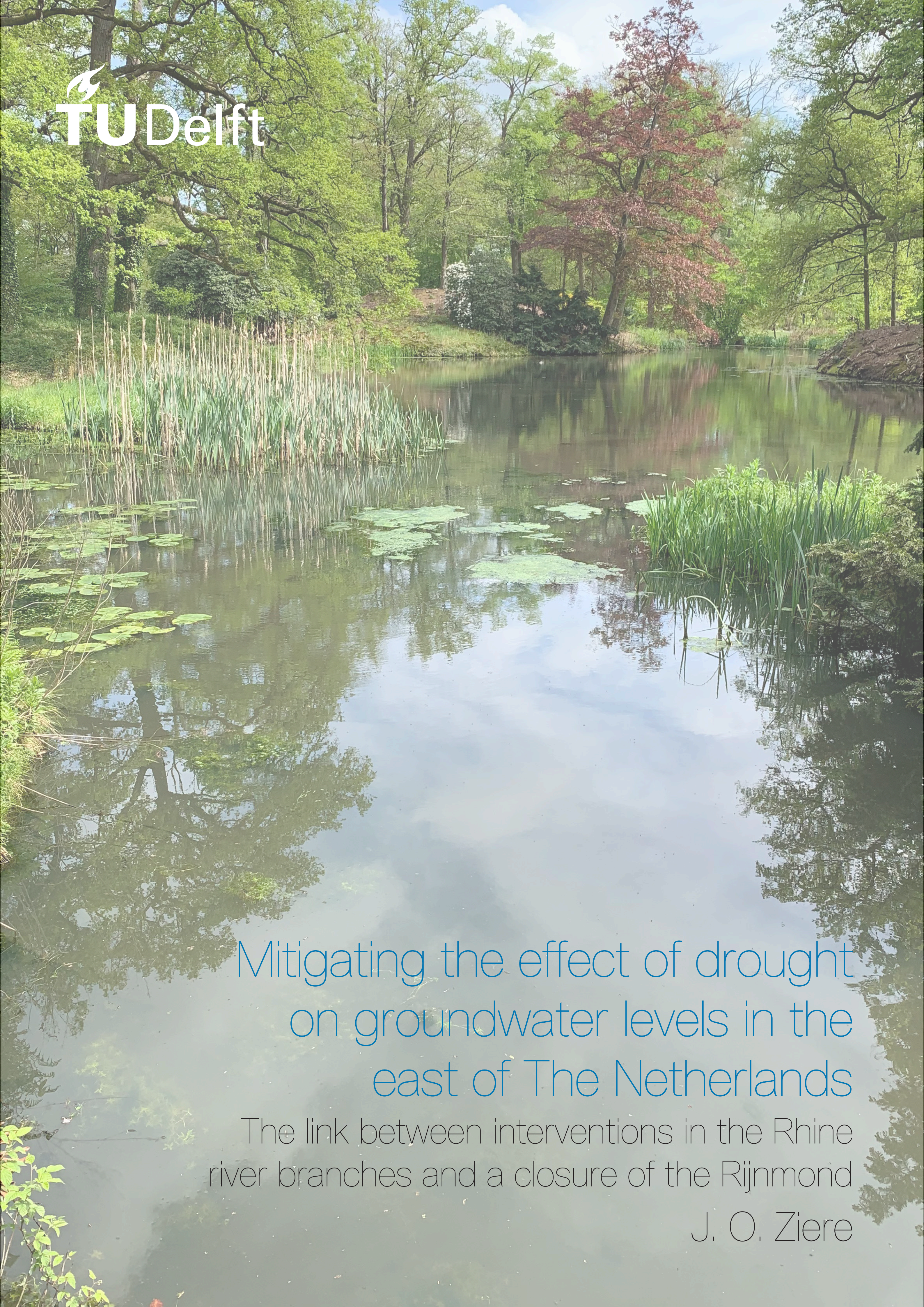

Mitigating the effect of drought on groundwater levels in the east of The Netherlands

The link between interventions in the Rhine river branches and a closure of the Rijnmond

J. O. Ziere

Mitigating the effect of drought on groundwater levels in the east of The Netherlands

The link between interventions in the Rhine river branches and a closure of the Rijnmond

by

J.O. Ziere

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Summary

Due to climate change, a new water management policy is considered in the Netherlands. The shift towards greater extremes in both wet periods and dry periods requires a more dynamic policy. The current water management policy is focused on the expected increased probability of high river discharges, due to which flooding of the low-laying parts of the Netherlands can have large economic consequences. The focus of this study is the higher occurrence rate of drier summers, which affects the east of the Netherlands where the groundwater levels have been decreasing during dry spells in recent years. It is investigated what effect the placement of a permanent water barrier in the Rijnmond (*Plan Sluizen*) has on the water levels in the Rhine branches, and if this can be an opportunity to help the drought prone area in the east of the Netherlands.

This study shows that replacing the Maeslantkering with a permanent barrier has no influence on the water levels upstream of Nijmegen in the Waal at average to low Rhine discharges (2000 - 600 m^3/s), and thus has no effect on the water distribution at the Pannerdensche Kop. If a permanent water barrier is concructed in the Rijnmond, the influence of the tide in the Rhine-Meuse estuary is eliminated. This means more control over the water levels in the downstream area of the Waal, but also that the salt intrusion into the Rijnmond every tidal cycle is stopped. Currently, since the Rijnmond has an open connection to the sea, salt intrusion is mitigated by discharging as much water as possible through the Nieuwe Waterweg when Rhine discharges are low, which negatively affects the discharge to other Rhine branches. If the fresh water demand to stop the salt wedge is eliminated, a different water distribution over the Rhine branches is possible, but structural changes at the bifurcation point have to be made in order to achieve this.

River water can be used to supply the east of the Netherlands with water. In this study, three options to do so are examined. The most promising options of these is placing a pumping station in the Rhine nearby Lobith and supplying the streams in the area with water, many of which fall dry in summer. From there, the water can be used for irrigation, infiltration, and other fresh water demands, relieving the stress on the groundwater during dry spells. By bringing in water, a buffer can be created in the unsaturated zone that can be used if the precipitation deficit becomes too large. This extraction option has an effect on the water levels in the Waal river, so it can only be used when water levels are sufficient for navigation. Building a permanent storm surge barrier is not a requirement, but because it increases the navigability of the Waal river, water can be extracted more often with a permanent barrier.

If the occurrence rate of droughts continues to rise as quickly as in recent years, this is a more acute problem than the relatively slow sea level rise. A solution to combat drought in the east of the Netherlands seems to be more urgent than a solution to mitigate sea level rise. However, a permanent barrier can help in mitigating the effect of drought on groundwater levels in the east of the Netherlands by allowing for more flexibility in using river water extraction.

Preface

This master thesis is the last requirement for my graduation at the Delft University of Technology to complete the master Hydraulic Engineering. This study was coined by the Dutch hydraulic engineer Frank Spaargaren, who could not look into this further before his death in October 2020. This study marks the next step using river engineering to adapt the Netherlands to the changing climate.

Writing a master thesis during a global pandemic was challenging, especially starting out. Working from home has forced a flexible work ethic and has tested my endurance to the maximum. In the end, I am all the more proud of the report here before you because of these challenges. In overcoming them, I leaned more than thought possible during this time.

Completing this thesis was not possible without the help of several people. I would like to express my gratitude to those people I depended upon during my graduation process.

In the first place, the members of my graduation committee are recognised. I would like to thank Matthijs Kok, who never wavered in his support as daily supervisor and chair of the graduation committee. In every weekly meeting he caused me to think about things I had not considered before and thereby increasing the quality of my work significantly. My second supervisor, Martine Rutten was also of paramount importance in writing this thesis, as she pushed me to deliver the right things on the right time. Many thanks for the other committee members: Vincent Beijk, Ralph Schielen and Wim Kanning for their astute observations and feedback. Also, Leo van Gelder was of great importance in showing me the insights needed of *Plan Sluizen* and supplying me with much-needed contacts in the Rhine-Meuse estuary.

My thanks also for the fellow students and members of the Delta Futures Lab, who helped me by always asking questions and sharing their knowledge. The meeting we had about the drought problems in the Netherlands has helped me to place this study in a more practical view and by showing me that there are multiple roads to Rome.

On a more personal level, I would like to thank my family and friends who directly and indirectly helped me in completing this thesis, by giving feedback and by distracting me from work at the right times. A special thanks to my parents, who supported me not only during this last hurdle in my academic career, but also by continually supporting me in the (many) years before. The last thank-you is reserved for my girlfriend, who has been a constant moral support in all my endeavors.

This thesis marks the end of my time as a student, which was a fantastic chapter of my life. Enjoy reading!

J.O. Ziere
Rotterdam, June 2021

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Chapter 1

Introduction

In this chapter, background and problem statement are introduced, as well as the objective and scope of the research (sections 1.1-1.4). In section 1.5, the thesis approach is covered.

1.1 Background

The climate on our planet is changing in a dramatic way. Because of the increase in greenhouse gases in the atmosphere, the mondial average temperatures have been rising since the industrial revolution (1790 - 1850), when greenhouse gases began to be emitted due to human exploits and use of fossil fuels. This correlation is apparent in Figure 1.1, where the global temperature rise and CO_2 emissions are shown. The rise in temperature has a large impact on the climate on earth, although the average global temperature rise has been "only" about one degree Celcius since 1850 (Alola & Kirikkaleli, 2021). As a result, sea levels have been increasing (Wahl et al., 2013), the glaciers and polar ice caps have been decreasing in size (Tepes et al., 2021) and the deserts are expanding (Bayram & Öztürk, 2021).

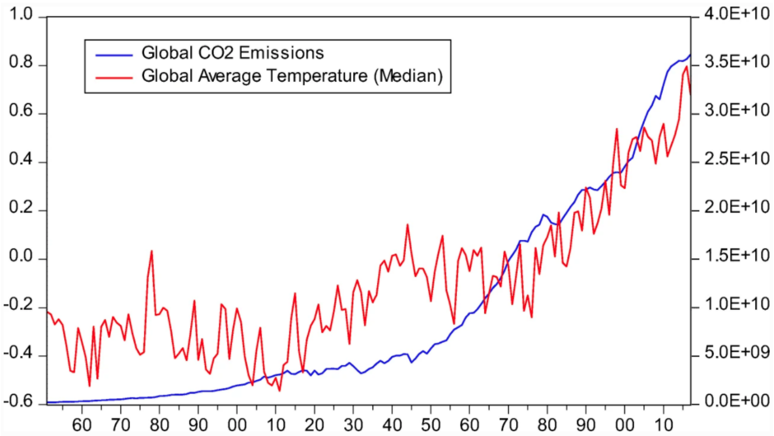
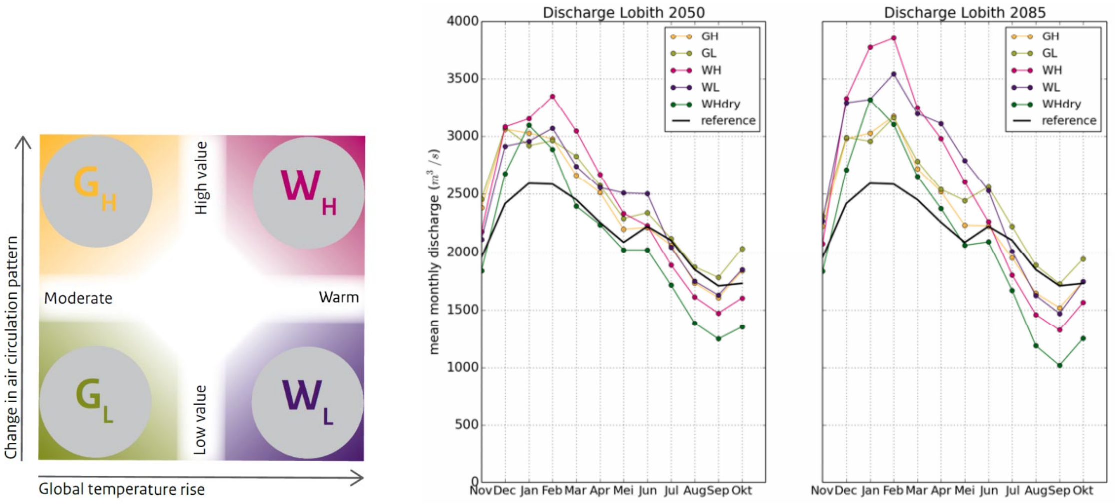


Figure 1.1: Global temperature rise (left axis) and global CO_2 emissions (right axis) since 1850 (Alola & Kirikkaleli, 2021)

In the Netherlands, the temperature has risen by 1.9 °C since 1950 (Cornes, van der Schrier, van den Besselaar, & Jones, 2018). In this thesis, two major problems of climate change for the Netherlands are considered: rising sea level and drier summers. Sea level rise is especially problematic for the Netherlands, because the majority of the surface area is below sea level. These low-lying areas are in danger of flooding if the flood defences are not adjusted to this rising sea level. In the east of the Netherlands, a different problem arises because of the rising temperatures: higher parts of the country are drying out in summer due to higher evaporation rates and lower precipitation amounts (Beersma & Buishand, 2007; Zee, 2020). The combination of these effects causes failure of harvest, and while this could be combated with different, adaptive farming techniques (van Duinen, Filatova, Geurts, & van der Veen, 2015), a fresh water deficit remains a problem for farmers. The farmers in the Netherlands ensure workable land by draining the surplus of precipitation in winter, which causes a limited water buffer in the unsaturated zone in summer. This restricts the infiltration of precipitation to the groundwater. In addition, drier summers also cause a low discharge of water in the Rhine branches, which has caused problems to shipping and millions of Euros in damage (Philip, Kew, van der Wiel, Wanders, & van Oldenborgh, 2020). Barge shipping is of great economic importance to the Netherlands because especially the Waal is an important shipping route to and from the Rotterdam harbour, the biggest port in Europe (Nientied et al., 2018).

The effects of climate change in the Netherlands are expected to increase in the future. The latest climate model of the Royal National Meteorological Institute of the Netherlands, the KNMI, considers four base scenarios based on temperature rise and atmospheric change (see Figure 1.2(a)). A high atmospheric change denotes a greater difference in precipitation throughout the year, expressing as more precipitation in winter and less in summer. Deltares has determined corresponding river discharges of the Meuse and Rhine river (Klijn, Hegnauer, Beersma, & Sperna Weiland, 2015; Sperna Weiland, Hegnauer, Bouaziz, & Beersma, 2015). To supplement the four KNMI scenarios, a fifth climate scenario was developed by Deltares for extremely dry summers and high atmospheric change, which is called the $W_{H,dry}$ scenario (Lenderink & Beersma, 2015). Using these five climate scenarios, the discharge of the Rhine has been projected for two moments in the future: 2050 and 2085 (Sperna Weiland et al., 2015).



(a) Climate scenarios as determined in the KNMI'14 report

(b) Predicted discharges of the Rhine at Lobith in 2050 and 2085 for different scenarios (Sperna Weiland et al., 2015)

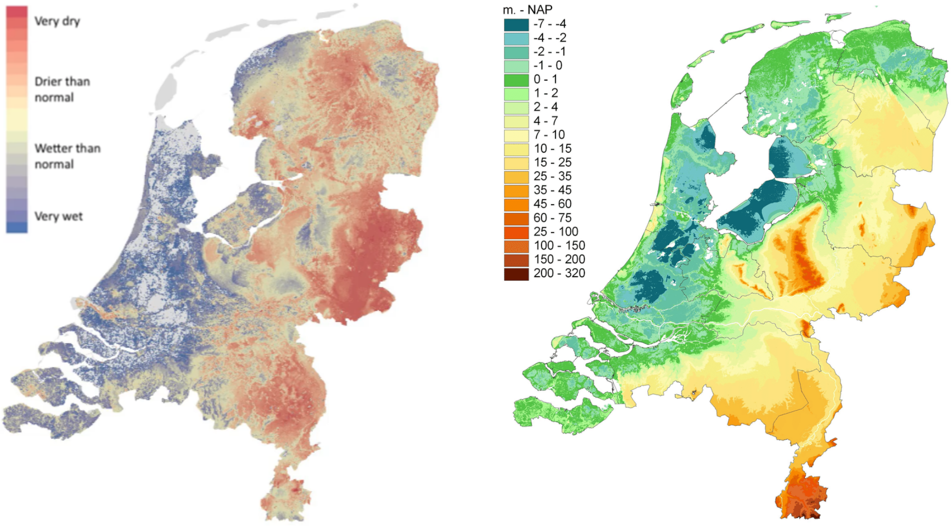
Figure 1.2: Climate scenarios and the corresponding Rhine discharge

As can be seen in Figure 1.2(b), the discharge in the winter will be higher in all scenarios, while the summer discharges will be less than the current situation (the reference value—the black line in Figure 1.2(b)) for most scenarios. In this study, the effects of a higher winter discharge are not considered, but the consequences of the changing climate require a dynamic water management policy. The current policy in the Netherlands is focused on flood risk mitigation and quick run-off of precipitation because, historically, the biggest risk in the Netherlands was a surplus of water. As was demonstrated by an experiment in which participants (grading from graduate students to water managers of the Delta

Program) dealt with the simulated effect of climate change on the river discharges in the Netherlands: "Participants were often focused on the peak discharges, as these result in the most severe impacts in this case and they tended to have less eye for the impacts of low flows" (Haasnoot, Schellekens, Beersma, Middelkoop, & Kwadijk, 2015). Therefore, in this study, the other effect of climate change is considered: drier summers.

1.1.1 Drier summers

In the last few years, droughts have occurred more frequently, causing damages in the Netherlands of 450 to 2080 million Euros in 2018 (Philip et al., 2020). Because of the consecutive dry summers in the Netherlands in 2018, 2019 and 2020, the groundwater stockpile in the east of the Netherlands has been depleted (Zee, 2020). This is illustrated in Figure 1.3(a), where drought in the east of the Netherlands is visible, even when the rest of the country is relatively wet. Because of deep sand layers in the east of the Netherlands, groundwater levels can deplete to a much greater extent than the more clay-rich soils in the western parts of the country, where an impermeable layer prevents the depletion of the aquifers. Because agriculture in the east of the Netherlands is dependent on precipitation for its fresh water demands, an absence of sufficient precipitation causes farmers not situated along the Twentekanalen (see Figure 1.4(b)) to use the only other fresh water source available in the area: groundwater. This agricultural use increases the strain on the groundwater levels during dry spells. The amount of infiltration of a single precipitation event is not sufficient to adequately restore these groundwater levels, and it may take the sandy soils of the higher elevated regions of the Netherlands (such as in the east and the Veluwe) 7 to 8 years to recuperate from two consecutive dry summers (Pouwels, de Louw, Hendriks, & Hunink, 2020). In order to restore the groundwater levels, first a precipitation surplus must occur. Yet, a surplus was not present in 2020, as can be determined by the cumulative precipitation deficit in the region of Enschede on the thirteenth of November 2020. The cumulative deficit of the growing season was 252 mm, where the average precipitation deficit in this area around this time should be approximately 25 mm (Waterschap Vechtstromen, 2020).



(a) Drought in the Netherlands in June 2019 (adapted from *HydroLogic*)

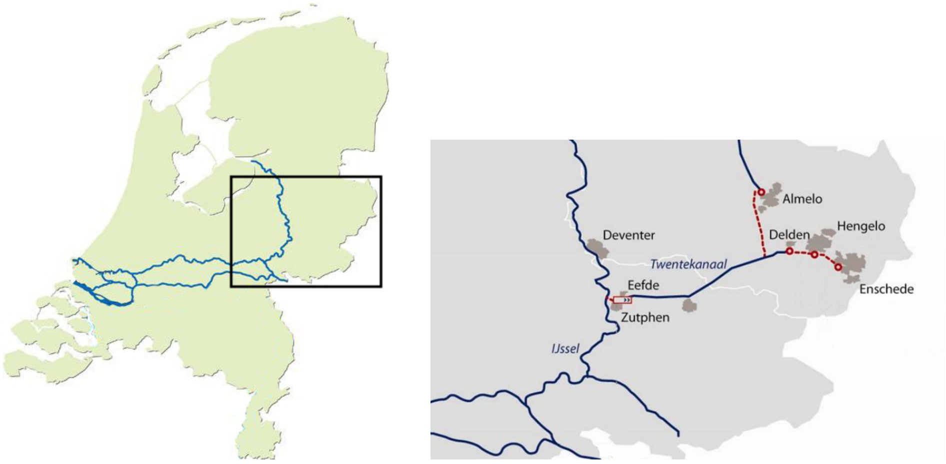
(b) Elevation of the Netherlands (Blom-Zandstra et al., 2009)

Figure 1.3: Drought and elevation of the Netherlands

Low groundwater levels could have far-reaching effects. The impact on ecology and agriculture is large (Zee, 2020). Groundwater depletion affects ecosystems, as there are many organisms directly and indirectly dependent on the availability of edible vegetation and water. Therefore, the groundwater table has a direct influence on surface water levels (De Vries, 1994). Furthermore, the risk of wildfires is enhanced when vegetation is dried out and temperatures are high, which is a danger to both animals and humans in the area.

1.1.2 Sea level rise

The Netherlands is adapted to living below sea level. A large portion of the country depends upon the integrity and effectiveness of dikes, barriers and other flood defences. In this study, a replacement of the storm surge barrier located in the Nieuwe Waterweg (the Maeslantkering) is considered. The barrier protects the city of Rotterdam and its surrounding area against high sea levels and storm surges. The Maeslantkering is a movable barrier which is closed when a high sea level is predicted. But the Maeslantkering is not sufficient when the sea level rise gets to 2 meters above NAP (Wilmink, Strijker, Aarninkhof, Kok, & Jonkman, 2019). Using the IPCC emission scenario, RPC8.5 (Stocker et al., 2013), that corresponds with the $W_{H,dry}$ scenario, the sea level rise in 2050 causes the Maeslantkering to be closed once per year (van den Hurk & Geetsema, 2020). The frequency of closing once per year is the predetermined signal value to implement adaptations to the changing situation (Kwadijk et al., 2010). This signal value determines the point at which a different solution in the Rijnmond must be considered, where the Rhine flows into the North Sea. A possible adaptation solution is placing a permanent barrier with a sea lock system in the Rijnmond to prevent flooding of Rotterdam and the hinterlands. In closing the Rijnmond with a modern sea lock system, the formation of a salt wedge is greatly inhibited, because the tide is stopped by the permanent barrier. Salt intrusion will still occur, but the amount of saline water that is forced into the estuary every tidal cycle is greatly diminished. The placement of a water barrier in the Rijnmond induces a water level change. This change causes a backwater curve, which in turn could influence the water distribution at the Pannerdensche Kop, especially at low Rhine discharges. The Pannerdensche Kop is situated 10 km inland from where the Rhine flows into the Netherlands, and at this bifurcation point the Rhine splits into the Waal and the Pannerdensch Kanaal. The Pannerdensch Kanaal splits into the IJssel and Nederrijn at the IJsselkop, see Figure 1.4(a). The Pannerdensche Kop is a static bifurcation point, and as such cannot be adapted to different discharges dynamically. The effect of the backwater curve following the construction of the permanent barrier on the water levels in the Rhine river system has not been determined yet.



