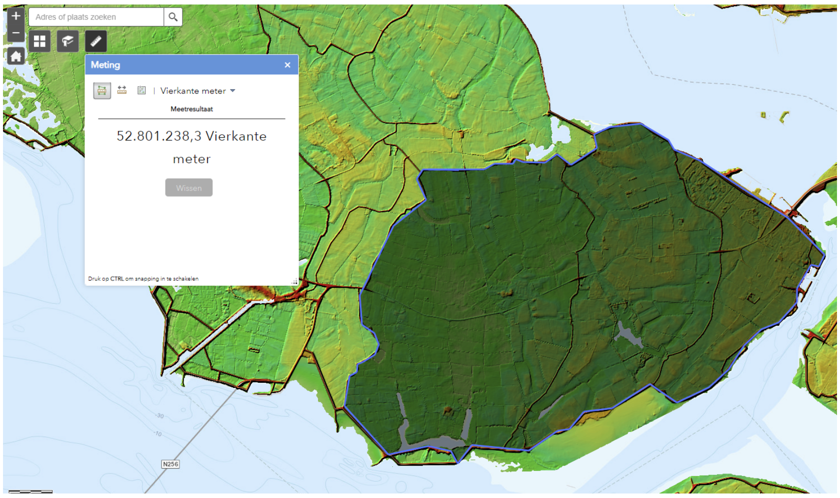


Vierkante meter

Meetresultaat

43.658.143 Vierkante meter

(b) Area 2



Vierkante meter

Meetresultaat

52.801.238,3 Vierkante meter

(c) Area 3

Figure A.13: Defined areas for the different parts of Schouwen-Duiveland that could benefit from a fresh water supply from the VZM. The background is an elevation map in which the higher grounds in the western part are clearly visible.

A.7. Appendix F: Results from different scenarios by using the DSS

The four tables in this appendix provide numbers that originate from the calculation with the tool for different two delta and climate scenarios for 2050 and 2085. In the tables, the respond in terms of rate of decline of the water level in the VZM is provided as well as the amount of days it would take for the water level to drop from +0.15 m NAP to -0.10 m NAP. It can be observed that in some cases the lowering rate is less than a centimeter. Changes of millimetres are more prone to influence of wind at bigger water surfaces. Therefore, the amount of days is not set on an exact amount, but provided in a range of days in which the water level of - 0.10 m NAP is reached.

Table A.1: Result from the tool into the development of the lowering process of the water level at the VZM for the scenario Stoom / WH in 2050. Three management options are calculated for the two choices of a water supply equal to 0.1 or 0.3 L/s/ha. The development of the water level is calculated in cm/d and the amount of days at which the water level of -0.10 m NAP is reached is provided.

Year	**2050**
Scenario	**Stoom / WH**
Start	**01/08/2050**

Initial water level VZM	0.15	m NAP
Uit te breiden oppervlakte	0	ha
Aanvoer WSBD Moerdijk	nee	
Uit gaan van delta- en klimaatscenario:	ja	
Jaar	2050	
Deltascenario / Klimaatscenario	stoom / WH	
Polders	all	

No outlet at Bath:	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-1.1	cm/d	-0.5	cm/d
reached -0.10 m NAP after	24	days	45-50	days

1 discharge channel every 2 days	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-2.8	cm/d	-1.9	cm/d
reached -0.10 m NAP after	10	days	14	days

1 discharge channel at Bath	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-4.2	cm/d	-3.7	cm/d
reached -0.10 m NAP after	6	days	7	days

Table A.2: Result from the tool into the development of the lowering process of the water level at the VZM for the scenario Rust / GL in 2050. Three management options are calculated for the two choices of a water supply equal to 0.1 or 0.3 L/s/ha. The development of the water level is calculated in cm/d and the amount of days at which the water level of -0.10 m NAP is reached is provided.

Year	**2050**
Scenario	**Rust /GL**
Start	**01/08/2050**

Initial water level VZM	0.15	m NAP
Uit te breiden oppervlakte	0	ha
Aanvoer WSBD Moerdijk	nee	
Uit gaan van delta- en klimaatscenario:	ja	
Jaar	2050	
Deltascenario / Klimaatscenario	Rust / GL	
Polders	all	

No outlet at Bath:	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-1	cm/d	-0.4	cm/d
reached -0.10 m NAP after	25	days	60-65	days

1 discharge channel every 2 days	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-3.2	cm/d	-2.2	cm/d
reached -0.10 m NAP after	8	days	12	days

1 discharge channel at Bath	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-5.2	cm/d	-4	cm/d
reached -0.10 m NAP after	5	days	7	days

Table A.3: Result from the tool into the development of the lowering process of the water level at the VZM for the scenario Stoom / WH in 2085. Three management options are calculated for the two choices of a water supply equal to 0.1 or 0.3 L/s/ha. The development of the water level is calculated in cm/d and the amount of days at which the water level of -0.10 m NAP is reached is provided.

Year	**2085**
Scenario	**Stoom / WH**
Start	**01/08/2085**

Initial water level VZM	0.15	m NAP
Uit te breiden oppervlakte	0	ha
Aanvoer WSBD Moerdijk	nee	
Uit gaan van delta- en klimaatscenario:	ja	
Jaar	2050	
Deltascenario / Klimaatscenario	stoom / WH	
Polders	all	

No outlet at Bath:	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-1.3	cm/d	-0.7	cm/d
reached -0.10 m NAP after	20	days	35-40	days

1 discharge channel every 2 days	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-2.9	cm/d	-1.9	cm/d
reached -0.10 m NAP after	9	days	13	days

1 discharge channel at Bath	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-3.8	cm/d	-3.3	cm/d
reached -0.10 m NAP after	7	days	8	days

Table A.4: Result from the tool into the development of the lowering process of the water level at the VZM for the scenario Rust / GL in 2085. Three management options are calculated for the two choices of a water supply equal to 0.1 or 0.3 L/s/ha. The development of the water level is calculated in cm/d and the amount of days at which the water level of -0.10 m NAP is reached is provided.

Year	**2085**
Scenario	**Rust /GL**
Start	**01/08/2085**

Initial water level VZM	0.15	m NAP
Uit te breiden oppervlakte	0	ha
Aanvoer WSBD Moerdijk	nee	
Uit gaan van delta- en klimaatscenario:	ja	
Jaar	2085	
Deltascenario / Klimaatscenario	Rust / GL	
Polders	all	

No outlet at Bath:	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-1.2	cm/d	-0.6	cm/d
reached -0.10 m NAP after	21	days	40-45	days

1 discharge channel every 2 days	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	3.2	cm/d	-2.5	cm/d
reached -0.10 m NAP after	8	days	11	days

1 discharge channel at Bath	0.3 L/s/ha		0.1 L/s/ha	
avg. decay of water level VZM	-5.1	cm/d	-3.9	cm/d
reached -0.10 m NAP after	5	days	7	days

A.8. Appendix G: Calculation of the needed water levels for different scenarios

Table A.5: Insights in the theoretical extra needed water level to withstand a period of 60 days with no fresh water supply for the two scenarios in 2050. As well as the theoretical initial water level at the VZM is provided and in the third column, the maximum duration is calculated when the water level may only be heightened to +0.5 m NAP.The green color indicates that the scenario was able to pass a period of 60 days, while the red values indicate that this scenario was not able to cover a period of 60 days when the initial water level at the VZM started at +0.5 m NAP and may be lowered to -0.10 m NAP.