(a) Rhine river system with the IJssel flowing north and the Waal flowing west

(b) Location of the Twentekanalen (adapted from Rijkswaterstaat, 2015)

Figure 1.4: Rhine river system and Twentekanalen

In the current situation, to stop the salt wedge from intruding too far inland, a minimum discharge of 1500 m^3/s of water is maintained in the Nieuwe Waterweg (Rijkswaterstaat, 2004), called flushing. When river discharges are average to high (above 1700 m^3/s at Lobith), salt intrusion in the Nieuwe Waterweg remains within reasonable limits. Therefore, river water from the Rhine does not need to be diverted through the entire Rhine-Meuse estuary system for flushing purposes (stopping the propagation of the salt wedge). In contrast, when discharges are below 1400 1700 m^3/s, the proportion that is discharged through the Nieuwe Waterweg is around 80% of water available in the Rhine river (Sloff, Van der Sligte, & Ottevanger, 2014). This causes the discharge of the IJssel to be affected more by the occurrence of low Rhine discharges, which in turn affects the navigability of the IJssel. The IJssel river is the main contributor of discharge to the IJsselmeer. The IJsselmeer is the largest fresh water buffer in the Netherlands and the main supplier of fresh water to the northern parts of the Netherlands during dry spells. However, the Waal is of higher economical value to the Netherlands, and, in consequence, sufficient water discharge over the Waal is prioritised over the water discharge over the IJssel. This results in additional stress on the east of the Netherlands, as the water from the IJssel river is sorely needed to irrigate the land in dry times.

1.2 Problem statement

In section 1.1, the need for climate change adaptation is presented. This study focuses on the strain on the groundwater levels in the east of the Netherlands. The adaptation solution of a new permanent storm surge barrier in the Rijnmond is used in the assessment of this problem because the effect of the placement of this barrier on the discharge distribution of the Rhine branches is unknown but it could provide a chance to reassess the current distribution of water over the Waal and IJssel river.
With a reassessment of water discharge available in the Rhine branches, the IJssel might receive a greater portion of the fresh water available if the water is not needed in the Waal for flushing. This is especially relevant for barge shipping in the IJssel, because flushing currently disproportionally affects the IJssel due to the fact that sufficient water discharge in the Waal is prioritised. Furthermore, throughout the year and especially in the months leading up to the summer, extra fresh water discharge could provide the east of the Netherlands through the Twentekanalen with extra water to irrigate this area and provides the IJsselmeer with additional water which can be used during droughts. This may also help combat salinisation of the IJselmeer, as in the current situation the water available in the IJsselmeer is in dry times not sufficient to stop the salt intrusion though the Afsluitdijk due to the locking processes for navigation and saline upwelling (Bonte & Zwolsman, 2010). The influence of the salinisation of the IJsselmeer is outside the scope of this thesis.

The east of the Netherlands cannot be supplied with water from a water reservoir through gravity flow, since the water level in the IJssel and IJsselmeer is about 10 m lower in altitude with regard to the area suffering from drought (see Figure 1.3). Therefore, a system has to be in place to move the water to the irrigation area, whether by pumping up water from Dutch water sources or by using higher water sources abroad. As can be seen in Figure 1.3, even when the rest of the Netherlands is relatively wet, the region east of the IJssel still deals with drought. The deep groundwater reserves need to be refilled, which is done most efficiently using infiltration of precipitation to the groundwater reserves. In absence of precipitation, surface water may be supplied by the IJssel or by the Twentekanalen (see Figure 1.4(b)) for infiltration to the groundwater, but additional infrastructure has to be installed for this option.

1.3 Objective

The objective of this study is to determine the effect a placement of a permanent water barrier in the Rijnmond has on the Rhine river system and whether this provides an opportunity to mitigate the effects of drought in the east of the Netherlands. This is done by first determining the effect of a closure of the Rijnmond on the river system. Secondly, the effect of river water infiltration in the east of the Netherlands on the water levels and navigability of the Waal and the IJssel is studied.

This leads to the main research question of this thesis:

In what way can the placement of a permanent water barrier in the Rijnmond help in restoring groundwater levels in the east of the Netherlands?

To help answer the main research question, five sub-questions are formulated:

1. *How does climate change influence the occurrence of droughts in the east of the Netherlands and the Rhine river system?*
   To fully understand the necessity of a solution for drought in the east of the Netherlands, the effect of climate change on the precipitation and evaporation is investigated, as well as the specific low water discharges in the Rhine river system.

2. *What is the hydrodynamical behaviour of the Rhine river system during dry spells?*
   To determine the operational limits of the Rhine branches, the river system is analysed. Such as the water distribution during average to low river discharges and the corresponding fresh water demands during dry spells.

3. *How can surface water be used to restore groundwater levels in the east of the Netherlands and how much water is needed in a dry summer?*
   To assess the effectiveness of surface water infiltration, several infiltration methods are studied. Based on these methods, the amount of water that can be supplied to the east of the Netherlands is determined.

4. *What impact does the placement of a permanent water barrier in the Rijnmond have on the Rhine river system at average to low flows on water levels and discharges?*
   Using the answers to sub-questions 1 and 2, several discharge scenarios are investigated and the effect of a permanent water barrier is determined.

5. *What is the impact of river water infiltration and redistribution on the Rhine river system at average to low flows on water levels and discharges?*
   The answers to sub-questions 1, 2 and 3 are used to study the effect of extra surface water infiltration in the east of the Netherlands.

1.4 Scope

The effect of placing a permanent water barrier in the Rijnmond and water infiltration in the east of the Netherlands will be assessed for the Dutch Rhine river system. Two hydrological parameters will be used to determine the behavior of the river system: water level and discharge. Because weirs are present in the Nederrijn/Lek to regulate the river discharge and water levels during low flows, that Rhine branch is more regulated than the Waal and IJssel rivers. With low Rhine discharges, only the amount of water that is needed to fulfill the fresh water demands along the Nederrijn is discharged through the river (Spijker & van den Brink, 2013). The considered river system is given in Figure 1.4(a). Two situations are considered at the Rijnmond: the current, open, situation and the closed situation. The closed situation is assumed to be a complete closure of the Nieuwe Waterweg and Calandkanaal.

The design of this sea-lock installation is outside the scope of this thesis. While determining the operational limits of the Waal river and the fresh water demands of the Rijnmond area, all Rhine branches and the Meuse river will be taken into consideration.

The river system that is considered covers all of the Dutch Rhine branches, with emphasis on the Waal and IJssel river. In order to assess the impact of changes in the river system and climate change on the river system, the driest climate scenario, $W_{H,dry}$, is chosen as the baseline for the considered Rhine discharges. This scenario projects the largest decrease in Rhine discharge of the climate scenarios in Figure 1.2(b), and is thus the critical scenario for this study. A range of possible river discharges is considered in this study, this is further explained in Chapter 3. The river system and its topography are determined in collaboration with Rijkswaterstaat, which has provided schematizations of the Rhine river system. These schematizations are adapted to reflect the river system as depicted in Figure 1.4(a), with and without a closure of the Rijnmond.

The study area for the groundwater drought mitigation consists of the region specified in Figure 1.4(a) with the black rectangle, between the IJssel and the German border. Three groundwater infiltration options are examined, all of which use the same infiltration method: supplying the streams in the area with external river water. This was determined in cooperation with experts (van Houweninge, 2020; van Houten, 2021).

1.5 Thesis approach and structure

The research of this thesis is divided in three phases: literature study, system analysis and answering the main question. The first three sub-questions are addressed using literature research and interviews with experts, while the fourth and fifth sub-questions will be answered using computational analysis. A general schematization of the research process of this thesis is depicted in Figure 1.5. A more detailed description of the methodology can be found in Chapter 2.

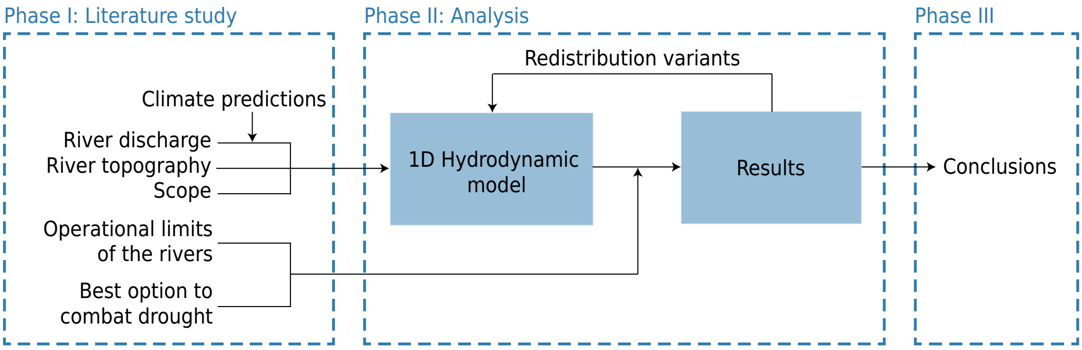


Figure 1.5: Research process

This thesis consists of 9 chapters, which are briefly discussed below.

Chapter 1. Introduction
In the first chapter, an introduction is provided to the research thesis. The background of the research is given, along with the problem statement, thesis goal and approach.

Chapter 2. Methodology
The second chapter concerns the methodology. This chapter includes the methods of gathering information and data analysis. In addition, the choice of analytical method used in this thesis is discussed as well as the model set-up.

Part I: Literature study

Chapter 3. Climate change in the Netherlands
The third chapter will entail the literature research on the effects of climate change on the river system and groundwater levels in the east of the Netherlands. In this chapter the first sub-question is answered.

Chapter 4. Rhine river system
In this chapter, the Rhine river system is analysed and the operational limits and water demands are determined. The distribution of the Rhine discharge in dry conditions is given in this chapter and the second sub-question is answered.

Chapter 5. Groundwater and infiltration
A possible solution for the groundwater problems in the east of the Netherlands area by using surface water is determined. Water demand, extraction locations and the effects on the drought-affected area are analysed in this section of the thesis. The third sub-question is answered in this chapter.

Part II: Computations and results

Chapter 6. Closing the Rijnmond
The sixth chapter shows the computational analysis results of closing the Rijnmond. This includes the model set-up. The effect on the river system is described in this chapter, along with the relevant data and computations that yielded these results. The fourth sub-question is answered in this chapter.

Chapter 7. Extraction and redistribution
In this chapter, the impact of water extraction in three different ways is examined. Also, the effect of redistribution is discussed, answering the fifth sub-question.

Part III: Discussion and conclusion

Chapter 8. Discussion
In this chapter, the results in the previous chapters are discussed, as well as the research approach and execution. This will be the basis for the concluding chapter.

Chapter 9. Conclusion and recommendations
In the last chapter, the conclusions of this thesis are drawn by answering the main research question using the previous chapters. The discussion chapter is used to formulate recommendations for future research.

Chapter 2

Methodology

In this chapter, the methodology used in this study is explained. This is done in two parts: sources and methods. The sources section concerns the raw data that is used in analysing the problem, while the methods explains the way the data is used to acquire the results.

2.1 Sources

The data sources used are divided into four categories: literature, interviews, software and schematizations. Each category is explained in the section below.

2.1.1 Literature study

To determine the impact of different climate scenarios and different river system orientations a literature study is done. The literature study focuses on three main subjects: 1.) the climate change in the Netherlands, 2.) the behaviour of the Rhine river system in the current and possible future situations and 3.) the groundwater situation in the east of the Netherlands. These three subjects correspond with the first three sub-questions of the research question. The advantage of literature study is that in a relatively short period of time a large amount of information can be gathered, independently of computations or other people.

2.1.2 Interviews

As an addition to the information gathered in the literature study, interviews have been conducted to acquire specific, location or company dependent information. In order to determine the water demands of the water boards, experts of the water boards Waterschap Rijn en IJssel and Waterschap Hollandse Delta have been consulted. The water treatment company Evides has also been contacted to acquire specific discharge data for water demands. In understanding the groundwater situation in the east of the Netherlands, in-depth knowledge is required to assess the influence of interventions, and an expert of hydrology in that area is contacted. The advantage of conducting interviews is that very specific knowledge can be acquired, but this knowledge is more subjective than the validated literature. The topics of the conducted interviews can be seen in Table 2.1, and a summary of the interview is presented in Appendix A.

2.1.3 SOBEK software

To determine the effect of different scenarios (climate and river system) the river discharge and water levels in the river system are most important for a first assessment of the impact. These parameters varying scenarios are determined fastest by conducting one dimensional hydrological computations for shallow water. In order to determine the water levels and discharges of a river system with several

Table 2.1: Conducted interviews

Interviewee	Topic	Date
G. van Houweninge	Drought Achterhoek	13/11/2020
T. IJpelaar	Water management Waterschap Hollandse Delta	14/01/2021
G. van Houten	Water management Waterschap Rijn en IJssel	15/01/2021
B. Schaaf	Water demand Evides	21/01/2021
G. Roelofs	Groundwater management Waterschap Rijn en IJssel	30/04/2021

branches, cross-sections and roughnesses a computational analysis is done, using 1D hydrodynamic modelling software. More detailed 2D or 3D hydrodynamic models can also be used (Baptist, 2005), but take up significantly more computation time and the detailed results using these computations don't present insights relevant for the research question and scope of this thesis.

Since the available 1D hydrodynamic software is similar to each other in method and result, SOBEK is chosen because this is most widely used in the Netherlands and by Rijkswaterstaat. The advantage of SOBEK is that it uses an efficient and stable numerical scheme to solve the hydrodynamic equations, the Delft scheme. This scheme uses a staggered grid, which is efficient for large networks and long time series because it uses a minimum degree algorithm with an iterative simulation technique (Deltares, 2019). The SOBEK software computes the water flow and corresponding water height by solving the de Saint-Venant et al., 1871 equations for unsteady flow. A series of assumptions have to be made in order to solve the shallow water equations (Deltares, 2021):

- Uniform, one directional flow over the cross section and there is no horizontal water level slope across the cross section.
- Hydrostatic water pressure because the curve of the streamline is small and the vertical accelerations are negligible.
- The resistance laws as used with steady flow are applicable to account for boundary friction and turbulence.
- The average bed slope of the channel is small so that the cosine of the angle it makes with the horizontal may be replaced by unity.

These assumptions result in a system of two equations which are solved numerically: The 1D continuity and momentum equation, Equations (2.1) and (2.2), respectively.

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \tag{2.1}$$

where:

A_T = Total area (sum of flow area and storage area) [m^2]
Q = Discharge [m^3/s]
q_{lat} = Lateral discharge per unit length [m^2/s]. Positive value refers to inflow. Negative value refers to outflow.

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_F}\right) + gA_F\frac{\partial \zeta}{\partial x} + \frac{gQ|Q|}{C^2RA_F} - w_f\frac{\tau_{wind}}{\rho_w} + gA_F\frac{\xi Q|Q|}{L_x} = 0 \tag{2.2}$$

where:

Q = Discharge [m^3/s]
t = Time [s]
x = Distance along the channel axis [m]

A_F = Flow area [m²]
g = Acceleration due to gravity [m/s²]
ζ = Water level [m]
C = Chézy value [m$^{1/2}$/s]
R = Hydraulic radius [m]
w_f = Water surface width [m]
τ_{wind} = water level [m]
ρ_w = water level [m]
ξ = water level [m]
L_x = Length of branch segment, accommodating an Extra Resistance Node [m]

Several parameters have to be defined in order to solve the equations. These parameters are confined in a schematization, while boundary conditions at the in- and outflow boundaries provide the variables. At the upstream boundary (or boundaries) of the schematization, a water discharge has to be defined while at the downstream boundary (or boundaries) a water height must be defined in order to have a well-defined computation.

2.1.4 Schematizations

The first step in analysing the river system is schematizing the river system. A schematization is a model of the reality, a simplification. The topography of a river system is defined (branch length, meanders, etc) and the cross-sections and hydraulic roughness of the system is determined. Together with the boundary data, the schematization provides the data needed to solve the shallow water equations in the specified computational nodes in the schematization. A schematization of the Rhine branches is available at Rijkswaterstaat, which uses SOBEK software. Because a schematization of the whole study area is not available at Rijkswaterstaat two schematizations are used. These are the Rhine-Meuse estuary schematization and the Rhine branches schematization. These schematizations have an overlap, which enables a transition of data between the schematizations. The schematizations will be adapted to reflect the system in Figure 1.4, with both the Rijnmond open and closed off and different extraction scenarios.

The linking of the two schematizations is done by defining a relation between the water discharge of the Waal river and the water height in the Waal river for different river configurations. The overlap between the schematizations consists of a part of the Waal river, between Hardinxveld and Tiel. Tiel is the upstream boundary of the Rhine-Meuse estuary schematization, while Hardixveld is the downstream boundary of the Rhine branches schematization. In the downstream boundary a water level has to be specified in order to provide a solvable system, while a water discharge has to be specified in the upstream boundary. To link the two schematizations, the water discharge at Tiel must be known while at Hardixveld the water level is of importance.

Rhine-Meuse estuary schematization

The adapted Rhine-Meuse estuary schematization (Buschman, 2018) can be seen in Figure 2.1 includes the Lek, the Hollandse IJssel, the system of canals and harhours in the Rotterdam area, the Haringvliet, the Waal and the Meuse rivers. The water demands of the water boards, drinking water and industry are defined as a lateral sink in the Brielse Meer. At the Haringvliet and Volkerrak sluices a discharge is defined, while at the Maasmonding a water level will be defined, the value of which will be determined using literature study.

Rhine schematization

The adapted Rhine schematization (Agtersloot, Michels, & Van der Veen, 2019) is shown in 2.2 and includes the Rhine, Pannerdensch Kanaal, Waal and IJssel river. The Nederrijn is schematised as a lateral sink because the effect of the Nederrijn discharge is important for the discharge distribution

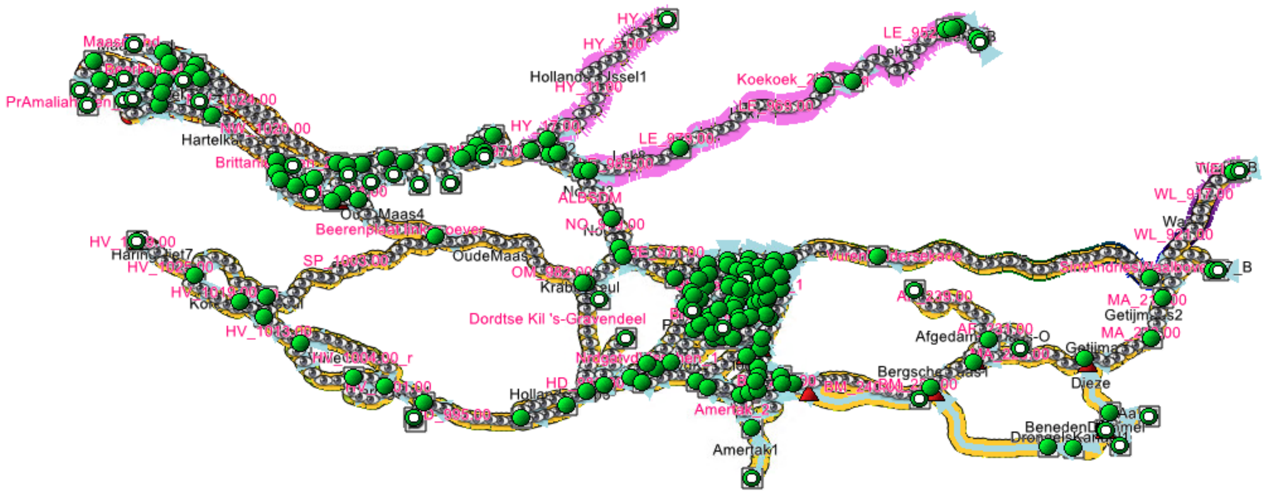


Figure 2.1: The adapted SOBEK schematization of the Rhine-Meuse estuary

at the IJsselkop, where the Pannerdensch Kanaal splits into the IJssel and the Nederrijn. The water levels in the Nederrijn are outside of the scope of this research however, so computational effort is saved by defining the Nederrijn as a lateral sink while still controlling the discharge distribution at the IJsselkop. At the downstream boundary of the IJsselmeer the water level is assumed to be constant, at the summer level of the IJsselmeer. The water level at Hardinxveld is defined using the Rhine-Meuse estuary schematization.

2.2 Methods

Using the literature study and interviews, the required data (consisting primarily of the value and location of the fresh water extractions and required water levels) is acquired to operate the SOBEK software. In addition to the schematizations the different discharge scenarios and river distribution scenarios must be defined. The river discharges are defined using historical data and literature on climate change and its effect on the river regimes.

The effect of changing river regimes and discharge distributions are determined by running the SOBEK 1D hydrodynamic modelling software (FLOW-1D). The water levels and discharges at specified points are recorded for different model orientations (combinations between discharge and river system) in order to be able to determine the differences between the computations. The water levels of the computation are given in reference to the Amsterdam Ordinance Datum (*Normaal Amsterdans Peil*, NAP), which is the standard vertical datum used for height data in the Netherlands. To translate these height datum values to navigation depth, the cross sections of the river at the observation points must be known. As can be seen in Figure 2.3, the water level ζ is a summation of the water depth h and the bed level z_b. The cross sections are determined using the river schematization, where the predetermined cross-sections can be found. The river bed level (z_b) at the border of the main section of the cross-section is chosen as the depth of the main channel. In the case of the cross-section of the IJssel at Eefde (Figure 2.4), this value is -0.43 m NAP (local height datum denoted by Z).

The base situation of an open Rijnmond was schematized using a tidal cycle. The data available in the SOBEK schematization specified a uniform tidal cycle, and is given in Figure 2.5. This tidal cycle was extended to provide more data and to decrease the chance of inaccuracies due to computational spin up. The peak in the cycle around January is to determine the reliability of the solution, how dependent the solution is to changes in the downstream boundary condition. To determine the impact of the

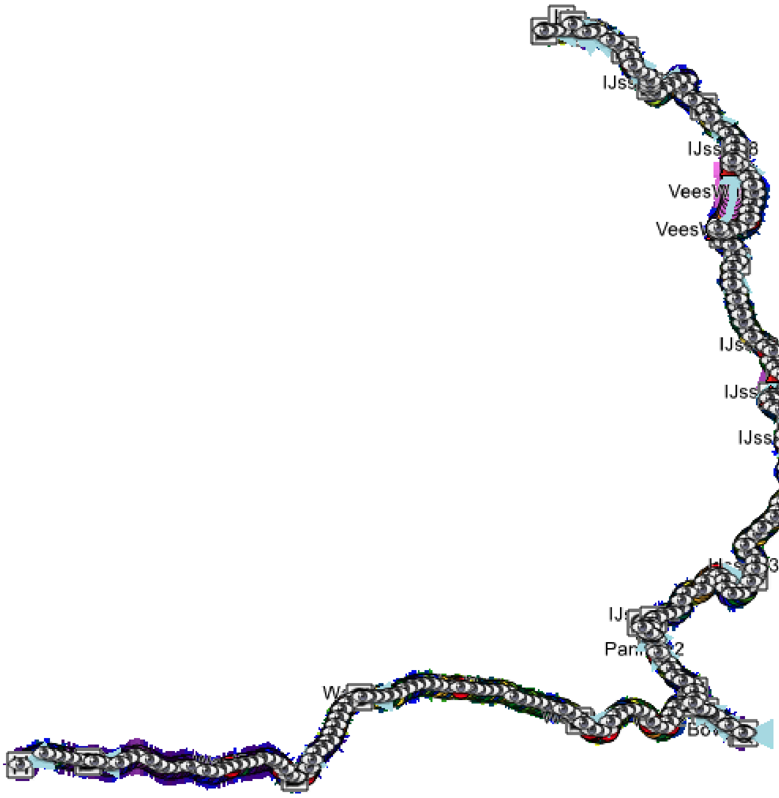


Figure 2.2: The adapted SOBEK schematization of the Rhine river system

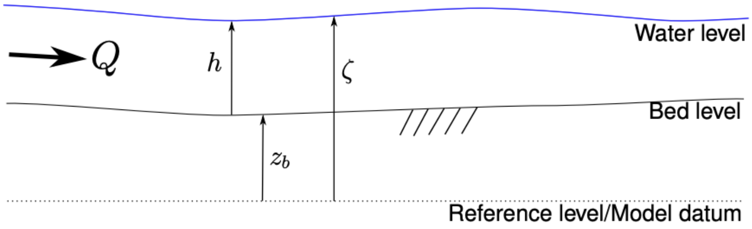


Figure 2.3: Difference in water, bed and reference level (Deltares, 2021)

closure of the Rijnmond a constant water height at the Rijnmond is defined using literature study. Using the Rhine-Meuse estuary schematization the water levels of the Waal up to Tiel can be computed. To determine the water levels of the rest of the Rhine river system the water level at Hardinxveld is determined using the Rhine-Meuse estuary schematization and is imported as a boundary condition in the Rhine branches schematization. The water height in Tiel is also recorded in order to validate the transition between the schematizations.

Rine-Meuse estuary

In order to transition between schematizations the water level in the Waal must be known, so a relation between several discharges and the water height is formulated. This is done for an open Rijnmond as well as a closed Rijnmond. In the open situation a tidal cycle is the downstream boundary condition, while a permanent barrier in the Rijnmond is simulated as a constant water height. There are two major water buffers in the Rhine-Meuse estuary: the Haringvliet and the Brielse Meer. In dry times the water level is preferred to be high in order to maximise the water buffer in the area. The maximum water level is 2.6 m + NAP at the Rijnmond, as the Noordereiland in Rotterdam is flooded

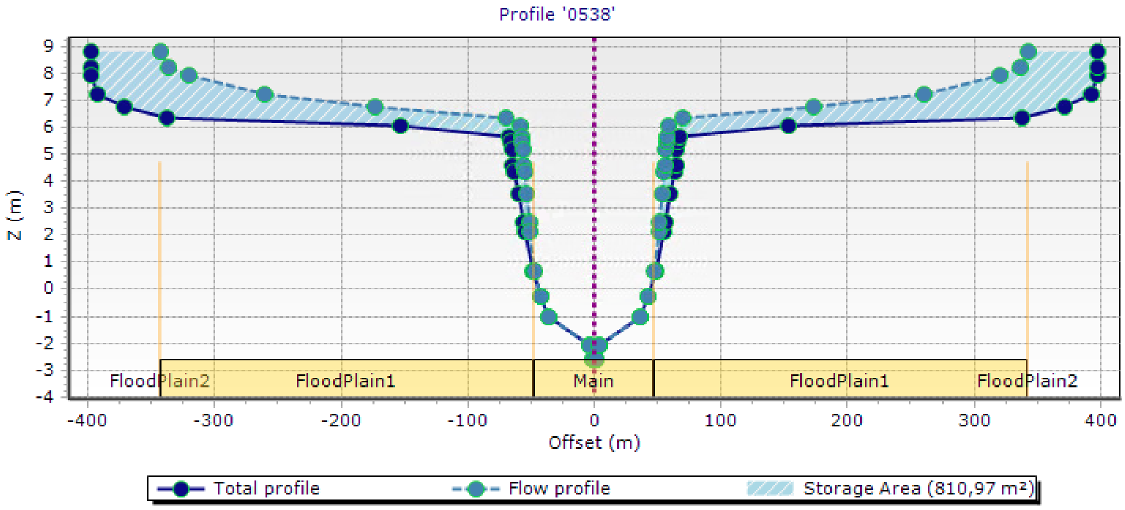


Figure 2.4: Cross-section of the Rhine schematization at Eefde in the IJssel

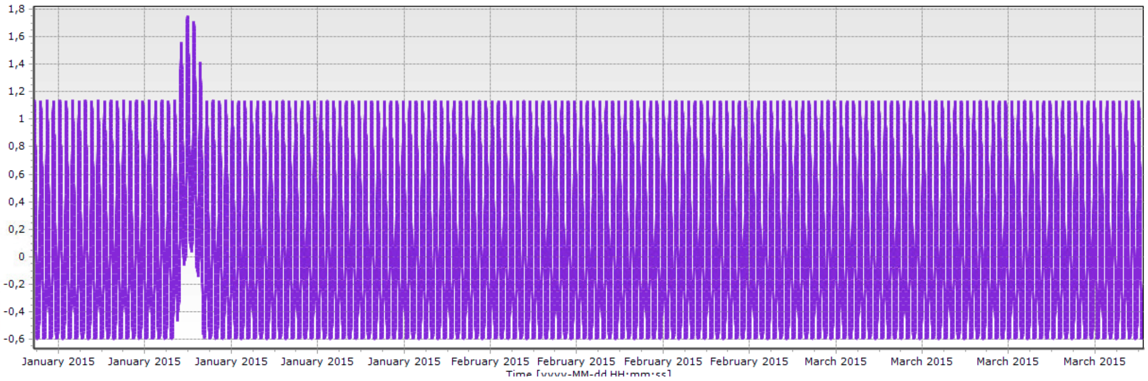


Figure 2.5: Tidal cycle at the Meuse river mouth

when the water level exceeds this value.

Rhine branches

In addition to determining the impact of the closing of the Rijnmond, the effect of the extraction of river water is computed. This water is used in the drought sensitive area in the east of the Netherlands. The impact of a redistribution of the available river water on the Rhine river system is also determined. For the extraction of river water, three extraction options are defined in this thesis:

- Pumping station in the IJssel
- Pumping station in the Rhine
- Canal from the Rhine further upstream of Lobith (in Germany)

To determine if a redistribution of the Rhine water is feasible, three options are defined:

- Canal from the Rhine further upstream of Lobith (in Germany)
- Using the Rijnstrangen to adjust the discharge to the Pannerdensch Kanaal
- Adjusting the bifurcation point at the Pannerdensche Kop

Due to time constraints and the complexity of the last redistribution option, adjusting the bifurcation point is beyond the scope of this research.

Chapter 3

Climate change in the Netherlands

Climate change presents a big problem for the Netherlands. Because our country is relatively flat with a large portion below the current sea level, floods have great consequences. After the flooding disaster of 1953 a new advisory committee was created to develop new flood risk policy, which it has been doing ever since (Yska, 2009). This committee, the Deltacommissie, determines the safety standards for flood risk in the Netherlands, which are based upon the projections of a changing climate. A relatively new problem has arisen for the higher parts of the Netherlands: drought. In this chapter two consequences of climate change are considered: drier summers and the sea level rise (SLR).

3.1 Drought

There are multiple definitions of drought. The most common definition is meteorological drought: a prolonged absence of precipitation. The focus of this study is hydrological drought, which is defined as "a lack of water in the hydrological system, manifesting itself in abnormally low streamflow in rivers and abnormally low levels in lakes, reservoirs, and groundwater" (Van Loon, 2015). Drought in the Netherlands is a consequence of more evaporation and less precipitation. This is influenced by climate change, as can be seen in Figure 3.1. First, meteorological drought is induced by dry summers, which then progresses toward hydrological drought. The trend in the Netherlands is toward higher temperatures in the summer, as is evident from the observed temperatures between 1950 and 2018 in the Netherlands, which have been increased by 1.9 °C (Cornes et al., 2018). Together with the increased evapotranspiration due to higher temperatures a soil water deficit occurs, which impacts the vegetation and agriculture. As been determined by Philip et al., 2020: "We thus conclude that although the trend in inland Apr-Sep precipitation is non-significant, agriculture droughts occur more frequently in 2018 than in 1950, which is due to trends towards higher temperatures and PET (potential evapotranspiration). For the future, we can expect either a continuation of the past trends in drought variables or even stronger drying trends due to changes in atmospheric circulation."

A projection of the driest climate scenario done by Deltares showed a 16% increase of evaporation and a 20% reduction of precipitation in the summer in 2050. By 2100, this effect may be doubled (Klijn et al., 2012). Extended periods of soil moisture drought, along with low amounts of run-off due to low precipitation causes the surface waters to be affected, as well as the groundwater levels. This is hydrological drought. Another study by Deltares (Arnold, 2011) projects that severe water deficits will occur yearly by 2050, including groundwater deficits in the high regions on the Netherlands (Beersma, Buishand, & Buiteveld, 2004; Bresser et al., 2005).

Groundwater levels are slowest of the hydrological water bodies to be affected by the dry spell, but also take the longest to recover from droughts. This is illustrated in Figure 3.2(a). In the east of the Netherlands, the groundwater levels have been depleted by the consecutive dry summers of 2018,

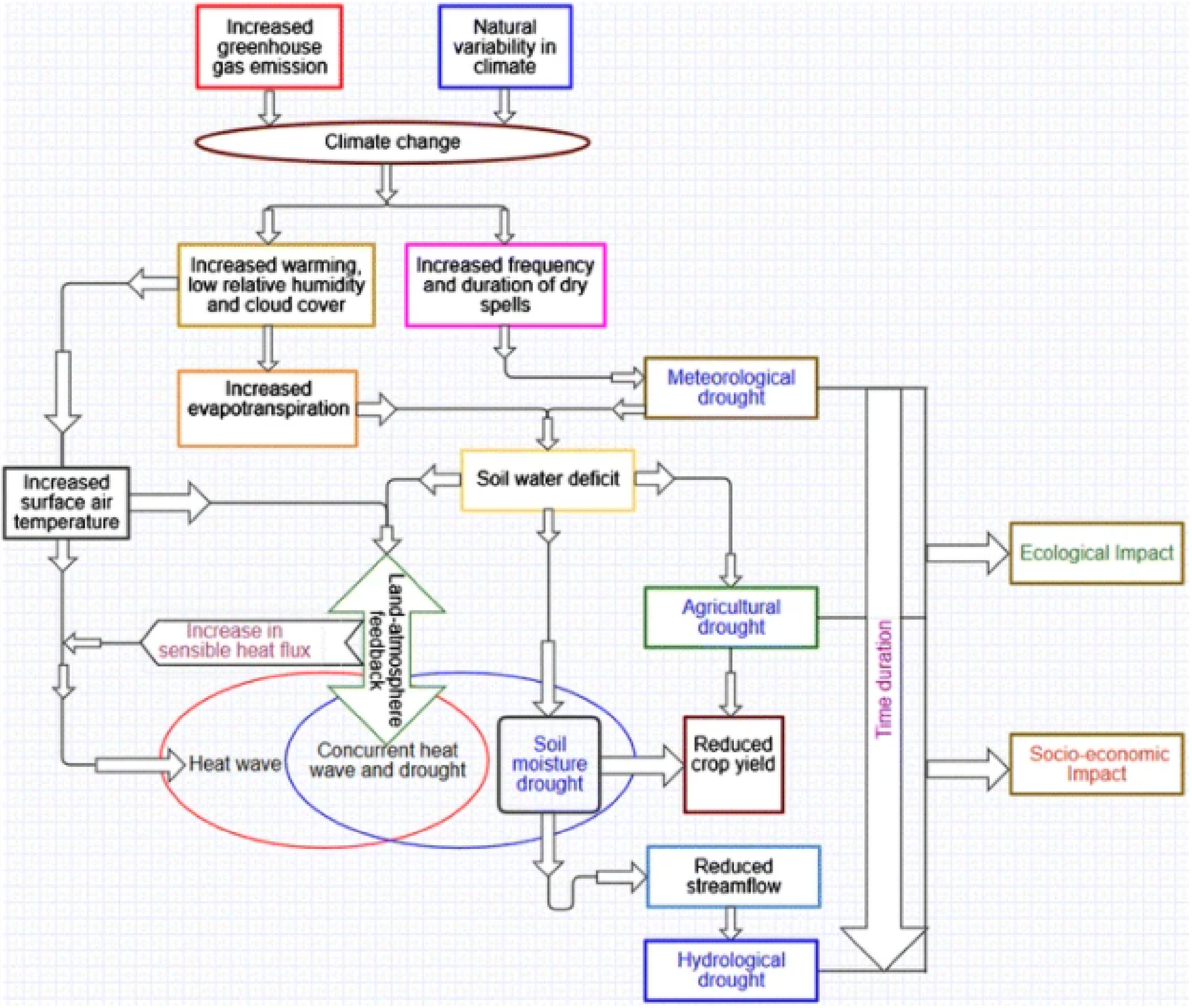
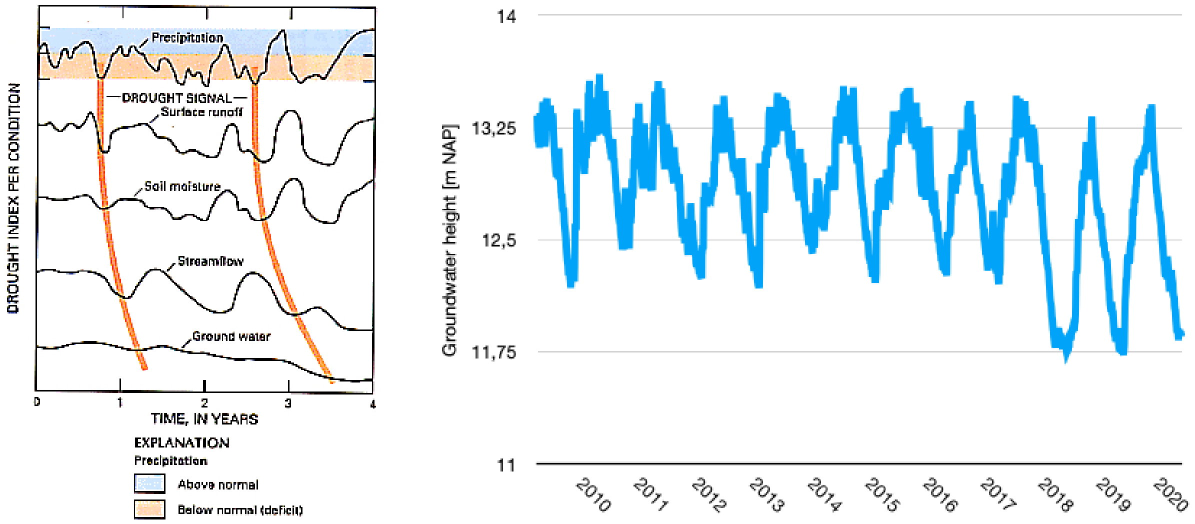


Figure 3.1: Relation of drought propagation under climate change (Mukherjee et al., 2018)

2019 and 2020. A full recovery of groundwater levels in the highest parts of the Netherlands may take up to 7 to 8 years (Pouwels et al., 2020). This can be seen in the east of the Netherlands, where the groundwater levels have not recuperated from the 2018 drought, see Figure 3.2(b). The effect of groundwater depletion on surface water is great (Kaandorp, 2019). Many streams in the east of the Netherlands are fed by groundwater, through local springs or diffuse seepage. Also, in agriculture groundwater is used for irrigation purposes. In this region, groundwater and surface water could be categorized as the same resource (De Vries, 1994; Winter, Harvey, Franke, & Alley, 1998).

For the Netherlands, the effect of drought on the groundwater differs depending on the region of the Netherlands. For the low-laying area of the Netherlands (generally the provinces of Zeeland, Zuid-Holland, Noord-Holland, Friesland and Groningen, see Figure 3.3) the effect on groundwater level is not significant, but the water quality is affected by the extra saline seepage induced by drought. For the higher parts of the Netherlands, the groundwater levels are lower on average because of climate change (Klijn et al., 2012), out of reach for the roots of the plants in the area during dry spells and thus completely dependent on precipitation and the water buffer in the unsaturated zone.



(a) Propagation of precipitation defecits through other components of the hydrologic cycle. (Modified from Changnon, 1987)

(b) Groundwater level in recent years in Linde, Gelderland (Munisense, 2021)

Figure 3.2: Effect of meteorological drought on groundwater levels

3.1.1 Effect of drought on the Rhine

The effect of droughts on the Dutch Rhine is large. Because of the changing climate, the rivers are becoming more dependent on precipitation and thus more fluctuations in discharge are expected. The Royal Dutch Meteorologic Institute (KNMI) has determined several climate scenarios. The effect of climate change on the discharge of the Rhine is projected to decrease on average by 5% to 8% in 2050. The river regime is not affected unilaterally, as both the droughts and floods will be more intense. The minimum discharges are projected to be decreased by 10% to 17% in 2050. Peak discharges are projected to increase by 2% to 6% in 2050 (Bergsma, Querner, & Van Lanen, 2010). A significant reduction in low diver discharge is expected after 2050, depending on the climate projection (Görgen et al., 2010).

To describe a value for the extreme low river discharges for the climate projections, the Agreed Low Discharge (ALD) has to be determined. The ALD is the discharge which on average will be undershot for 20 days per year. Currently, the Agreed Low Discharge of the Rhine at Lobith is determined as 1020 m^3/s (Doornekamp, 2019). The ALD for the KNMI scenarios W_H and $W_{H,dry}$ have been determined by Deltares (van der Mark, 2019) and are given in Table 3.1.

Table 3.1: Agreed Low Discharge for the Rhine for two of the KNMI scenarios (van der Mark, 2019)

Climate scenario	2050	2085
W_H	1013 m^3/s	985 m^3/s
$W_{H,dry}$	866 m^3/s	791 m^3/s

Figure 3.3: The regions of low-laying the Netherlands (green) and high-laying the Netherlands (brown) (Jeuken et al., 2012)

In the current situation, the Agreed Low Discharge is not representative of the extreme low Rhine discharges, as this discharge will be undershot for an average of 20 days per year. To determine a value of the extreme low discharge, historical data is analysed. The historically lowest Rhine discharge is 575 m^3/s, in 1929. This was 70% of the ALD at that time. Therefore, the assumed extreme low discharges corresponding to the climate scenarios of Table 3.1 are 70% of their respective ALD, which are given in Table 3.2.

Table 3.2: Extreme low discharge for the Rhine for two of the KNMI scenarios

Climate scenario	2050	2085
W_H	709 m^3/s	690 m^3/s
$W_{H,dry}$	606 m^3/s	554 m^3/s

3.2 Sea level rise

The sea level of the North Sea has been rising with about 20 to 30 cm per century (Wahl et al., 2013). This can be seen from Figure 3.4, where the level of the North Sea has been steadily increasing when greenhouse gases have been produced in a greater manner than before. The average sea level rise (SLR) of the last 120 years of the North Sea was 1.9 mm per year. The significant wave height of the North Sea is also increasing under the effects of sea level rise (Bindels, 2020), putting further strain on the flood defences of the Netherlands.

One of the flood defences against the sea water is the Maeslantkering, a storm surge barrier in the Nieuwe Waterweg which protects the city and port of Rotterdam against high water levels on the North Sea. The barrier closes when the water levels in Rotterdam are projected to be more than 2 m + NAP. Because of the sea level rise, the barrier will have to close more often: several times a year

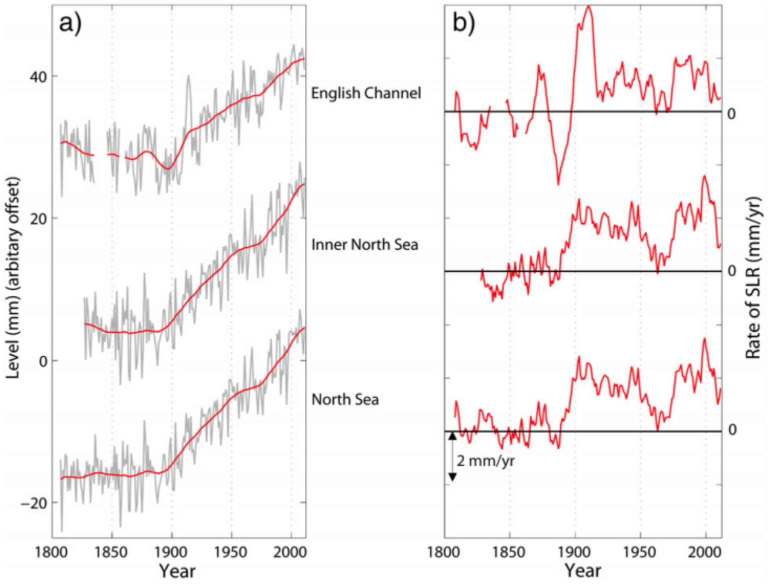


Figure 3.4: Observed sea level rise in the North Sea (Wahl et al., 2013)

with a SLR of 1 m and twice per day with a SLR of 2 m (Wilmink et al., 2019). According to some climate projections, the SLR could be 2 m already around 2100 when extra effects from polar melting are taken into account (Le Bars, Drijfhout, & de Vries, 2017), as can be seen in Figure 3.5. The Deltascenarios, which are the projections of the Dutch meteorologic institute (KNMI), project a SLR of maximally 80 cm in 2085 (Wolters et al., 2018).