2050 Stoom/WH			**Theoretical extra water level needed for 60 days [cm]**	**Theoretical intial WL needed for 60 days [+ m NAP]**	**max duration with initial WL +0.5 m NAP [days]**
0.3 L/s/ha					
No flushing at Bath	-1.1	cm/d	66	0.56	54.5
Every 2nd low tide flushing	-2.8	cm/d	168	1.58	21.4
Normal flushing operation	-4.2	cm/d	252	2.42	14.3

0.1 L/s/ha					
No flushing at Bath	-0.5	cm/d	30	0.2	120.0
Every 2nd low tide flushing	-1.9	cm/d	114	1.04	31.6
Normal flushing operation	-3.7	cm/d	222	2.12	16.2

2050 Rust/GL			**Theoretical extra water level needed for 60 days [cm]**	**Theoretical intial WL needed for 60 days [+ m NAP]**	**max duration with initial WL +0.5 m NAP [days]**
0.3 L/s/ha					
No flushing at Bath	-1	cm/d	60	0.5	60.0
Every 2nd low tide flushing	-3.2	cm/d	192	1.82	18.8
Normal flushing operation	-5.2	cm/d	312	3.02	11.5

0.1 L/s/ha					
No flushing at Bath	-0.4	cm/d	24	0.14	150.0
Every 2nd low tide flushing	-2.2	cm/d	132	1.22	27.3
Normal flushing operation	-4	cm/d	240	2.3	15.0

Table A.6: Insights in the theoretical extra needed water level to withstand a period of 60 days with no fresh water supply for the two scenarios in 2085. As well as the theoretical initial water level at the VZM is provided and in the third column, the maximum duration is calculated when the water level may only be heightened to +0.5 m NAP. The green color indicates that the scenario was able to pass a period of 60 days, while the red values indicate that this scenario was not able to cover a period of 60 days when the initial water level at the VZM started at +0.5 m NAP and may be lowered to -0.10 m NAP.

2085 Stoom/WH			**Theoretical extra water level needed for 60 days [cm]**	**Theoretical intial WL needed for 60 days [+ m NAP]**	**Max. duration with initial WL +0.5 m NAP [days]**
0.3 L/s/ha					
No flushing at Bath	-1.3	cm/d	78	0.68	46.2
Every 2nd low tide flushing	-2.9	cm/d	174	1.64	20.7
Normal flushing operation	-3.8	cm/d	228	2.18	15.8

0.1 L/s/ha					
No flushing at Bath	-0.7	cm/d	42	0.32	85.7
Every 2nd low tide flushing	-1.9	cm/d	114	1.04	31.6
Normal flushing operation	-3.3	cm/d	198	1.88	18.2

2085 Rust/GL			**Theoretical extra water level needed for 60 days [cm]**	**Theoretical intial WL needed for 60 days [+ m NAP]**	**Max. duration with initial WL +0.5 m NAP [days]**
0.3 L/s/ha					
No flushing at Bath	-1.2	cm/d	72	0.62	50.0
Every 2nd low tide flushing	-3.2	cm/d	192	1.82	18.8
Normal flushing operation	-5.2	cm/d	312	3.02	11.5

0.1 L/s/ha					
No flushing at Bath	-0.6	cm/d	36	0.26	100.0
Every 2nd low tide flushing	-2.5	cm/d	150	1.4	24.0
Normal flushing operation	-3.9	cm/d	234	2.24	15.4

A.9. Appendix H: Pumping station financials

During a period of drought, WSBD prefers a low as possible water level at the VZM in order to flush its system through the Mark, Dintel and Vliet into the VZM. the polders that depend on a fresh water supply from the VZM, a high water level at the VZM is preferred (RHDHV, 2020). In this thesis, it was found that an initial water level of +0.50 m NAP is theoretically feasible. With the open connections of the Dintel and Vliet, this would result in higher water levels in the regional system of WSBD. Flushing would not be possible as there is no potential water level difference over the culvert in Oosterhout. Moreover, flooding could occur with these water levels. Therefore, a short ”back of the envelope” economic calculation is presented in this appendix to provide a global view on the numbers.