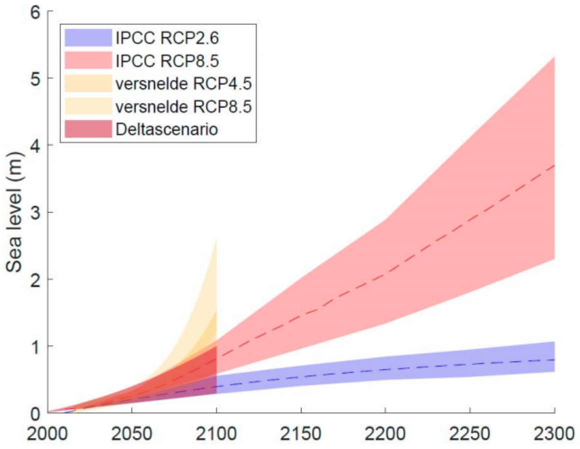


Figure 3.5: Projected sea level rise according to several scenarios (van den Hurk & Geetsema, 2020)

3.2.1 Future of the Maeslantkering

Because the Measlantkering is not sufficient to withstand the storm surges if SLR accelerates, a different flood defence should be considered. When the signal value of a closure of the Maeslantkering of once per year is reached, a different solution has to be designed in order to have a working barrier against the sea water when the barrier is not enough to prevent flooding of the hinterland (Kwadijk et al., 2010). There are several options to create a barrier for storm surges, but a movable storm surge barrier such as the Maeslantkering is deemed inefficient. In order to achieve the same access to the Port of Rotterdam (the same closing frequency as it is now) the flood risk of the entire city of Rotterdam must be decreased. This includes increasing the height of the river dikes and the ground level of the outer dike areas, which has great economic consequences. A preliminary study shows that a permanent barrier in the Rijnmond is deemed to be the best alternative for the habitability of the area, with a sea lock system to allow access to the Port of Rotterdam (Oosterling & van Liempd, 2020). The best location of this permanent barrier is given in Figure 3.6. At this location, only the sea dikes have to be reinforced while the river dikes can stay at the current level. This provides an economic advantage over other locations of the permanent barrier.

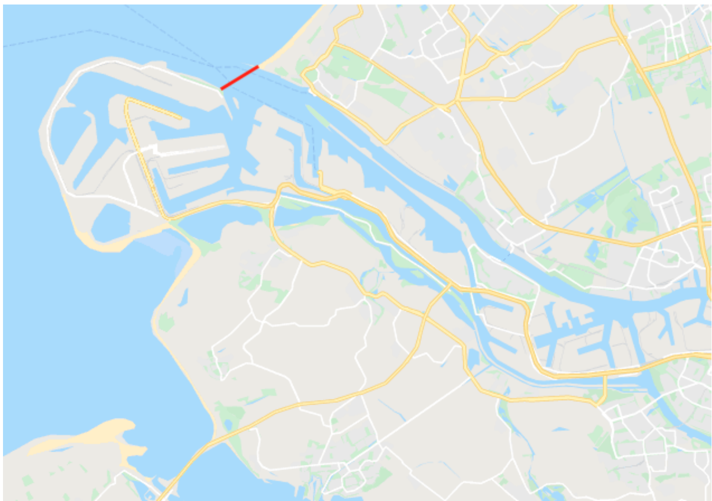


Figure 3.6: Location of the permanent flood defence in the Rijnmond indicated in red

3.3 Conclusions

In this section the answer is formulated to the first sub question: How does climate change influence the occurrence of droughts in the east of the Netherlands and the Rhine river system?

Because the temperatures are continuing to rise (1.9 °C since 1950) and the higher occurrence rate of droughts in the last few years, the load on the groundwater levels in the Netherlands is expected to increase. Because the groundwater levels are the slowest of the hydrological water bodies to respond to meteorological drought, this water reserve is affected last. However, it is also the slowest to recharge, so groundwater deficits are a long-term problem problem and could continue for up to 8 years in the case of the higher regions of the Netherlands. This causes damages to agriculture and ecology, as these are dependent on the groundwater when precipitation rates are low. For the driest climate scenarios the evaporation is increased by 16% while the precipitation is reduced by 20% in 2050, and this effect may be doubled by 2100. This causes a yearly severe deficit in water by 2050, both in the undammed regions of the Rhine river system and the groundwater levels in the higher regions of the Netherlands.

The Rhine river system is affected by climate change, becoming more dependent on precipitation for its discharge. This means the differences in discharge will get bigger, and more dry spells are expected to occur. On average throughout the year, the Rhine discharge is projected to decrease by 5 to 8%. The amount of low Rhine discharges are also expected to be reduced, down to an amount of 554 m^3/s for the most extreme climate scenario. Because of sea level rise the Maeslantkering must be adapted to the higher levels of the North Sea, and an option to resolve this problem is constructing a permanent barrier in the Rijnmond, along with a sea lock system. The location of this barrier is assumed to be at the westernmost location of the Rijnmond. The lower limit of the Rhine discharge that will be considered in the analysis of the river system will range from 2000 m^3/s to 600 m^3/s, average to extremely low flows.

Chapter 4

River system

In this chapter the considered river system is discussed. First, the whole Dutch Rhine river system is described and its reaction on low Rhine discharges. The water demands of the Waal, IJssel and Twentekanalen are examined more closely later on in the chapter.

The Rhine river originates in the Alps in Switzerland. The river is one of the largest rivers in Europe and serves as a major shipping route for the ports of Cologne, Düsseldorf, Rotterdam, Strasbourg and Basel. The Rhine river enters the Netherlands nearby Lobith, at Rhine kilometer 857. A short distance away, at Rhine kilometer 867, the river splits at the Pannerdensche Kop into the Waal river and the Pannerdensch Kanaal, which in turn splits into the Nederrijn and the IJssel at the IJsselkop. In this thesis, when the Rhine discharge is mentioned the discharge of the Bovenrijn at Lobith is considered.

Most of the Rhine discharge flows through the Waal river. At the Agreed Low Discharge (ALD, the Rhine discharge which will be undershot for an average of 20 days per year) of the Rhine of 1020 m^3/s (Doornekamp, 2019), the discharge distribution of the Waal-Pannerdensch Kanaal is 80%-20% (Sloff et al., 2014). In dry conditions, the discharge through the Pannerdensch Kanaal will primarily flow through the IJssel. The rest of the river water is discharged through the Nederrijn/Lek. The discharge distribution at the Pannerdensche Kop is fixed, and the available Rhine discharge will be distributed over the Pannerdensch Kanaal and the Waal river in the same distribution. There are no weirs or locks in the Waal and IJssel branches, while the Nederrijn has adjustable weirs to regulate the river discharge. A schematization of the entire Dutch Rhine river system can be seen in Figure 4.1.

4.1 Discharge distribution

The current river discharge distribution over the Rhine branches is depicted in the figures below. The distributions are given for an average-to-dry situation of 1400 m^3/s of Rhine discharge at Lobith, a dry situation of 1000 m^3/s and an extremely dry situation of 800 m^3/s. The current return periods (determined using the discharge data from the time period of 1901 - 2015) for low Rhine discharges is given in Table 4.1. The discharge NM7Q denotes the lowest mean low-water discharge for 7 consecutive days, and is determined using a general extreme value distribution with L-moment parameter estimation method (Brahmer et al., 2018). With a changing climate, these return periods are subject to change.

Table 4.1: Return periods for NM7Q Rhine discharge at Lobith

Return period [years]	2	5	10	20	50	100
NM7Q discharge [m^3/s]	1075	908	829	769	705	665

Figure 4.1: Topographical map of the Rhine river system in the Netherlands

4.1.1 Average-to-low Rhine discharge

The water distribution over all Rhine branches is given in Figure 4.2. The Haringvliet sluices are partially closed when the Rhine discharge at Lobith gets below 1700 m^3/s to create a fresh water buffer in the Haringvliet. The discharge to the Nederrijn/Lek river is kept at 25 m^3/s by adjusting the weir in Driel, which is the discharge required for freshwater demands. As can be seen in Figure 4.2, very little water reaches the Nieuwe Waterweg through the Lek.

When the river discharge is still high enough, which is the case at 1400 m^3/s, the Haringvliet sluices are slighty open to flush out the salt water in the Haringvliet. The Volkerak sluices are also opened to provide fresh water. With a Rhine discharge of 1400 m^3/s there are no restrictions on the intake of fresh water, as there is enough water available in the Nieuwe Waterweg to prevent the salt tongue from propagating too far inland (flushing). However, the majority of the water available is regulated to flow through the Nieuwe waterweg.

4.1.2 Low Rhine discharge

In a dry situation, with a Rhine discharge of 1000 m^3/s, all weirs and sluices in the Meuse-Rhine estuary are closed (barring seepage and losses) to ensure maximum discharge through the Nieuwe Waterweg. The Prins Bernhard locks are opened to provide the Amsterdam Rijnkanaal (ARK) with sufficient fresh water. The water distribution of the Rhine river system is given in Figure 4.3. When the Rhine river discharge is at this level, salt intrusion at the Meuse-Rhine estuary begins to cause problems. Several inlets for fresh water are too saline and a separate fresh water source is needed, which is provided by extracting water further upstream in the ARK or Nederrijn/Lek river. This fresh water supply is not sufficient to prevent the saline seepage in Rijnland.

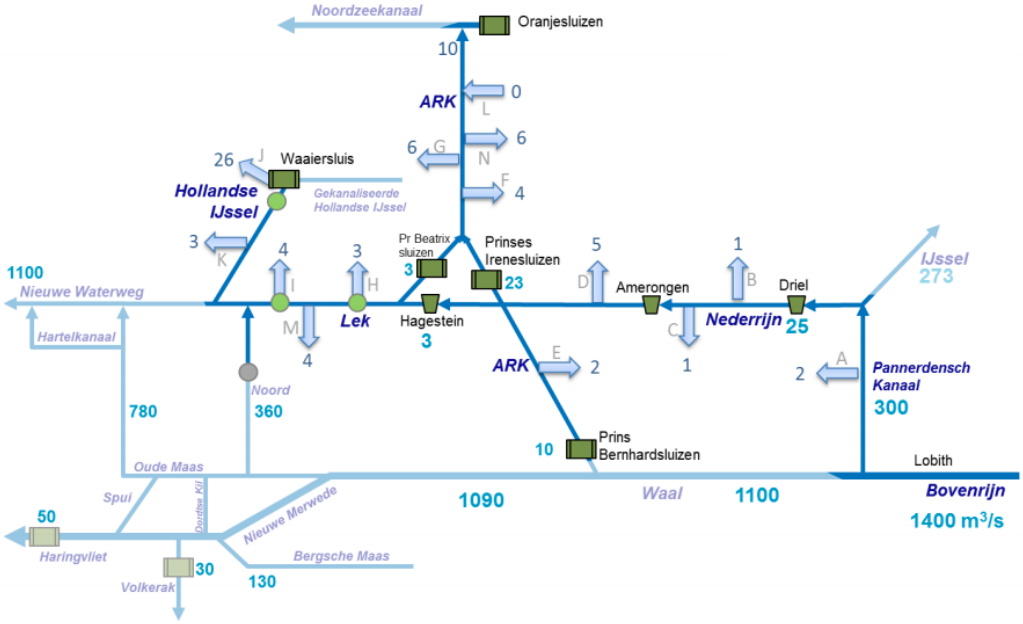


Figure 4.2: Water distribution of the Rhine branches with a Rhine discharge of 1400 m^3/s (Spijker & van den Brink, 2013)

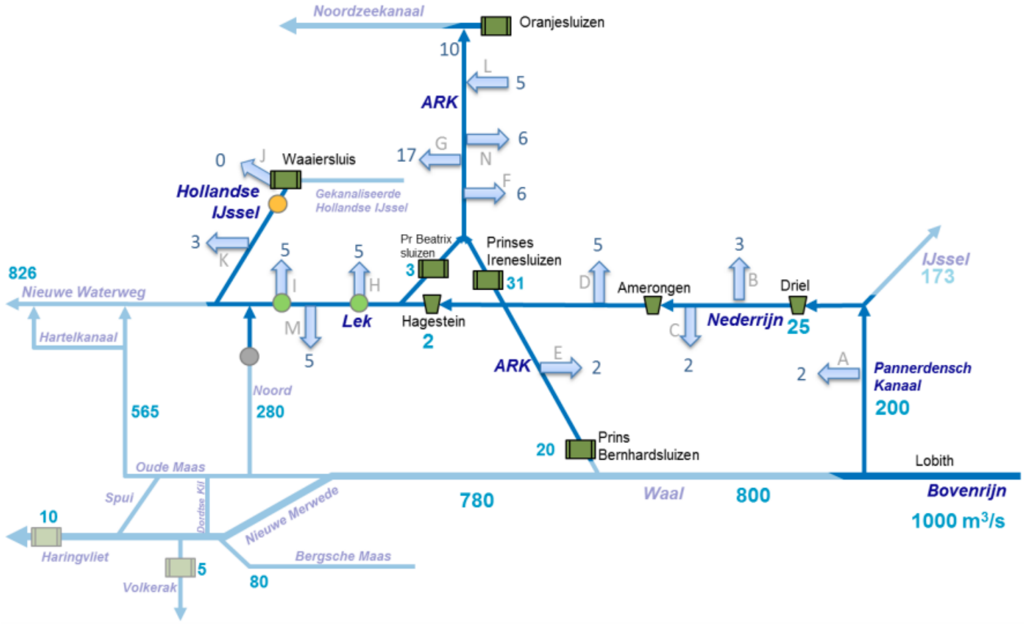


Figure 4.3: Water distribution of the Rhine branches with a Rhine discharge of 1000 m^3/s (Spijker & van den Brink, 2013)

4.1.3 Extremely low Rhine discharge

In extreme cases, the Rhine discharge reaches 800 m^3/s or below. The water distribution in this case can be seen in Figure 4.4. While the distribution strategy is not changed, the effects of salt intrusion are more pronounced. Salt water propagates further inland, restricting the extraction of fresh water. Most of the water available is discharged through the Nieuwe Waterweg, and the discharge over the Nederrijn/Lek is restricted to 22 m^3/s.

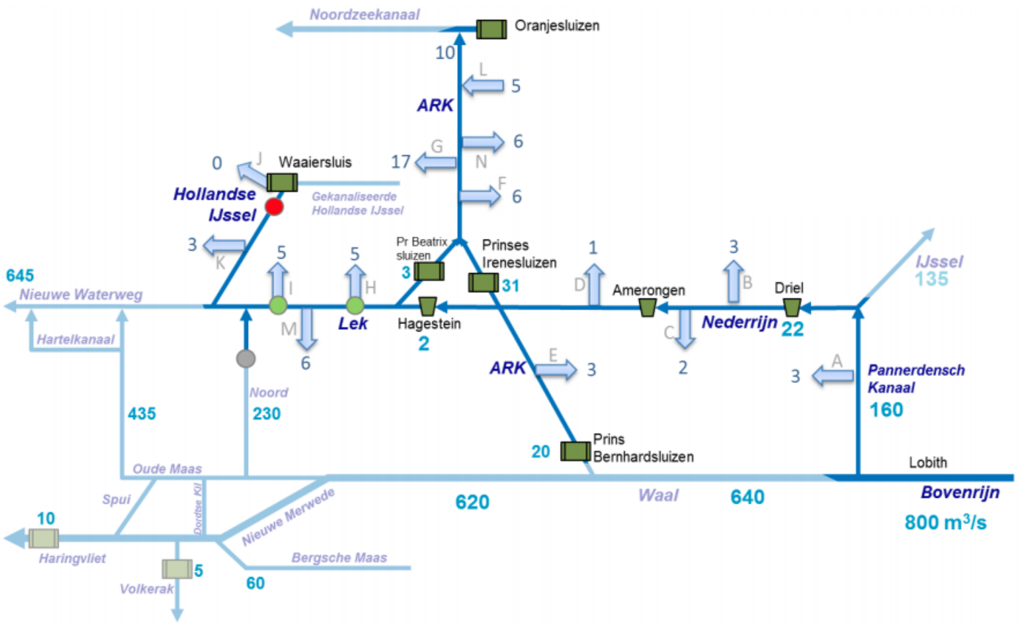


Figure 4.4: Water distribution of the Rhine branches with a Rhine discharge of 800 m^3/s (Spijker & van den Brink, 2013)

4.2 Waal river

The Waal river system is composed of the Waal river branch of the Rhine, which several tributaries. The Meuse river also joins the Waal estuary in the west of the Netherlands, forming the Meuse-Rhine estuary. Because of this interconnectivity, the river system is more complex than a single river.

As can be concluded from the previous section, most of the Rhine discharge is guided to flow through the Waal river. In dry situations, most of the Waal discharge flows through the Nieuwe Waterweg to prevent salt intrusion to propagate too far inland to minimize the problems for fresh water intakes. Also the Waal is of great importance to the Port of Rotterdam for barge shipping, so navigability of the Waal is prioritized over other Rhine branches.

As analysed by Verschuren, 2020, the Waal river reaches the limit of its traffic capacity when its discharges is at 800 m^3/s or lower. This occurs when the Rhine discharge is at 1000 m^3/s, as can be seen in Figure 4.3. The largest bottleneck is in a river bend in Nijmegen.

4.2.1 Water demand in the Meuse-Rhine estuary

In the Meuse-Rhine estuary the Waal interconnects with the Meuse river to form the largest delta of Europe. As can be seen in Figure 4.5, the locks in the estuary can be manipulated in such a way that the Rhine discharge flows through the Nieuwe Waterweg. In peak demand, the water authorities extract 0.5 l/s/ha of land to deal with evaporation and saline seepage (IJpelaar, 2021). The total area which extracts water from the Waal discharge in the Meuse-Rhine estruary is roughly 1200 km^2 (*Maps and Directions*, 2020) which is $1.2\cdot 10^5$ ha. The total peak demand is $6\cdot 10^4$ l/s, which is 60 m^3/s.

Apart from the direct fresh water inlets, the water from the Bielse Meer, a lake just west of Rotterdam, is used to supply the industry of the Port of Rotterdam with fresh water, as well as the region north of the Nieuwe Waterweg. The total peak demand of water from the Brielse Meer in history was 168.329 m^3 per day, which amounts to 2 m^3/s. Apart from the use of fresh river water for industry or irrigation, the water is used for drinking water and is extracted by the company Evides. The water inlets are situated at two places in the Meuse-Rhine estuary: Beerenplaat in the Oude Maas-Spui bifurcation and in the Haringvliet. The combined peak demand of these inlets are 15 m^3/s (Schaaf, 2021). The total fresh water demand of the Meuse-Rhine estuary is 60+2+15 = 77 m^3/s.

Figure 4.5: Topograpical overview of the Meuse-Rhine estuary with the locations of important weirs and locks

4.2.2 Effect of closing the Rijnmond

When a permanent barrier is constructed in the Rijnmond, salt intrusion is greatly diminished. Saline seepage will not be affected, but there will be no forming of a salt wedge in the river system. In dry conditions (Rhine discharges below 1200 m^3/s) closing the Rijnmond has a big effect on the estuary. As the water levels in the Nieuwe Waterweg can now be regulated, the fresh water buffer in the Haringvliet is much larger when water levels are higher. The maximum water height that can be achieved at the Measlantkering is 2.6 m + NAP, the maximum water height for the river dikes in Rotterdam. The water buffer in the Haringvliet and in the Brielse Meer is used to supply the water boards with water in order to prevent saline seepage, and the water inlets can be used more efficiently if the water level is at the maximum level. The placement of a permanent barrier in the Rijnmond is hypothesised not to influence the water distribution at the Pannerdensche Kop, this will be further investigated in chapter 6.

In case of a closing of the Rijnmond, a different water distribution could be maintained in the Meuse-Rhine estuary. More discharge through the Haringvliet sluices will allow for fish migration, positively influencing the ecology of the entire river system. Extra discharge into the Haringvliet will also flush out more of the salt water introduced by the tides, increasing its value as a fresh water buffer. Existing plans are to maintain a discharge of 100 m^3/s through the Haringvliet sluices for these goals (IJpelaar, 2021).

4.3 IJssel river

At Pannerden, the Rhine bifurcates into the Waal river and the Pannerdensch Kanaal, which in turn splits up at the IJsselkop nearby Arnhem into the IJssel and the Nederrijn. It is used as a shipping route to the city of Deventer and Zwolle, as well as Hengelo, Enschede en Almelo via the Twentekanalen. The IJssel is the main contributor to the fresh water discharge to the IJsselmeer, which is a large fresh water buffer for the northern provinces of the Netherlands.

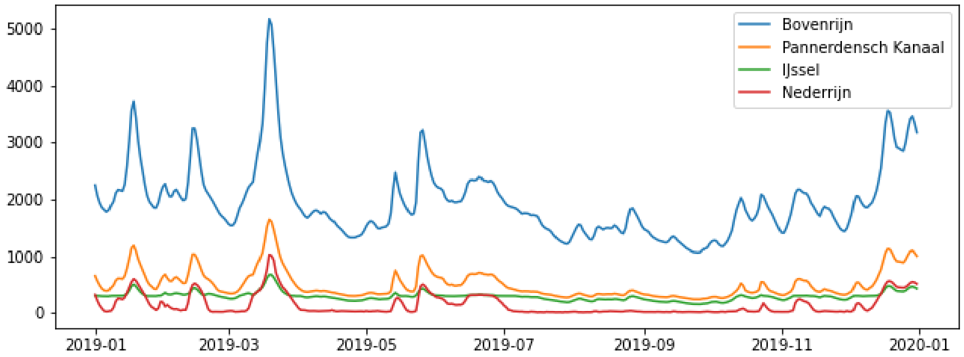
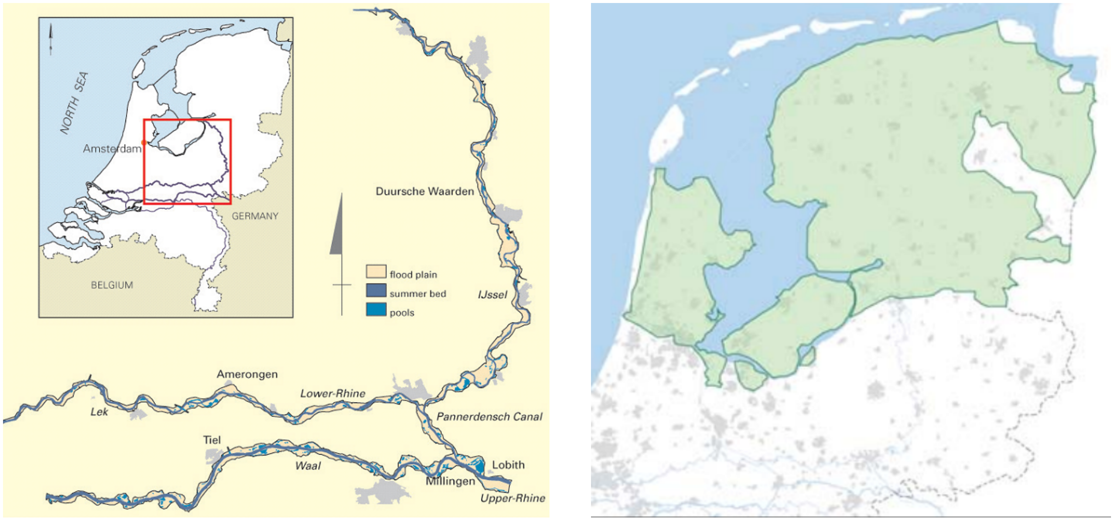


Figure 4.6: Distribution of the Rhine discharge for several Rhine branches during 2019

The goal is to supply the IJssel with a minimum of 285 m^3/s in order to ensure navigability and fresh water demands along the IJssel and to the IJsselmeer are met. For Rhine discharges at Lobith of 1500 m^3/s or lower, a lower discharge flows through the IJssel as the Nederrijn must be supplied with 25 m^3/s (as can be seen in Figure 4.2) in order to guarantee water quality and fresh water supply (Tuin, 2013). With a Rhine discharge between 1500 m^3/s and 2350 m^3/s the IJssel is supplied with a constant discharge of 285 m^3/s by manipulating the weir at Driel to adjust the discharge in the Nederrijn. In case of Rhine discharges above 2350 m^3/s the weir at Driel is fully opened (Brinke, 2004). As can be seen from Figure 4.6, the IJssel discharge is kept relatively constant, only in dry or wet situations the discharge varies considerably.



(a) Rhine river system with the IJssel river flowing north (Yossef, 2016)

(b) Region of the Netherlands dependent on the IJsselmeer for fresh water (Bos, 2014)

Figure 4.7: IJssel river system and its importance in the fresh water management of the Netherlands

As the IJssel is also the main contributor to the fresh water discharge to IJsselmeer, enough discharge is vital in order to keep the IJsselmeer at a sufficient water level. The northern provinces of the Netherlands around the lake rely on the IJsselmeer to supply a great part of their fresh water demands. As can be seen in Figure 4.7(b), most of the northern parts of the Netherlands dependent on fresh water supply from the IJsselmeer.

4.4 Twentekanalen

The Twentekanalen is a system of three canals which provide a shipping route to the cities of Hengelo, Enschede en Almelo. Several weirs are present in the canal system: at Eefde, Delden and Hengelo. Because the water level differences over these weirs are high, the water losses due to the locking process are great and reduce the upstream water level significantly. To restore the water levels, there are pumps installed next to the weirs which pump water to the upstream reach of the canal. The water discharge is generally between -10 and 20 m^3/s, with a negative discharge denoting the extruding of water from the IJssel using the installed pumps. The canal is supplied with water from the surrounding streams, but when the discharges are low or stop completely, the installed pumps are used to pump up water out of the IJssel and into the higher parts of the canal. This is done during droughts to supply the water authorities with enough water to maintain the water height in the cities and fulfill fresh water demands. A more detailed analysis of this system is given in Chapter 5.

Figure 4.8: The location of the Twentekanalen in the study region

4.5 Conclusions

The second sub-question is as follows: What is the behaviour of the Rhine river system during dry spells? In this section an answer to this question is formulated.

The Rhine river system is a dynamic system, and the discharge distribution is changed as the water supply changes. In the current situation, most of the water in the Rhine during dry spells is discharged through the Nieuwe Waterweg in order to stop the salt wedge from propagating too far inland. This is because the water inlets are dependent on fresh water and too much salt will be problematic, as drinking water companies and agriculture is dependent on a fresh water supply.

The discharge of the Waal river needs to be be kept above 800 m^3/s to prevent reaching the traffic limit. With the current water distribution this is reached when the Rhine discharge at Lobith is at least 1000 m^3/s. The peak fresh water demands for drinking water, industry and irrigation in the Meuse-Rhine estuary are determined to be 77 m^3/s. Extra discharge to the Haringvliet is an improvement for the fish migration as well as an increase in the fresh water buffer.

The fresh water discharge of the IJssel river is ideally kept at 285 m^3/s, which fulfills both navigation and other fresh water demands. The IJssel also provides fresh water to the IJsselmeer, which is a large water buffer for the northern parts of the Netherlands. Because the water in the IJsselmeer cannot be used in restoring the groundwater levels in the east of the Netherlands, this is not within the scope of this research. An added inflow to the IJsselmeer has nonetheless several advantages during dry spells.

Creating a permanent barrier in the Rijnmond will greatly inhibit the forming of a salt wedge, increasing the reliability of fresh water inlets as well as more control over the water levels in the Meuse-Rhine estuary. A discharge through the Nieuwe Waterweg of 1100 m^3/s when the Rhine discharge is 1400 m^3/s is enough to stop the salt intrusion. When a permanent barrier is constructed, this discharge is not required to stop the salt wedge, so more discharge is available for redistribution (about 300 m^3/s). The Rhine river discharge distribution at the Pannerdensche Kop is not hypothesised to change when the Rijnmond is closed, this will be further analysed in the SOBEK computation in Chapter 6.

Chapter 5

Groundwater and infiltration

The main focus of this thesis is mitigating the effects of drought on groundwater in the east of the Netherlands. As previously mentioned and as can be seen in Figure 1.3(b), the elevation of the east of the Netherlands is significantly higher than the water levels of the IJssel. The affected region that will be considered is predominantly covered by two water authorities: Waterschap Rijn en IJssel and Waterschap Vechtstromen. The area of interest can be seen in Figure 5.1.

(a) Location of the area of interest in the Netherlands

(b) Area of interest with rivers drawn in blue

Figure 5.1: Area of groundwater drought in the east of the Netherlands

The consecutive dry summers of 2018 and 2019 have had a big impact of the groundwater table in the east of the Netherlands. As can be seen in Figure 5.2, the measured three lowest groundwater levels in these years are significantly lower than the mean low groundwater level up to that point (Bartholomeus et al., 2020). Two droughts in consecutive years have such an impact on the groundwater levels that it takes several years for the groundwater levels to return to normal. For high sandy soils, it can take up to 8 years (Pouwels et al., 2020). The most effective method to restore the groundwater levels is by infiltrating the precipitation and containing the precipitation inside the area instead of draining to the surface water. When precipitation rates are high, farmers tent to drain their fields

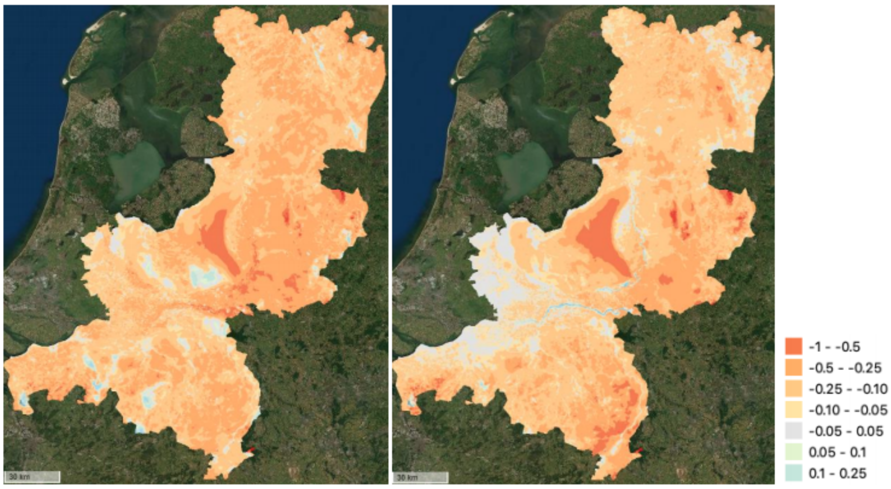


Figure 5.2: The mean of the three lowest measured groundwater levels (LG3) in 2018 (left) and 2019 (right) relative to the mean low groundwater level (GLG) [m] (Bartholomeus et al., 2020)

quickly in order to be able to work them with heavy machinery. Because of this low retention time, the groundwater levels are not increased as much as could have been the case when all precipitation infiltrates to the groundwater.

As is analysed by Deltares (Hunink et al., 2019), the groundwater levels are subject to change due to the changing climate. In Figure 5.3 the change in irrigation out of groundwater is shown for historical data with different climate scenarios. For the climate scenarios with little climate change (R2050 and R2085) the water demand does not change significantly due to the higher precipitation rates in these scenarios. For the drier scenarios however the water demand out of groundwater will increase, up to almost $40 \cdot 10^6$ m^3 per year extra for extremely dry years. This demand can only be met with higher infiltration rates, either by locally storing the precipitation or by actively infiltrating and increasing the groundwater levels.

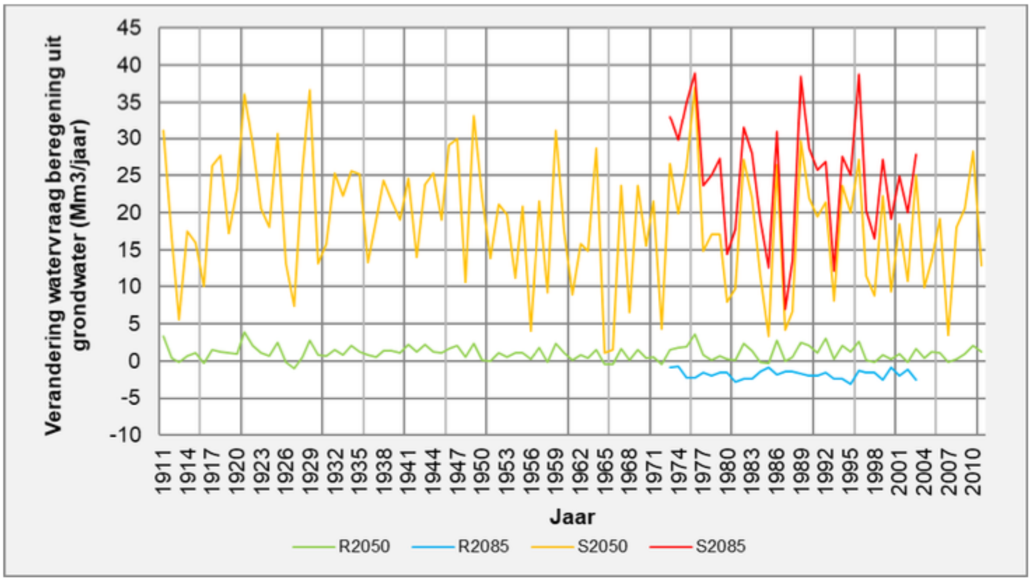


Figure 5.3: Change in irrigation from groundwater in the Oostelijke Zandgronden for different weather scenario's for historical data (Hunink et al., 2019)

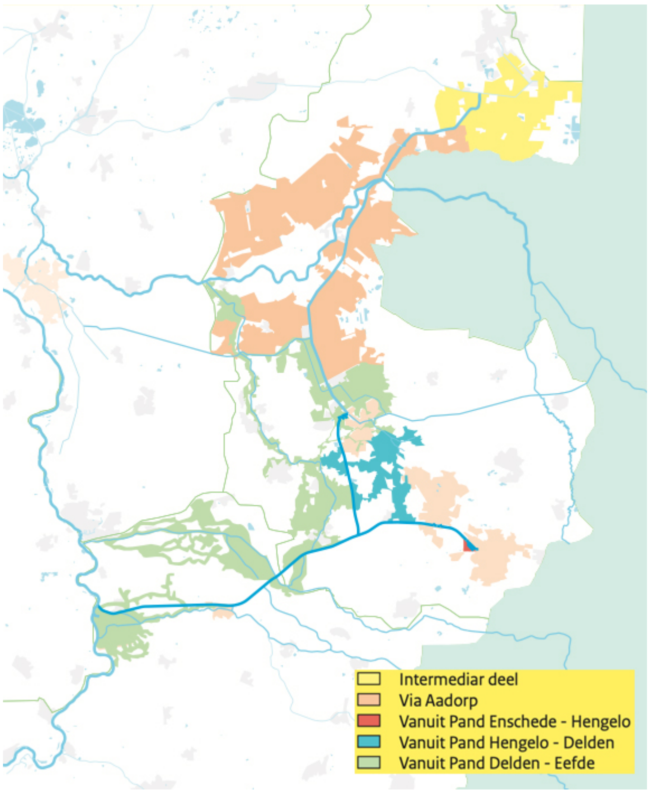


Figure 5.4: Infiltrated area out of the Twentekanalen (Rijkswaterstaat, 2020)

5.1 Infiltration from the Twentekanalen

During dry summers, the area north and to the east of the Twentekanalen can be supplied with water out of the Twentekanalen (see Figure 5.4). The streams to the north of the Twentekanalen are lower in elevation than the canal itself, providing a effective method to disperse the water over the area. These streams flow into the Overijsselse Vecht, which has a positive influence on the groundater table in that area, as can be seen in Figure 5.5.

5.1.1 Amount of infiltration

As determined by the Waterakkoord Twentekanalen in 2017, a set of agreements between Rijkwaterstaat, the provinces and the water authorities in the area, the theoretical maximum water demand out of the Twentekanalen is 27.5 m^3/s (Rijkswaterstaat, 2017). An amount of 4.14 m^3/s is used by Rijkswaterstaat in order to maintain water levels and account for evaporation and water losses due to locking. The rest of the water is used by the water authorities to maintain smaller waterways and groundwater levels.

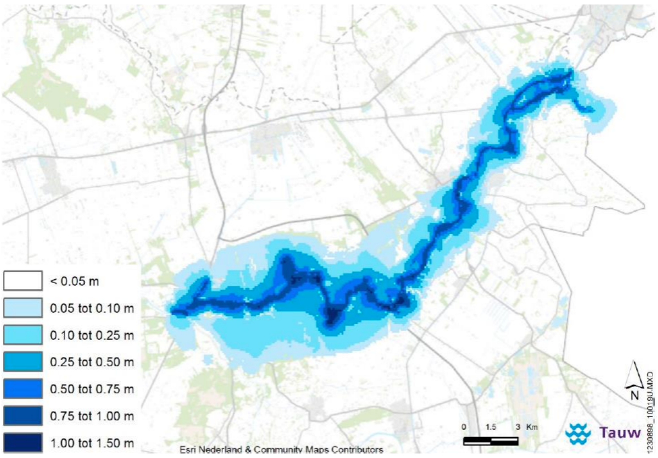
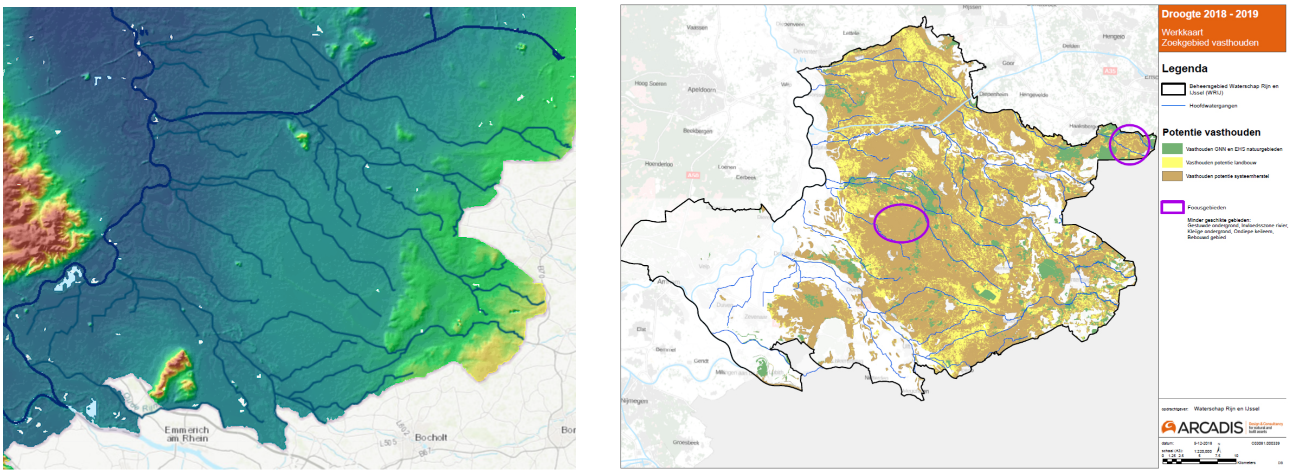


Figure 5.5: Influence of a 1 m rise of the Overijsselse Vecht on the groundwater level (Waterschap Vechtstromen, 2017)

5.2 Extra infiltration

To supply the area south of the Twentekanalen with water, three options are examined: Pumping from the IJssel, pumping from the Rhine and constructing a canal from the Rhine through Germany. Because the majority of the region of Waterschap Rijn and IJssel is at least 10 m higher than the surrounding rivers (see Figure 5.6(a)), the inflow of fresh water using gravity is not an option in this part of the Netherlands. A solution for this is to pump water out of the surrounding rivers to supply a few chosen small rivers with water. This can be done during the whole year. Only 10% of the area as shown in Figure 5.6(a) can be irrigated using gravity (van Houten, 2021), which is the western green area indicated in Figure 5.4. The rest of the area is dependent on precipitation. Because the soil of the easternmost, higher regions of the area are harder loamy soils, groundwater infiltration is not as effective as infiltration in sandy soils. The impermeability of the soil inhibits infiltration. Most of the region consists of sandy soils, where infiltration is possible and effective, see Figure 5.6(b).



(a) Height profile of Waterschap Rijn en IJssel

(b) Area within the Waterschap Rijn en IJssel where water storage is possible (coloured areas) (Waterschap Rijn en IJssel, 2018)

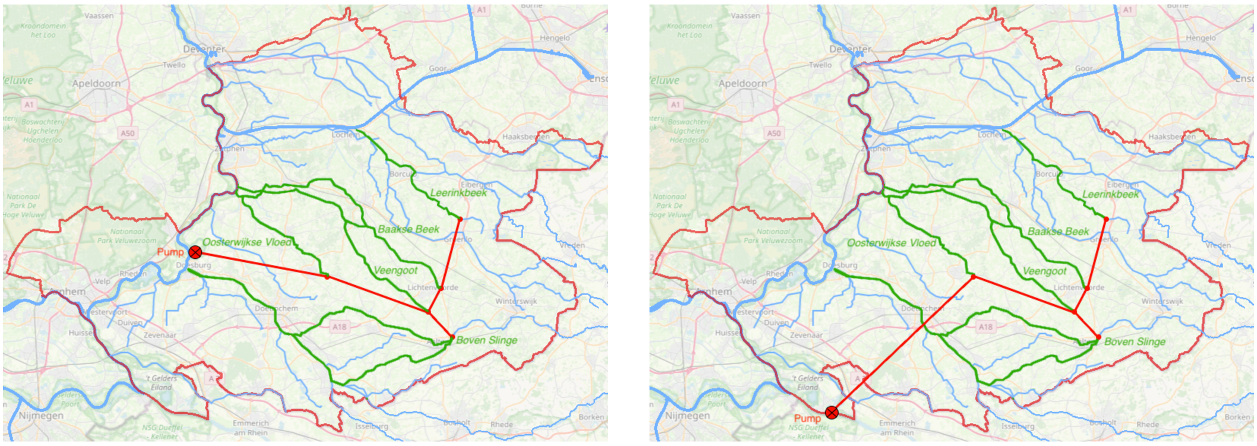
Figure 5.6: Height profile and water storage possibilities of Waterschap Rijn en IJssel

5.2.1 Extraction from the IJssel

To extract water from the IJssel a pump and pressure pipe has to be installed for this purpose. A possible placement of this pipe can be seen in Figure 5.7(a). The height difference this pressure pipe has to bridge is about 20 meters, from lowest to highest point. At the begin of each supplement, a pond will be constructed for the pipe to flow into. From this pond the supplied water will flow into the indicated streams, where the water level will be regulated with the existing weirs in the system.

5.2.2 Extraction from the Rhine

A different possibility is to place a pump in the Rhine river at Lobith. The height difference is comparable to the pipe out of the IJssel, however the length is greater because the extraction point is further away as can be seen in Figure 5.7(b). This results in higher costs. The method of supplying the water to the streams is the same as extraction from the IJssel.



(a) River water extraction out of the IJssel (b) River water extraction out of the Rhine

Figure 5.7: Groundwater infiltration out of the IJssel and Rhine, streams to be supplied with water indicated in green

5.2.3 Canal out of Germany

To supply the area with river water using gravity, a canal has to be constructed further upstream, originating in Germany. The highest point of infiltration in the study area is about 20 m + NAP, so the canal must be constructed at a point higher than that. With an average channel slope of 0.1 m per km, the canal out of Germany must originate at Dusseldorf, where the bed elevation of the Rhine is 29 m + NAP, see Figure 5.8. The length of the canal is about 90 km.

5.2.4 Amount of infiltration

In order to maximise the effect on the groundwater table in the area of interest, several streams are chosen to supplement with water. These streams are, from north to south, the Leerinkbeek, Baakse Beek, Veengoot, Oosterwijkse Vloed and the Boven Slinge. These streams are indicated in Figure 5.7(a) with a green colour. The amount of water which will be supplied to these streams is determined using the discharge data of the water authority Waterschap Rijn en IJssel (Waterschap Rijn en IJssel, 2021a). A discharge with the average return period of one year is chosen to provide a discharge which, although high, does not cause any problems for the region while still ensuring maximum supply of water. The discharge with a return period of one year for each stream can be found in Table 5.1. The total amount of water to be supplied to the streams amounts to 17.5 m^3/s, when the streams are not discharging water naturally.

Figure 5.8: Canal out of Germany

Table 5.1: Discharge with a return period of one year for the chosen streams

Stream	Leerinkbeek	Baakse Beek	Veengoot	Oosterwijkse Vloed	Boven Slinge
Discharge with a return period of one year	2 m^3/s	1.5 m^3/s	3 m^3/s	1 m^3/s	10 m^3/s

5.2.5 Costs

In this section, a very quick assessment is made for the cost of each extraction option. This purely to enable a comparison, not to accurately project project costs. A sufficient water pump costs €50 million per 100 m^3/s as the upper limit as determined in the study for pumps in the Markermeer (Van Waveren & Roos, 2015). The cost of a pump with a capacity of 20 m^3/s would be €10 million. This would be the case for both the pump in the IJssel at Doesburg and the pump in the Rhine at Lobith. The pipe length differs between the two; the pipe for extracting out of the IJssel is approximately 49 km, extracing out of the Rhine requires 63 km of pressure pipe. The cost of a kilometer of pipe is approximately €1 million, as stated in the *Structuurvisie Buisleidingen 2012-2035* (Ministerie van Infrastructuur en Milieu, 2012). The total costs for extraction from the IJssel and Rhine would amount to €59 and €73 million, respectively.

As a reference, the costs for a proposed canal from Germany to the Netherlands is €1.3 billion for a length of 50 km (Panteia, 2013). For a canal with a length of 90 km, this would be €2.3 billion if linear extrapolation is applied. This is significantly more than water extraction using a pump. A canal has other benefits, such as enabling shipping. The overview of approximate costs per option can be found in Table 5.2.