From PDOK (*Dutch: Publieke Dienstverlening Op de Kaart*), the Dutch institute for mapping services, data was obtained on land use. The map ’basisregistratie gewaspercelen (brp)’ contains information on the type of vegetation and crop type per lot. This data was imported into QGIS. Per polder area, the area of crop types were calculated. The results can be found in Table A.7. The total area per crop type was then used in the calculation of the total agricultural revenue. Numbers on revenue per crop type were difficult to obtain. For the crop types potato, union, corn, wheat and beets numbers can be found at the CBS. These are the crop types that are mostly used in the Netherlands. Many other crop types are harvested in the polders at a small scale. Yield numbers on these smaller groups are not available. These were therefore combined in the groups ’else’, ’fruits’, ’plants’ and ’grassland’. For these four groups, assumptions were made for the revenue and average yield values were applied. In Table A.8, the results are summarized.

Table A.7: Area per polder used by crop type and land use.

	Auvergnepolder	Goeree-Overflakkee	Nieuw-Vossemeer	Prins Hendrik polder	Reigersbergsche polder	Tholen	Sint Philipsland	**Total**
Land-use/ crop type	Surface [ha]	Surface [ha]	Surface [ha]	Surface [ha]	Surface [ha]	Surface [ha]	Surface [ha]	**[ha]**
Nature	0.87	3.69	0	0	0	255.69	8.89	**269.14**
Grassland	209.89	685.49	372.63	44.77	201.5	390.48	1948	**3852.76**
Potatoes	122.33	730.2	270.47	6.49	135.29	274.79	2123.35	**3662.92**
Beets	47.46	272.68	95.19	0	56.8	171.32	883.08	**1526.53**
Corn	65.43	93.06	133.96	21.76	63.47	72.37	233.38	**683.43**
Wheat	107.42	557.43	151.63	1.58	157.56	383.34	1358.35	**2717.31**
Unions	8.46	241.8	55.51	11.46	80.84	42.52	431.78	**872.37**
Else	58.15	297.56	124.66	22.51	34.81	124.84	548.09	**1210.62**
Fruits	10.8	13.04	95.48	0	65.14	18.31	253.03	**455.8**
Plants	102.86	196.7	85.78	17.53	109.22	225.06	693.45	**1430.6**
Total [ha]	**733.67**	**3091.65**	**1385.31**	**126.1**	**904.63**	**1958.72**	**8481.4**	

Table A.8: Calculated revenue and yield per crop type.

	Total	Yield	Total Yield	Revenue	Total revenue
	[ha]	[kg/ha]	[kg]	[€/100kg]	[€]
Nature	269.14	0	0		€ -
Grassland	3852.76	10800	41609808	2	€ 832,196.16
Potatoes	3662.92	46000	168494320	13.5	€ 22,746,733.20
Beets	1526.53	61300	93576289	3.34	€ 3,125,448.05
Corn	683.43	25000	17085750	24.6	€ 4,203,094.50
Wheat	2717.31	8400	22825404	16.26	€ 3,711,410.69
Unions	872.37	61300	53476281	14.16	€ 7,572,241.39
Else	1210.62	5000	6053100	14	€ 847,434.00
Fruits	455.8	44200	20146360	25	€ 5,036,590.00
Plants	1430.6	20000	28612000	15	€ 4,291,800.00
Total [ha]			**451879312**		**€ 52,366,947.99**

Based on these values, it is estimated that the total revenue of the agricultural sector is 52 million euros when using average values for yield and revenue in the Netherlands. These cost we want to compare to the costs of a pumping station. The connection between the VZM, Dintel and Vliet can be closed. There are already locks in place to prevent consequences of high water level at the VZM in the regional system of WSBD. It was assumed that at the locations of these locks, a pumping station will be located. In general, the costs for a pumping station are equal to 15,000,- per m^3 per minute in the Netherlands. When assuming a water level at the VZM is too high during the months June, July and August, the total duration is 82 days. The growing season (15 March-15 July) also The average discharge in 2018 for these days was 1.7 m^3/s for the Vliet and 6.9 m^3/s for the Dintel. When implementing a pumping station at both connections, the costs are equal to $€15,000 * (6.9 + 1.7) = €129,000$ per minute. From this value, it seems that operating a pumping station of this size is not economically feasible. As only average values were used as discharges, the peak discharges will probably be higher, resulting in a bigger capacity needed.