5.2.6 Impact of extra infiltration

To determine the effect of the extra infiltration on the groundwater levels in the area, an indication is made how much water can potentially be infiltrated during dry spells in the area of Waterschap Rijn en IJssel. To give an estimation of the amount of infiltration directly from the stream bed, the surface

Table 5.2: Approximate cost comparison between extraction options

Extraction option	Costs
Extraction from the IJssel	€$59 \cdot 10^6$
Extraction from the Rhine	€$73 \cdot 10^6$
Canal out of Germany	€$2.3 \cdot 10^9$

area of the supplied streams are calculated. The surface area of the streams is given in Table 5.3. The total area of the streams is 1.6 km^2, and with a average infiltration of 10 mm per day (Roelofs, 2021), the volume of infiltration is $1.6 \cdot 10^4$ m^3 per day. This is a discharge of 0.18 m^3/s which infiltrates to the groundwater directly, so this is not a significant portion of the freshwater discharge that is supplied to the streams. Extra measures are needed to use the supplied water efficiently.

Table 5.3: Surface area of the selected streams (Waterschap Rijn en IJssel, 2021c)

Stream	Length [km]	Average width [m]	Surface area [km^2]
Leerinkbeek	8.4	6	$5.0 \cdot 10^{-2}$
Baakse Beek	31.0	11	$3.4 \cdot 10^{-1}$
Veengoot	33.8	10	$3.4 \cdot 10^{-1}$
Oosterwijkse Vloed	13.2	5	$6.6 \cdot 10^{-2}$
Boven Slinge	63.0	12	$7.6 \cdot 10^{-1}$
Total			1.6

A possible extra measure is to use the agriculture for irrigation. If all farmland in the Waterschap Rijn en IJssel uses the surface water from the streams instead of using the groundwater to irrigate the crops, the load on the groundwater table is decreased while the extra irrigation causes infiltration to the groundwater. Waterschap Rijn and IJssel has a total surface area of 1878 km^2, of which 6.8% is used as farmland for crops (Waterschap Rijn en IJssel, 2021b). This amounts to a total of 128 km^2 used for crops. To determine the volume of water that can be used for irrigation the precipitation deficit for the three driest months of 2018 in the growing season of Hupsel is determined, see Figure 5.9. The three months of 2018 in the growing season (April to September) with the highest precipitation deficit are May (deficit of 89.0 mm, (KNMI, 2018c)), June (deficit of 73.5 mm, (KNMI, 2018b)) and July (deficit of 130.5 mm, (KNMI, 2018a)), totalling a deficit of 293.0 mm. To compensate this deficit with surface water, $4.1 \cdot 10^5$ m^3 per day is needed. Assuming that the farmland is irrigated for 9 hours per day, this requires a discharge of 12.6 m^3/s.

If the entire precipitation deficit is compensated with surface water for the crops, for 6.8% of the area the deficit would be 0 mm, a compensation of 293.0 mm. This would be an average compensation of 20 mm for the whole area of Waterschap Rijn en IJssel, so this would be an increase of 20 mm of the groundwater table across the area. This is 30% of the total amount of precipitation in the time period of three months (May-July 2018), and is 3.7 times the amount of precipitation in July 2018 (5.4 mm).

If the precipitation deficit of the entire area of Waterschap Rijn en IJssel is compensated by surface water, 184.6 m^3/s would be needed. This is too much for the existing infrastructure to cope with, and a equal distribution of the water across the area would be needed. However, if water infiltration occurs before the dry spell is causing major problems, the water buffer in the unsaturated zone can be greater than without infiltration. The water buffer in the unsaturated zone can be increased by 100 mm across the area (Roelofs, 2021). This would require a volume of water of $1.9 \cdot 10^8$ m^3, which would be 124 days of supplying water to the area with a discharge of 17.5 m^3/s. This is under the assumption

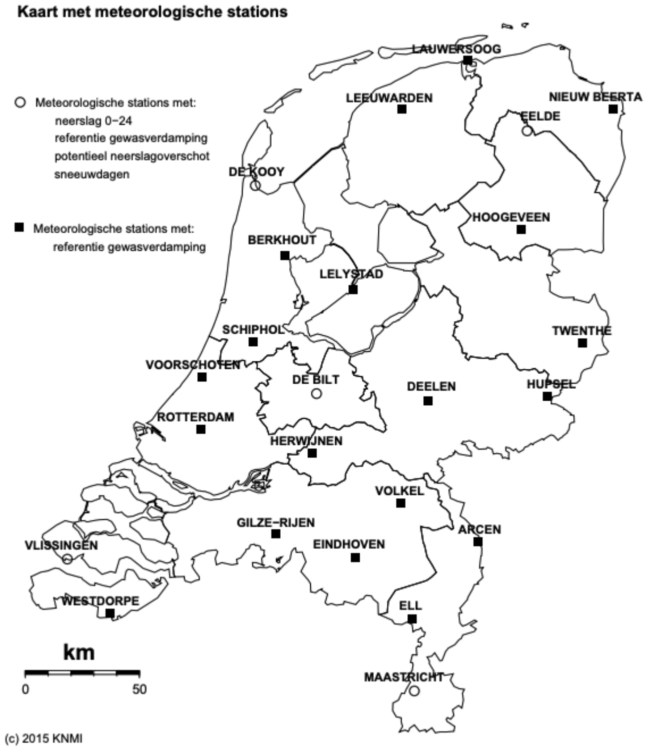


Figure 5.9: Meteorological stations in the Netherlands (KNMI, 2018c)

that all supplied water is infiltrated to the unsaturated zone with a 100% efficiency.

5.3 Conclusions

The sub-question that will be answered in this section is: How can surface water be used to restore groundwater levels in the east of the Netherlands and how much water is needed in a dry summer?

The most effective method of groundwater restoration is through precipitation and containing the precipitation in the area for as long as possible. However, as climate change causes an increase in occurrence of dry spells and drier summers, the way the water is used in the east of the Netherlands must change in order to combat the deficit in groundwater in the summer. Surface water can help in lightening the load on the groundwater levels during droughts by supplying water to the farmlands. Instead of pumping up groundwater to irrigate the crops, surface water can be used if the streams in the area are supplied with water. The water that does not evaporate infiltrates through to the groundwater, increasing the buffer.

The amount of water that can be supplied throughout the year for the fresh water demands of the study area is determined to be 45 m^3/s, the capacity of the streams in the area. The peak fresh water demand supplied to the Twentekanalen from the IJssel is 27.5 m^3/s to maintain water levels in the channel and supply the surrounding region with fresh water. An additional 17.5 m^3/s can be supplied to several streams in the southern part of the study area, but extra infrastructure has to be installed for this purpose. The extra infrastructure examined in this thesis are extraction from the IJssel, extraction from the Rhine and a canal out of Germany.

If the streams are used to transport the water to the area, the maximal discharge of 17.5 m^3/s can be used in multiple ways. The water can be used directly for uses which otherwise would use groundwater, such as irrigation or keeping water levels within operable levels. The second way the water can be used is to infiltrate it into the unsaturated zone in the area, which is used as a buffer when precipitation deficits occur. The first method can be used while a drought is happening (requiring sufficient Rhine discharge), while the latter method can be used to create a fresh water buffer before a drought occurs.

The direct infiltration of the supplied water in the streams is equal to 0.18 m^3/s. This shows that extra measures are needed in order to use the supplied water effectively. If all farmland for crops is supplied with river water during the driest months in the growing season, 12.6 m^3/s is needed. This would mean an increase of groundwater level of 20 mm for the whole area. This leaves about 5 m^3/s of discharge, which can be used to maintain ponds, gardens and waterways surrounding the streams. The water buffer that can be stored in the unsaturated zone in the summer is in the study area equal to 100 mm. To supply this volume of water, 124 days of supplying 17.5 m^3/s to the streams must be achieved with a 100% infiltration rate.

Chapter 6

Closing the Rijnmond

In this chapter the effect of a closure of the Rijnmond with a permanent water barrier is determined using computational analysis. The set-up for the computations are given, as well as the results and conclusions of this section.

6.1 Set-up

The Rhine-Meuse estuary schematization encompasses the downstream reaches of the Waal, Nederrijn/Lek and the Meuse river, as well as Hollandse IJssel. The entire Rijnmond area is schematized, including the Haringvliet. The upstream boundaries are in the Waal, Meuse, Nederrijn/Lek and Hollandse IJssel rivers. The downstream boundaries are defined at the Rijnmond, where the Nieuwe Waterweg and Callandkanaal flow into the North Sea. The other downstream boundaries are at the Haringvliet sluices and at the Volkerrak sluices, but these have been defined as lateral outflows in order to simulate and regulate the outflow of water through these sluices. At the Meuse river mouth the two situations are defined: an open connection to the sea with a tidal cycle and the closed situation, which is simulated as a constant water height of 2.6 m + NAP. This level ensures maximum fresh water buffer in the Haringvliet and Brielse Meer while no flooding takes place in the Rotterdam area. The flow through the Haringvliet sluices are set at 100 m^3/s, while the flow through the Volkerrak sluices are dependent on the water discharge through the Waal river (as can be seen in Figures 4.2 to 4.4). A discharge of 5 m^3/s through the Volkerrak sluices is assumed when the rhine discharge below 1400 m^3/s, while an unrestricted 30 m^3/s is assumed when Rhine discharges are 1400 m^3/s or higher. As determined in Chapter 4, a peak water demand of 77 m^3/s is needed in the Rijnmond area for industry and irrigation, so a lateral sink at the Brielse Meer is defined for all situations. The discharge through the Hollandse IJssel is neglected, as this branch is not of importance during low Rhine discharges.

Because the results are dependent on the computations of two schematizations, several iterations have been done to determine the correct boundary conditions. The first iteration was based on historical data and previous studies, and ranges from 1600 to 460 m^3/s and corresponds with the defined Rhine discharges of 2000 to 600 m^3/s. The discharges through the Lek and Meuse are extrapolated using Figures 4.2, 4.3 and 4.4. This first iteration showed that the discharge distribution at the Pannerdensche Kop was unaffected by the change in water level due to the placement of a permanent barrier in the Rijnmond, so the Rhine branches schematization was used to determine the exact discharge through the Waal at Tiel in order to produce the correct water levels at Hardinxveld. The discharges as determined by this second iteration can be found in Table 6.1. The water level at Hardinxveld was used as a boundary condition for the Rhine schematization, which was a constant water level for the closed situation and a time-dependent water level for the open situation.

Table 6.1: Discharges used as final input in the Rhine-Meuse estuary schematization

Rhine discharge	Waal discharge at Tiel	Lek discharge	Meuse discharge
600	470	1	40
800	630	2	60
1000	787	2	80
1400	1103	3	130
1700	1290	30	150
2000	1452	90	180

The set up for the Rhine branches schematization is given in Table 6.2. The downstream boundary condition has to be specified in two locations: at Hardinxveld in the Waal (just east of the Biesbosch) and at the IJsselmeer. The boundary condition at Hardinxveld is determined using the discharge-water height relation determined in the Rhine-Meuse estuary schematization. The water height of the IJsselmeer is kept constant at -0.2 m NAP, which is the summer level of the IJsselmeer and provides the largest fresh water buffer. The upstream water boundary condition is a range of discharges, from 2000 m^3/s to 600 m^3/s at Lobith. The water flow through the Nederrijn is dependent on the discharge through the Pannerdensch Kanaal, as the IJssel discharge is kept at 285 m^3/s. The discharge through the Nederrijn is modelled as a lateral sink to minimise the computation cost and to control the discharge flowing through the IJssel and Waal river. The Amsterdam Rijn Kanaal (ARK) inlet at the Prins Bernhard sluices is likewise schematized as a lateral sink. This leaves the system as can be seen in Figure 2.2.

Table 6.2: Set up for the Rhine branches schematization

Rhine discharge	Nederrijn discharge	ARK discharge	Waal discharge (SOBEK)	IJssel discharge (SOBEK)
600	21	20	470	89
800	22	20	630	128
1000	25	20	787	168
1400	25	10	1103	262
1700	90	10	1290	310
2000	220	10	1452	318

6.2 Results

The results of the computations are given for the Rhine-Meuse estuary schematization as well as the Rhine branches schematization. The transition between the two schematizations is examined.

6.2.1 Results of the Rhine-Meuse estuary schematization

As the goal of this computation is to determine the effect of the closure of the Rijnmond on the water levels in the Waal and the water distribution at the Pannerdensche Kop, the water levels at Hardinxveld are important. This is the boundary of the Rhine branches schematization. The water levels at Hardixveld and Tiel using the Rhine-Meuse estuary schematization are given in Tables 6.3 and 6.4. The difference in average water level between the open and closed situation is significant, especially for the water level at Hardinxveld. The difference in water level at Tiel is greater for lower Rhine discharges, which indicates a greater impact of the closing of the Rijnmond for extremely low Rhine discharges.

Table 6.3: Average water level at Hardinxveld and at Tiel for different Rhine discharges, open situation

	Water level Hardinxveld		Water level Tiel	
Rhine discharge [m^3/s]	Average [m NAP]	Amplitude [m]	Average [m NAP]	Amplitude [m]
600	0.25	0.33	1.56	0.05
800	0.32	0.34	2.05	0.04
1000	0.38	0.35	2.49	0.03
1400	0.51	0.37	3.32	0.02
1700	0.60	0.36	3.79	0.01
2000	0.67	0.36	4.17	0.01

Table 6.4: Water level at Hardinxveld and at Tiel for different Rhine discharges, closed situation

Rhine discharge [m^3/s]	water level Hardinxveld [m NAP]	water level Tiel [m NAP]
600	2.61	2.93
800	2.61	3.15
1000	2.62	3.39
1400	2.65	3.96
1700	2.66	4.32
2000	2.68	4.63

For the open situation, the average value of the water level is determined once the steady-state solution has been reached. An example of the results for the open situation can be seen in Figure 6.1, where the Rhine discharge of 1400 m^3/s situation is modelled. It can be seen that the water level at Hardinxveld is affected significantly by the tidal cycle, while the water level variation at Tiel is not affected as much. As can be seen, the peak in the water height in January has no significant effect on the solution at Tiel, which is the case for all Rhine discharge situations. This shows that the water levels upstream of Tiel are primarily dependent on the upstream boundary condition. The time-dependent water levels at Hardinxveld which are used as boundary conditions for the open situation can be found in Appendix B.

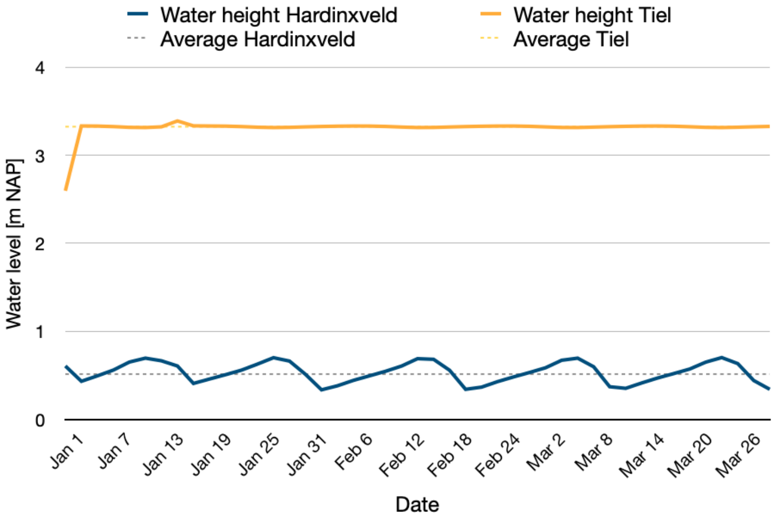


Figure 6.1: Water levels at Hardinxveld and Tiel for the open situation with a Rhine discharge of 1400 m^3/s using the Rhine-Meuse estuary schematization

6.2.2 Results of the Rhine branches schematization

The effect of the placement of a permanent barrier in the Rijnmond on the Rhine river system is determined in several observation points in the Waal, which can be seen in Figure 6.2.

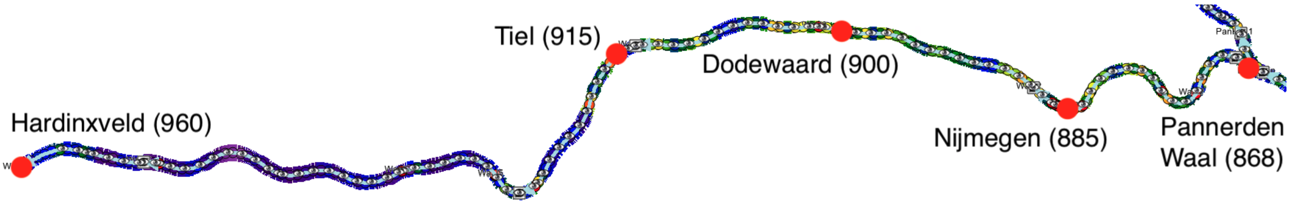


Figure 6.2: Observation points in the Waal river, Rhine kilometers indicated

In the open situation, the tidal cycle is most noticeable in the lowest Rhine discharge situation, but this amounts to a change in water level at Tiel of 5 cm. This effect is even less prominent further upstream, as can be seen in Figure 6.3. The average values have been given in Table 6.7, while the closed situation results are a constant value.

Table 6.5: water levels in the Waal for different Rhine discharges, open situation

	Water level, average [m NAP]				
Rhine discharge [m^3/s]	Hardinxveld	Tiel	Dodewaard	Nijmegen	Pannerden Waal
600	0.27	1.46	2.85	4.28	5.90
800	0.34	1.94	3.37	4.79	6.44
1000	0.41	2.36	3.83	5.25	6.92
1400	0.54	3.27	4.75	6.13	7.79
1700	0.62	3.79	5.29	6.57	8.29
2000	0.69	4.18	5.70	7.03	8.68

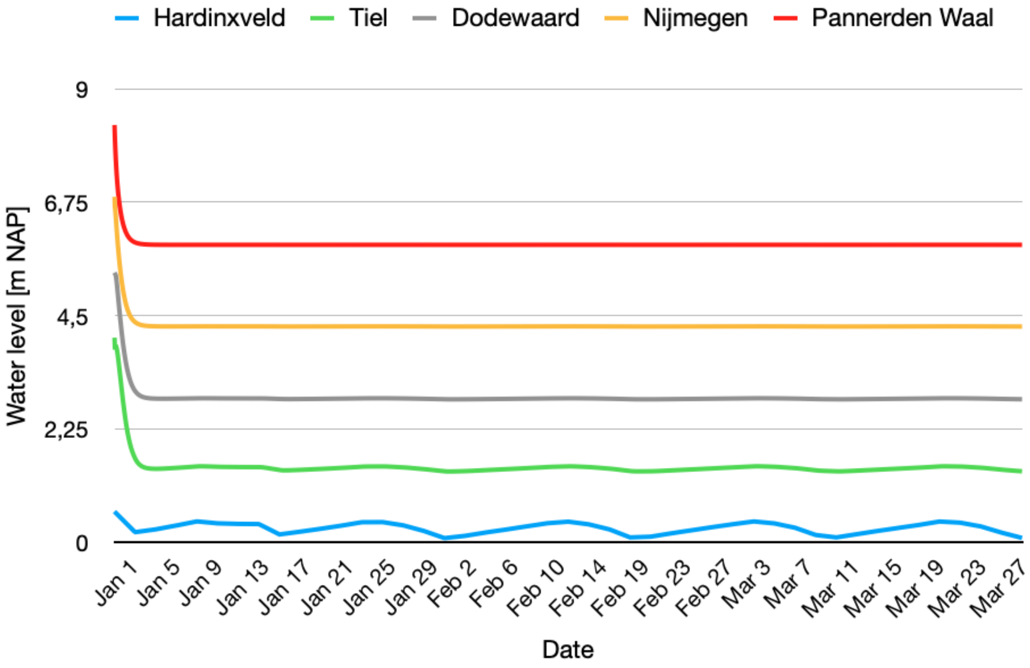


Figure 6.3: Water levels in the Waal for a Rhine discharge of 600 m^3/s, open situation

To convert the water level data to the navigation depth, the river bed levels of the main channel (z_b) is determined using the method specified in Chapter 2. The values of the bed levels are given in Table 6.6. Using the values of Table 6.6, the navigation depth is determined. This is the water depth at the border of the main channel, and if this water depth is equal or greater than 2.8 m, the channel is deemed usable for navigation (Koedijk, 2020).

Table 6.6: Main channel depths in the Waal river

	Location in Waal river				
	Hardinxveld	Tiel	Dodewaard	Nijmegen	Pannerden Waal
Bed level z_b [m NAP]	-5.45	-1.27	0.56	0.72	3.76

Table 6.7: Navigation depths in the Waal for different Rhine discharges, open situation

	Navigation depth, average [m]				
Rhine discharge [m^3/s]	Hardinxveld	Tiel	Dodewaard	Nijmegen	Pannerden Waal
600	5.72	2.73	2.29	3.56	2.14
800	5.79	3.21	2.81	4.07	2.68
1000	5.86	3.63	3.27	4.53	3.16
1400	5.99	4.54	4.19	5.41	4.03
1700	6.07	5.06	4.73	5.85	4.53
2000	6.14	5.45	5.14	6.31	4.92

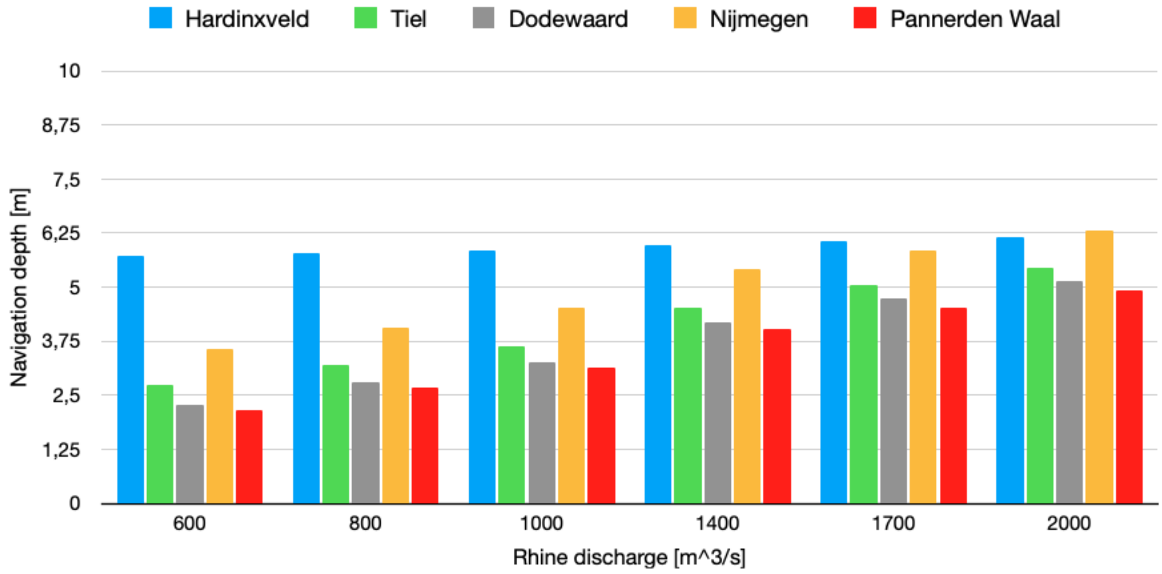


Figure 6.4: Navigation depths for different Rhine discharges, open situation

The water levels for the closed Rijnmond situation is given in Table 6.8 and the navigation depths are given in Table 6.9. As can be seen, the downstream water levels are affected significantly by the placement of a permanent barrier in the Rijnmond, but has little to no effect on the water levels at the bifurcation (at most 3 cm, which is negligible). The discharges through the Waal just downstream of the bifurcation are given in Table 6.10

Table 6.8: Water level in the Waal for different Rhine discharges, closed situation

	Water level [m NAP]				
Rhine discharge [m^3/s]	Hardinxveld	Tiel	Dodewaard	Nijmegen	Pannerden Waal
600	2.61	2.90	3.44	4.43	5.93
800	2.61	3.10	3.83	4.93	6.47
1000	2.62	3.33	4.21	5.37	6.94
1400	2.65	3.93	5.02	6.23	7.82
1700	2.66	4.31	5.51	6.73	8.32
2000	2.68	4.63	5.89	7.12	8.71

Table 6.9: Navigation depths in the Waal for different Rhine discharges, closed situation

	Navigation depth [m]				
Rhine discharge [m^3/s]	Hardinxveld	Tiel	Dodewaard	Nijmegen	Pannerden Waal
600	8.06	4.17	2.88	3.71	2.17
800	8.06	4.37	3.27	4.21	2.71
1000	8.07	4.60	3.65	4.65	3.18
1400	8.10	5.20	4.46	5.51	4.06
1700	8.11	5.58	4.95	6.01	4.56
2000	8.13	5.90	5.33	6.40	4.95

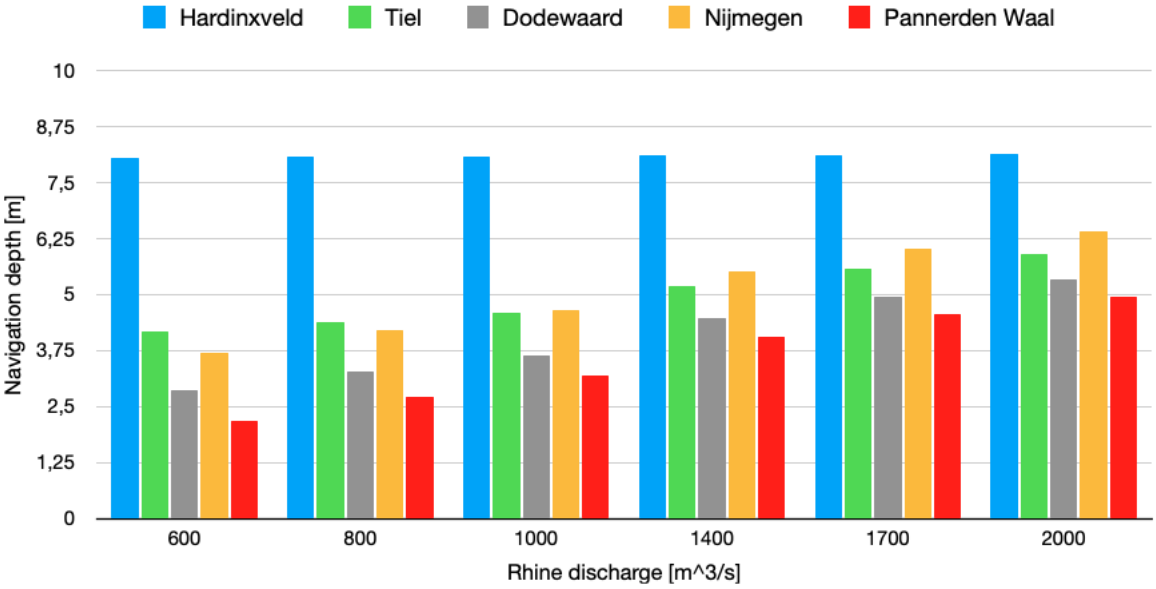


Figure 6.5: Navigation depths for different Rhine discharges, closed situation

Table 6.10: Waal discharge just downstream of bifurcation for open and closed situation

	Waal Discharge [m^3/s]			
Rhine discharge [m^3/s]	Open situation	Closed situation	Difference [m^3/s]	Percentage [%]
600	491	490	1	0.3
800	652	651	2	0.3
1000	811	809	2	0.2
1400	1120	1117	3	0.3
1700	1310	1307	3	0.2
2000	1462	1459	2	0.2

6.2.3 Comparing the schematizations

To compare the transition between the schematizations, the water level for the closed Rijnmond at Tiel is chosen as a benchmark. This point is present in both schematizations and is the upstream boundary for the Rhine-Meuse estuary schematization. The closed situation is chosen for this purpose because this returns a constant value and as such provides a more stable comparison. The results of this comparison can be found in Table 6.11. As can be seen, the transition between the two schematizations introduces some errors. This can be explained in two ways: a discrepancy while rounding the input and the uncertainty of the computation near the upstream boundary. The Rhine-Meuse estuary schematization uses a rounded value for the discharge through the Waal river, while the Rhine branches schematization calcultates it specificly. In the same manner, the downstream boundary value used in the Rhine branches schematization is a rounded off value of the water level at Hardinxveld as computed with the Rhine-Meuse estuary schematization. The second reason the values are not completely the same is that an uncertainty exists at the boundary condition in the Rhine-Meuse estuary schematization because the water level at Tiel is determined using predetermined relations between discharge and water level. In using this relation, measure and extrapolation errors can occur affecting the uncertainty at the boundary condition (Buschman, 2018). This error can be up to 0.3 m in magnitude, the difference in water levels as determined by the two schematizations is significantly less. The water level at Tiel as determined using the Rhine branches schematization is deemed more reliable for this reason. The water levels determined in Hardixveld using the Rhine-Meuse estuary schematization are located far enough from the boundary to be more reliable.

Table 6.11: Water level at Tiel for the closed situation using different schematizations

	Water level at Tiel [m]		
Rhine discharge [m^3/s]	Rhine-Meuse estuary	Rhine branches	Difference [m]
600	2.93	2.90	0.03
800	3.15	3.10	0.05
1000	3.39	3.33	0.06
1400	3.96	3.93	0.04
1700	4.32	4.31	0.01
2000	4.63	4.63	0.00

6.3 Conclusions

The sub-question that is answered in this section is: What impact does the placement of a permanent water barrier in the Rijnmond have on the Rhine river system at average to low flows on water levels and discharges?

As computed with the SOBEK software and schematizations, the impact of a closure of the Niewe Waterweg on the river system is contained within the Waal river branch for average (2000 m^3/s) to extremely low (600 m^3/s) Rhine discharges. The discharge through the Waal river is unaffected, as the water levels at the bifurcation point are not affected by a permanent barrier at the Meuse river mouth. The water levels downstream of Dodewaard (at Rhine kilometer 900) are increased significantly for the lowest Rhine discharges, which increases the navigability of the river up to that point. At Hardixveld, the navigation depth is increased by 2.32 m for the lowest Rhine discharge of 600 m^3/s. At Dodewaard, the navigation depth is increased from 2.29 m to 2.88 m for a Rhine discharge of 600 m^3/s. This increase in water depth causes this section to be better navigable for extremely low discharges (Rhine discharge of 600 m^3/s), as the minimum navigation depth of 2.8 m is exceeded. As the notorious bottleneck in the Waal at Sint Andries (situated between Hardinxveld and Tiel along the Waal) is downstream of this location, the navigability can be expected to be increased here as well.

The water levels at the Pannerdensche Kop are not affected by a placement of a permanent barrier in the Rijnmond. The effect of the backwater curve introduced by a constant water height at the Rijnmond is negligible at the Pannerdensche Kop. Because the water levels at this bifurcation point are not affected, the discharge distribution is not affected. The backwater curve is most pronounced when the Rhine discharge is lowest (600 m^3/s), but the discharge and water levels in the Bovenrijn and IJssel river are not affected.

The transition between the Rhine-Meuse estuary schematization and the Rhine branches schematization is sufficiently accurate. The water levels as computed by the Rhine-Meuse estuary schematization are higher for each discharge scenario, with a maximum of 0.06 m. Due to inaccuracies at the boundary in the Rhine-Meuse estuary schematization, the error in water levels at the boundary can be up to 0.3 m, so the water levels as computed by the Rhine branches schematization are more reliable.

Next to the effect of the permanent barrier on the water levels in the Waal, multiple additional advantages (excluding the decreased flood risk) are specified: greater control over water levels in the Rijnmond area, an increased fresh water buffer in the Haringvliet and Brielse Meer and an improved ecological value of the Rhine because the Haringvliet sluices can be opened more during low Rhine discharges.

Chapter 7

Extraction and redistribution

In this chapter, the set-up and results of extraction and redistribution is given. In the last section the results are summarised in a conclusion.

7.1 River water extraction

As previously determined, three options of river water extraction are examined in this section: extraction from the IJssel, extraction from the Rhine and a canal from the Rhine out of Germany. In this section first the set-up of the computational analysis is presented and secondly the results are shown.

7.1.1 Set-up

The boundary conditions and set-up of the Rhine branches schematization are kept the same as specified in section 6.1, with discharges as shown in Table 6.2. The addition to the schematization are extra lateral sinks, to simulate the extraction of water out of the river.

Because the analysis of the effect of the closure of the Rijnmond shows that the water distribution is not affected by the water level at Hardinxveld, the closed situation is chosen as the base case. This is because the model converges to the steady-state solution faster in the closed situation, saving computation time. The observation points where the water level will be monitored are shown in Figure 7.1, with the corresponding Rhine kilometer shown between brackets. The minimal water depth of the IJssel river up to Olst at Rhine kilometer 957 is 2.5 m (Koedijk, 2020). The river bed level (z_b) corresponding with the specified points in Figure 7.1 are given in Table 7.1.

Table 7.1: Main channel depths in the IJssel river

	Location in IJssel river							
	Pan. Kanaal	IJsselkop	Doesburg	Dieren	Eefde	Olst	Katerveer	Ketelmeer
Bed level z_b [m NAP]	4.03	4.46	2.62	0.69	-0.43	-2.35	-4.3	-3.39

Extraction from the IJssel

To simulate the extraction of water out of the IJssel, two lateral sinks are defined. One of the sinks is situated at Eefde, where the connection to the Twentekanalen is situated. The second, new, location of extraction is at the location as specified in Figure 5.7(a), nearby Doesburg. The discharge that is pumped out of the IJssel into the Twentekanalen is assumed to be 27.5 m^3/s, as previously determined. The effect of an extra pumping station in the IJssel is determined by placing a lateral sink in the location specified in Figure 5.7(a).

Extraction from the Rhine

To determine the effect of pumping the required water out of the Rhine, the lateral sink at Doesburg in the IJssel is moved to Lobith in the Rhine. The lateral sink for the Twentekanalen at Eefde is kept in the IJssel, as this demand does not change. The rest of the parameters are the same as the extraction from the IJssel scenario.

Canal out of Germany

Because the Rhine branches schematization encompasses only the Dutch Rhine river system, a canal out of Germany cannot be modelled as a separate river branch. In order to simulate the discharge through this canal, the Rhine discharge has been decreased by 50 m^3/s for all discharge scenarios, while the lateral sink nearby Doesburg (as specified in the extraction from the IJssel scenario) has been changed to a lateral source of 20 m^3/s. This means that 30 m^3/s had been extracted from this channel in Germany and the Netherlands for irrigation and other water demands.

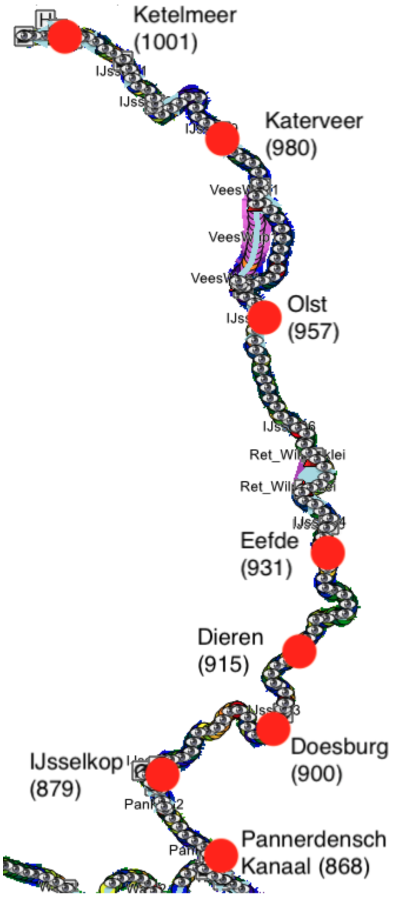


Figure 7.1: Observation points in the IJssel river, Rhine kilometers indicated

7.1.2 Results

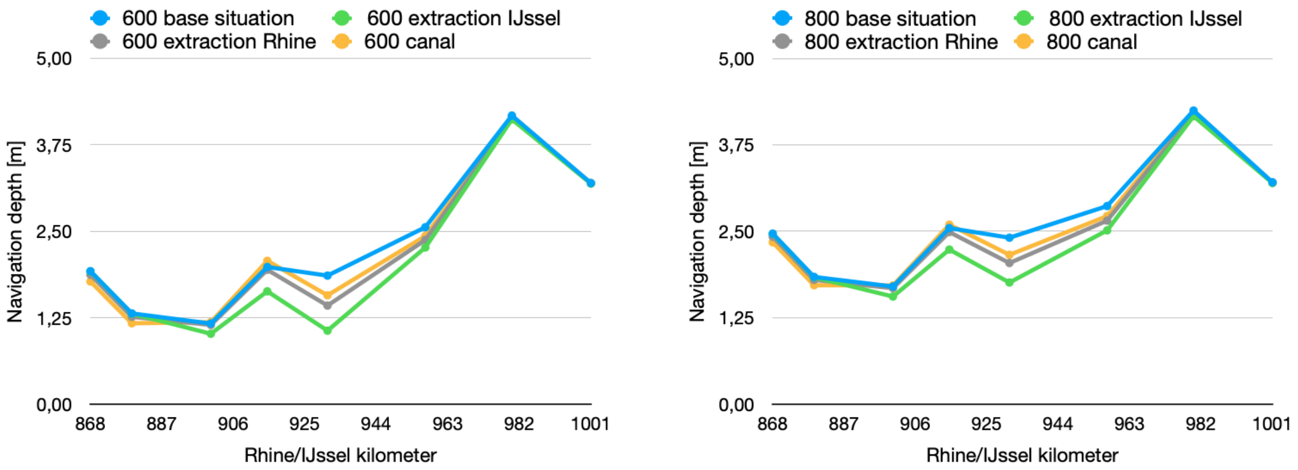
The water levels computed using the Rhine branches schematization both with and without extraction can be seen in Table 7.2. The calculated corresponding navigation depths can be found in Table 7.3. The navigation depths in the IJssel river are shown per Rhine discharge in Figure 7.2, with and without river water extraction.

Table 7.2: Water level at specified locations in the IJssel river for multiple Rhine discharges, with and without extraction

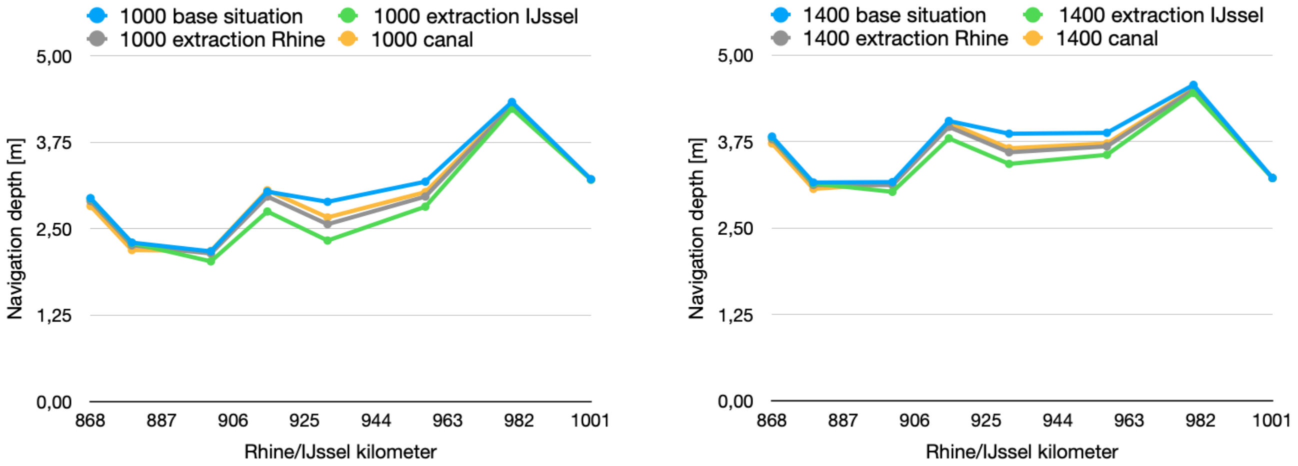
Rhine discharge	Water level at location in IJssel river [m NAP]							
[m^3/s]	Pan. Kanaal	IJsselkop	Doesburg	Dieren	Eefde	Olst	Katerveer	Ketelmeer
600 base situation	5.96	5.78	3.79	2.68	1.43	0.21	-0.13	-0.19
600 IJssel extraction	5.96	5.77	3.64	2.33	0.64	-0.08	-0.18	-0.20
600 Rhine extraction	5.90	5.73	3.77	2.64	1.00	0.03	-0.16	-0.20
600 canal	5.81	5.63	3.81	2.77	1.15	0.08	-0.15	-0.19
800 base situation	6.50	6.30	4.32	3.24	1.98	0.52	-0.05	-0.18
800 IJssel extraction	6.49	6.30	4.18	2.93	1.33	0.16	-0.14	-0.19
800 Rhine extraction	6.45	6.26	4.30	3.18	1.61	0.31	-0.10	-0.19
800 canal	6.37	6.18	4.34	3.29	1.73	0.37	-0.09	-0.19
1000 base situation	6.97	6.76	4.79	3.73	2.46	0.83	0.03	-0.17
1000 IJssel extraction	6.97	6.75	4.65	3.44	1.90	0.47	-0.07	-0.18
1000 Rhine extraction	6.93	6.72	4.76	3.65	2.13	0.61	-0.03	-0.18
1000 canal	6.86	6.65	4.80	3.75	2.23	0.68	-0.01	-0.18
1400 base situation	7.85	7.62	5.78	4.74	3.43	1.53	0.27	-0.17
1400 IJssel extraction	7.84	7.60	5.64	4.49	3.00	1.21	0.15	-0.17
1400 Rhine extraction	7.82	7.58	5.74	4.65	3.16	1.33	0.20	-0.17
1400 canal	7.75	7.53	5.76	4.71	3.22	1.37	0.21	-0.17
1700 base situation	8.34	8.03	6.23	5.18	3.85	1.84	0.40	-0.16
1700 IJssel extraction	8.34	8.01	6.08	4.94	3.45	1.54	0.28	-0.17
1700 Rhine extraction	8.31	7.99	6.18	5.10	3.61	1.66	0.32	-0.17
1700 canal	8.24	7.93	6.21	5.16	3.67	1.70	0.34	-0.17
2000 base situation	8.71	8.21	6.40	5.35	4.02	1.97	0.46	-0.15
2000 IJssel extraction	8.70	8.19	6.26	5.12	3.63	1.67	0.33	-0.17
2000 Rhine extraction	8.67	8.17	6.36	5.27	3.78	1.79	0.37	-0.17
2000 canal	8.61	8.11	6.38	5.33	3.84	1.83	0.39	-0.16

Table 7.3: Navigation depths at specified locations in the IJssel river for multiple Rhine discharges, with and without extraction

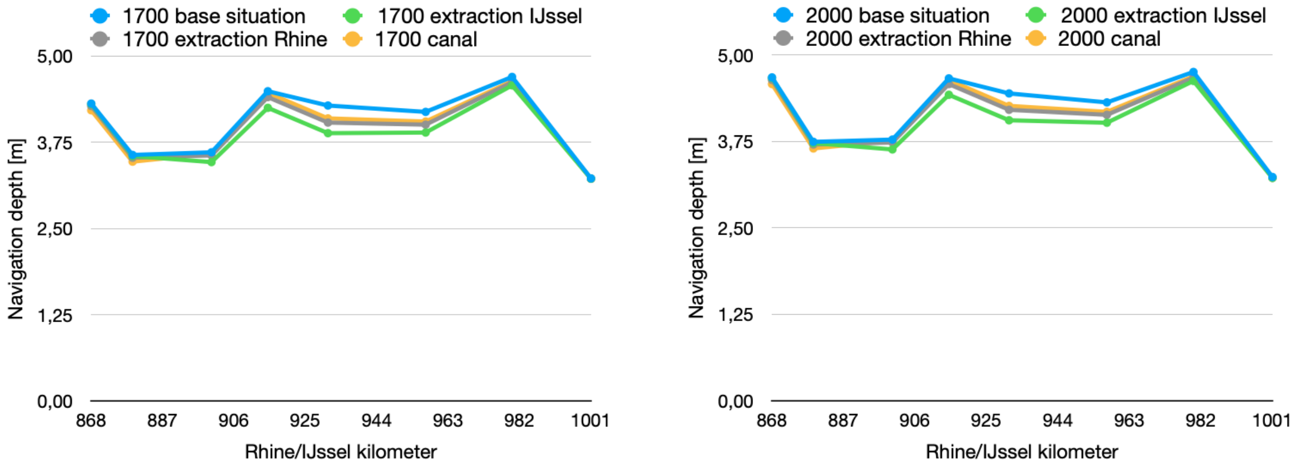
Rhine discharge	Navigation depth at location in IJssel river [m]							
[m^3/s]	Pan. Kanaal	IJsselkop	Doesburg	Dieren	Eefde	Olst	Katerveer	Ketelmeer
600 base situation	1.93	1.32	1.17	1.99	1.86	2.56	4.17	3.20
600 IJssel extraction	1.93	1.31	1.02	1.64	1.07	2.27	4.12	3.19
600 Rhine extraction	1.87	1.27	1.15	1.95	1.43	2.38	4.14	3.19
600 canal	1.78	1.17	1.19	2.08	1.58	2.43	4.15	3.20
800 base situation	2.47	1.84	1.70	2.55	2.41	2.87	4.25	3.21
800 IJssel extraction	2.46	1.84	1.56	2.24	1.76	2.51	4.16	3.20
800 Rhine extraction	2.42	1.80	1.68	2.49	2.04	2.66	4.20	3.20
800 canal	2.34	1.72	1.72	2.60	2.16	2.72	4.21	3.20
1000 base situation	2.94	2.30	2.17	3.04	2.89	3.18	4.33	3.22
1000 IJssel extraction	2.94	2.29	2.03	2.75	2.33	2.82	4.23	3.21
1000 Rhine extraction	2.90	2.26	2.14	2.96	2.56	2.96	4.27	3.21
1000 canal	2.83	2.19	2.18	3.06	2.66	3.03	4.29	3.21
1400 base situation	3.82	3.16	3.16	4.05	3.86	3.88	4.57	3.22
1400 IJssel extraction	3.81	3.14	3.02	3.80	3.43	3.56	4.45	3.22
1400 Rhine extraction	3.79	3.12	3.12	3.96	3.59	3.68	4.50	3.22
1400 canal	3.72	3.07	3.14	4.02	3.65	3.72	4.51	3.22
1700 base situation	4.31	3.57	3.61	4.49	4.28	4.19	4.70	3.23
1700 IJssel extraction	4.31	3.55	3.46	4.25	3.88	3.89	4.58	3.22
1700 Rhine extraction	4.28	3.53	3.56	4.41	4.04	4.01	4.62	3.22
1700 canal	4.21	3.47	3.59	4.47	4.10	4.05	4.64	3.22
2000 base situation	4.68	3.75	3.78	4.66	4.45	4.32	4.76	3.24
2000 IJssel extraction	4.67	3.73	3.64	4.43	4.06	4.02	4.63	3.22
2000 Rhine extraction	4.64	3.71	3.74	4.58	4.21	4.14	4.67	3.22
2000 canal	4.58	3.65	3.76	4.64	4.27	4.18	4.69	3.23



(a) Rhine discharge of 600 m^3/s (b) Rhine discharge of 800 m^3/s



(c) Rhine discharge of 1000 m^3/s (d) Rhine discharge of 1400 m^3/s



(e) Rhine discharge of 1700 m^3/s (f) Rhine discharge of 2000 m^3/s

Figure 7.2: Navigation depth of the IJssel river for different Rhine discharges and river scenarios

The base scenario has no extraction. For the IJssel extraction, water is extracted at Rhine kilometer 910 (17.5 m^3/s) and 931 (27.5 m^3/s). In the Rhine extraction option, only the extraction at km 931 is present, while for the canal there is an inflow of 20 m^3/s at km 910 as well as extraction at km 931.

As can be seen from Figure 7.2, the extraction of river water has the largest impact on the water level at Eefde (Rhine kilometer 931) in all discharge situations. The biggest change in navigation depth is when discharges are low because a greater portion of the available river water is extracted from the system.

Placing the pumping station in the Rhine is preferable to a pumping station in the IJssel. Because the water in the streams is not expected to be fully used, this accomplishes three benefits. Firstly, moving the extraction point to the Rhine removes the extra load on the IJssel river system. Secondly, the streams are supplied with water, increasing the resilience to drought and thirdly the remainder of the water is transferred to the IJssel, increasing the flow to the IJsselmeer. However, the amount of water that can be supplied in this way is restricted to the capacity of the streams, so this is does not increase the navigability of the IJssel significantly. As can be seen in Figure 7.2, none of the extraction options have a significant impact on the minimum navigation depth of the whole river. The bottleneck for Rhine discharges of 1400 m^3/s or less is at Doesburg (IJssel kilometer 900), and the water levels at this location are not significantly changed by the extractions.

As can be seen from the computations in the Waal in subsection 6.2.2, the water level just after the bifurcation in the Waal is the critical point whether navigation is possible. If the navigation depth at Pannerden in the Waal is more than 2.8 m, the whole Waal will have a navigation depth greater than 2.8 m. For this reason, the navigation depths at that point in the Waal will be considered when assessing the navigability of the entire Waal river. In Table 7.4 the impact of the interventions on the navigation depth in the Waal is shown for the different Rhine discharges. As can be seen, the extraction of water out of the IJssel has no effect on the navigability of the Waal. The other two interventions (extracting from the Rhine and the canal) do have an effect on the navigation depth of the Waal river. The impact of extraction from the Rhine on the water level in the Waal is very small however, at most 6 cm for a Rhine discharge of 600 m^3/s. The impact of the canal from Germany is largest, but is still 15 cm or less. With a closed Rijnmond, the minimum navigation detpth of 2.8 m is reached with a Waal discharge of about 700 m^3/s. The corresponding Rhine discharge depends on the extraction option used. A polynomial relation is assumed between 600 and 1400 m^3/s for each option (see Figure 7.3), which fit the data very well (R^2 values of 0.999 or higher, see Appendix B). The trendline equation is used to determine the Rhine discharge at which point the navigation depth at Pannerden in the Waal is equal to 2.8 m. The results can be seen in Table 7.5.

Table 7.4: Waal discharge just downstream of bifurcation without and with extraction variants

	Navigation depth just after the Pannerdensche Kop in the Waal [m]			
Rhine discharge [m^3/s]	Base situation	IJssel extraction	Rhine extraction	Canal
600	2.17	2.17	2.11	2.02
800	2.71	2.70	2.66	2.58
1000	3.18	3.18	3.14	3.07
1400	4.06	4.05	4.03	3.96
1700	4.56	4.56	4.53	4.47
2000	4.95	4.94	4.92	4.86

Table 7.5: Rhine discharge when the minimal navigation depth in the Waal is equal to 2.8 m

	Base situation	IJssel extraction	Rhine extraction	Canal
Rhine discharge [m^3/s]	825	827	876	884

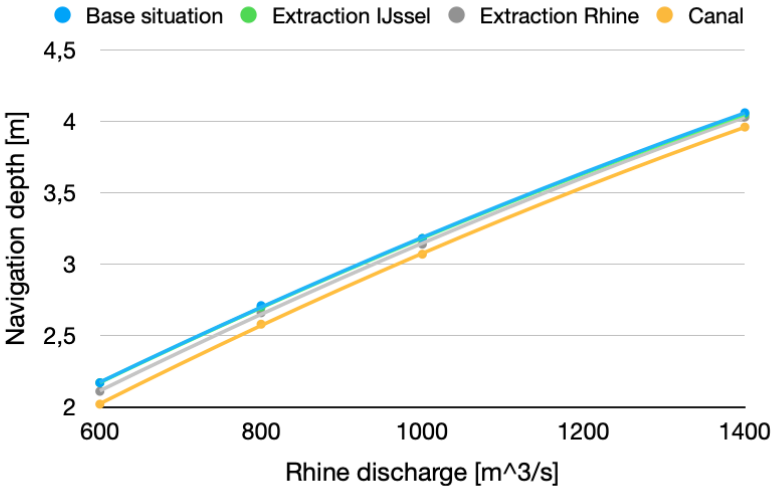


Figure 7.3: Navigation depth just after bifurcation point at Pannerden in the Waal for different Rhine discharges

Table 7.6: Rhine discharge when the minimal navigation depth in the IJssel is equal to 2.5 m

	Base situation	IJssel extraction	Rhine extraction	Canal
Rhine discharge [m^3/s]	1121	1182	1169	1144

The extraction of water from the IJssel has no significant influence on the water levels at the bifurcation points at Pannerden (Pannerdensche Kop) and at Driel (IJsselkop). This is reflected in the comparison between the Waal discharge without extraction and with the extraction variants, which can be seen in Table 7.7. The extraction of water from the Rhine has a larger effect of the discharge distribution because the discharge of 17.5 m^3/s is extracted before the bifurcation point at the Pannerdensche Kop. The difference in Waal discharge between the base situation and the extraction from the Rhine is for all discharge situations about 14 m^3/s. This shows that extracting water out of the Rhine mostly affects the discharge through the Waal river. This is also reflected in the small difference in the water level at the IJsselkop (see Table 7.2) between these two scenarios.

Table 7.7: Waal discharge just downstream of bifurcation without and with extraction variants

	Waal Discharge [m^3/s]			
Rhine discharge [m^3/s]	Base situation	IJssel extraction	Rhine extraction	Canal
600	490	490	476	450
800	651	651	637	612
1000	810	809	796	771
1400	1119	1117	1106	1083
1700	1310	1307	1296	1272
2000	1462	1459	1448	1424

7.2 Discharge redistribution

An increase of water flow to the IJssel increases the navigability of the IJssel and increases the fresh water buffer in the IJsselmeer, the largest fresh water lake of the Netherlands. As can be learned from Figures 6.5 and 7.2, the minimal shipping depth on the two rivers is not reached at the same Rhine discharge. The Waal is mostly usable for barge shipping if the Rhine discharge reaches 800 m^3/s, while the minimal navigation depth on the IJssel is only reached at 1400 m^3/s in the base situation. As can be seen in Table 7.8, this occurs at an IJssel discharge of about 250 m^3/s. This means that between a Rhine discharge of 800 and 1400 m^3/s a redistribution of water over the Waal and IJssel rivers is desirable.

Table 7.8: Rhine, Waal and IJssel discharge for a closed situation without extraction

Rhine discharge [m^3/s]	Waal discharge [m^3/s]	IJssel discharge [m^3/s]
600	490	89
800	651	127
1000	810	166
1400	1119	258
1700	1310	303
2000	1462	321

7.2.1 Set-up

As determined in Chapter 2, three options can be used to achieve a different water distribution at the Pannerdensche Kop, which are the Rijnstrangen, a pumping station in the Rhine and a modification to the bifurcation point at the Pannerdensche Kop. This last option will not be examined further, as this is a complex problem and lies outside the scope of this research.

Rijnstrangen

A way to influence the water distribution is by using an extra channel which extracts water from the Rhine and deposits into the Pannerdensch Kanaal. One such channel exists in the form of an old riverbed, the Rijnstrangen (see Figure 7.4). Using an adjustable weir, a specified amount of water can be let into the Rijnstrangen and flows into the Pannerdensch Kanaal. Using the Rhine branches schematization, this has been schematized as a lateral sink in the Bovenrijn at the location of Lobith (the start of the Rijnstangen) and a lateral source into the Pannerdensch Kanaal at the end of the Rijnstrangen. As determined above, this computation has been done with Rhine discharges of 800 and 1000 m^3/s.

Figure 7.4: Location of the Rijnstrangen (adapted from Van Rossum, 2021)

Canal out of Germany

The set up to determine the effect of this option is the same as specified in section 7.1.1.

7.2.2 Results

As can be seen from Table 7.9, using the Rijnstrangen is not an efficient way to influence the discharge distribution of the Waal and IJssel. To achieve an increase in IJssel discharge of 10 m^3/s, more than 100 m^3/s has to flow through the Rijnstrangen. This efficiency decreases with higher discharges through the Rijnstrangen. An explanation for this phenomenon is that that although the water is discharged to the Pannerdensch Kanaal, the inlet into the Pannerdensch Kanaal is close to the bifurcation point at the Pannerdensche Kop. This causes a the backwater curve which influences the water levels at the Pannerdensche Kop. These water levels are comparable to the situation without discharge through the Rijnstrangen, so the discharge distribution is not affected significantly.

Table 7.9: Impact of discharge through the Rijnstrangen on the discharges of the Waal and IJssel

Rhine discharge [m^3/s]	Rijnstrangen discharge [m^3/s]	Waal discharge [m^3/s]	IJssel discharge [m^3/s]
800	0	651	127
	50	645	133
	100	642	136
	150	640	138
	200	639	139
1000	0	809	166
	50	804	171
	100	800	175
	150	797	178
	200	796	179

The impact of the canal on the discharge distribution can be seen in Table 7.10. The discharges at the IJsselkop are expected to be lower than the IJssel discharge without canal because the canal discharges into the IJssel after the bifurcation, at Doesburg. For this reason, the IJssel discharge further downstream of this point is compared, at Dieren. At Dieren an increase in IJssel discharge is observed of 8-10 m^3/s. The amount of water extracted from the Rhine is 50 m^3/s, so the effectiveness of the canal is 16-20%.

Table 7.10: Waal and IJssel discharge with and without canal

		IJssel discharge [m^3/s]	
Rhine discharge [m^3/s]	Waal discharge [m^3/s]	IJsselkop discharge	Dieren discharge
600	490	89	89
600 canal	450	79	99
800	651	127	127
800 canal	612	116	136
1000	810	165	165
1000 canal	771	154	174
1400	1119	256	256
1400 canal	1083	242	262
1700	1310	300	300
1700 canal	1272	288	308
2000	1462	318	318
2000 canal	1424	306	326

7.3 Conclusions

The subject of this section is answering the fifth sub-question of the research question: What is the impact of river water infiltration and redistribution on the Rhine river system at average to low flows on water levels and discharges?

The extraction of water out of the IJssel has no effect on the water distributions at the Pannerdensche Kop and at the IJsselkop. The extraction has a significant effect on the water levels in the IJssel river. However, the decrease in water level is no cause for a significant decrease in navigability, as the extraction does not cause the navigation depths to be the minimum for the entire river. In the case of a Rhine discharge of 1000 m^3/s (Figure 7.2(c)) the navigation between Eefde and Zutphen/Katerveer is decreased with about 20% due to the extraction of water out of the IJssel, but shipping to Doesburg or further upstream the Rhine was already greatly diminished whether extraction takes place or not. The extraction of water out of the Rhine does not affect the navigation depths in the IJssel as much, but affects the navigability of the Waal river, requiring an additional Rhine discharge of 51 m^3/s before the Waal reaches the minimal navigation depth of 2.8 m. The canal affects the water levels in the IJssel the least while still enabling groundwater infiltration. This intervention has a significant effect on the navigability of the Waal however, requiring that 59 m^3/s extra Rhine discharge is needed before navigation is possible on the Waal.

A redistribution of the water in the Rhine over the Waal and IJssel river is desirable for Rhine discharges between 800 and 1400 m^3/s, but using the Rijnstrangen is not efficient as a lot of water has to flow through the Rijnstrangen for a small increase in IJssel discharge (a discharge of 150 m^3/s through the Rijnstrangen for an increase of 11 m^3/s through the IJssel, being 7% effective). A canal out of Germany is more effective (16-20% of the discharge through the canal results in an increase of IJssel discharge), decreasing the Waal discharge with 38-40 m^3/s while increasing the IJssel discharge with 8-10 m^3/s. The difference in discharge change is infiltrated along the course of the canal, 30 m^3/s. As can be seen in Figure 7.2, this increase in IJssel discharge does not increase the navigability. On the contrary, because the IJssel discharge is less than the base case before the canal flows into the IJssel the navigability in that section is decreased. Because this already is the critical point for navigation on the IJssel, the navigability of the whole IJssel is diminished. The increase in discharge to the IJsselmeer increases the water buffer in the lake and if the canal is suitable for navigation, this bottleneck in the IJssel may be avoided by sailing the canal into Germany.

A third option is adjusting the Pannerdensche Kop to influence the distribution, but a seperate study is needed in order to determine its validity.

Chapter 8

Discussion

In this chapter, the results of the literature study and system analysis are discussed devided into two sections: extraction and redistribution. The limitations of this study and assumptions made during the research are considered in the second section of this chapter.

8.1 Extraction

As shown in chapters 3 and 5, the need for a solution for the groundwater deficits will increase due to climate change. Additional measures have to be taken in the east of the Netherlands to combat drought. This is required to preserve the cultural heritage, ecology and agriculture in the area. A different water management strategy is needed to minimise the economical and ecological damages of drought. Based on discussions with the water boards in the east of the Netherlands (van Houten, 2021; Roelofs, 2021), the primary measure that is recommended to be implemented is containing the precipitation in the higher elevated regions of the study area, whereas the current policy is to drain the precipitation as fast as possible from the farmlands in order to be able to work the fields with heavy machinery. When the total amount of precipitation and evaporation in the east of the Netherlands is taken into account, there is a net surplus of precipitation (Roelofs, 2021). However, storage off all precipitation of the wet winter period in the area until it is needed in the summer is not achievable with the current agricultural policy. There is a conflict of interest in storing the water in the unsaturated zone. If all precipitation in winter is stored in the unsaturated zone, the water table in the farmlands would be too high to be workable with machinery. The solution for the farmers is to drain the excess precipitation, slowing the groundwater recharge and increasing the flow to the surface water. Although seasonal forecasts exist, they are not reliable in predicting the precipitation for northern Europe, limiting the amount of planning that can be done in water management (Weisheimer & Palmer, 2014). There is no reliable way to adjust the water management a season prior to a dry spell, and perpetually planning for the eventuality of a dry summer will affect the agriculture.

A more dynamic method to mitigate the effect of dry spells is to introduce external surface water. This allows for groundwater recharge if groundwater levels are dropping and for irrigation water if a dry spell occurs. This river water can be used in multiple ways: e.g. direct infiltration to the groundwater, infiltration via surface water or direct spray irrigation. The external river water that is added to the ecosystem should be of sufficient quality in order to not damage the ecology, e.g. no contamination with pollutants, excess nutrients, etc. Also, some types of vegetation in the area are dependent on the upwelling groundwater because of the high amount of minerals this contains.

The extraction options as examined in this study are only effective if an adequate distribution network is available. If such a network is implemented and used, supplying the streams in the area with river water is an effective measure to reduce groundwater use and allow for restoration of groundwater levels. The three examined options of river water extraction (extraction from the IJssel, extraction from the Rhine and a canal from Germany) have different advantages and disadvantages. An overview can be seen in Table 8.1, where 0 denotes a neutral impact, - denotes a negative influence and + shows a positive impact. The extraction from the IJssel has the least impact on the navigability of the Waal, but has the largest impact on the water levels of the IJssel, decreasing the navigation depth up to 42% at Eefde. Extraction from the Rhine does cause a decrease in navigability of the Waal, but does not influence the IJssel water levels as much as the extraction from the IJssel option. The canal from Germany increases the discharge to the IJsselmeer but does not increase the navigability of the IJssel as the bottleneck for navigability of the IJssel is in the first 25 km of the river and the canal flows into the IJssel downstream of this bottleneck. The construction costs are highest for the canal (approximatly €2.3 billion), while the two pumping options are much cheaper, ranging from approximately €59 million (IJssel extraction) to €73 million (Rhine extraction).

Table 8.1: Comparison of the extraction options on four criteria

Criteria	Extraction from the IJssel	Extraction from the Rhine	Canal
Navigability of the Waal	0	-	- -
Navigability of the IJssel	0	0	0/+
Discharge to the IJsselmeer	-	+	++
Implementation cost	-	- -	- - - -

Taken the above considerations into account, the option using extraction from the Rhine has the greatest positive impact while limiting the disadvantages. This option has the added benefit of increasing the discharge of the IJssel when not all extracted water is used. This is not anticipated to improve the navigability of the IJssel, but does increase the fresh water buffer in the IJsselmeer. While pumping water from the Rhine does influence the navigability of the Waal, the added benefit of a pumping installation is that it can be used dynamically. When water levels in the Waal are not sufficient to enable infiltration (around a Rhine discharge of 876 m^3/s), the pump should not be used. If enough infiltration buffers along the reach of the streams are constructed, these buffers can be filled up when traffic on the Waal is low (e.g. at night) which then can be used for irrigation when the pumps are shut off.

8.2 Redistribution

While the placement of a permanent barrier does not directly influence the water distribution at the Pannerdensche Kop, a different distribution is possible when structural changes are made to the river system. The water demand for flushing the salt wedge is eliminated, which reduces the fresh water demand of the Waal river. The only other major water demand of the Waal is maintaining navigability. As shown in this study, the minimal navigation depth in the Waal is guaranteed at a lower Rhine discharge (about 850 m^3/s) than the discharge needed for flushing in the Nieuwe Waterweg (achieved with a Rhine discharge of 1400 m^3/s). This means that with a permanent barrier, there is greater flexibility in adjusting the discharge distribution for low Rhine discharges. Extra discharge through the IJssel, as well as supplying the IJsselmeer with extra water, could be beneficial for the higher regions in the east of the Netherlands, where the impact of drought has been great in the past years. The other water demands, such as keeping the Waal navigable, are influenced by a redistribution and should be examined further if a redistribution is considered.

The redistribution options studied in this thesis, using the Rijnstrangen or using the canal from Germany, are not effective in increasing the navigability of the IJssel. Using the Rijnstrangen, only a effeciveness of 7% is achieved (150 m^3/s flow through the Rijnstrangen to increase the IJssel discharge by

11 m^3/s). The canal is more effective in redistribution (of the 50 m^3/s extracted from the Rhine in Germany, 20 m^3/s is assumed to flow to the IJssel), but flows into the IJssel downstream of the bottleneck for navigability. The discharge to the IJsselmeer is improved with both the Rhine extraction option and the canal, but the effect on the water management of the IJsselmeer of this extra discharge is not analysed. Based on the above, it can be hypothesised that the most effective way to increase the navigability of the IJssel for low Rhine discharges is adjusting the bifurcation point at the Pannerdensche Kop. Additional research is needed to prove the validity of this hypothesis.

8.3 Methodological limitations

In this study, the only way of using the river water is by supplying the streams with water, from where it can be used elsewhere. This is done because the streams disperse the water over the area, increasing the accessibility to the surface water. However, direct infiltration to the groundwater might be more effective in recharging the groundwater levels and therefore further research is needed to determine the most effective way river water can be used.

In analysing the river system, the climate projections of the KNMI are used to determine the possible Rhine discharges. The frequency of occurrence of dry spells is not further implemented into this study. While this study shows the hydrological effect of a permanent barrier in the Rijnmond and river water extraction at different Rhine discharges, further research is needed to determine the effectiveness of the implementations. For instance, an analysis of the effect of a permanent barrier on the amount of days that river water can be extracted is a good addition to the research in this study. This study was done to provide a base scenario that could be used in future research to further analyse this problem. Additionally, this study has only analysed Rhine discharges from 2000 to 600 m^3/s, while extremely high Rhine discharges of 16000 m^3/s can occur. Because this study focuses on the effects of drought, the high Rhine discharges are not taken into account. As the effects of the backwater curve of the permanent barrier and extraction are more pronounced when river discharges are low, the critical discharges are considered in this study.

The effect of a new storm surge barrier in the Rijnmond is influenced by the type of barrier. In this study, only a permanent barrier is considered and the assumption is made that the salt intrusion from the tidal cycle is stopped by this barrier. The location and type of sea lock could influence the salt intrusion as well, and this effect is neglected in this study. While there are lock systems that limit the amount of salt water in the estuary, traditional sea locks introduce saline water every time the lock is used. Because the current barrier, the Measlantkering, is sufficient until at least 2050, the specifics of the barrier and sea locks can be more accurately determined when the Maeslantkerng must be adapted. This study shows the effect of a constant water height in the Rijnmond area, which can be achieved when a permanent barrier is constructed.

The way the water levels and discharges are determined in this study is by one dimensional (1D) hydrodynamic modelling. The SOBEK schematization used is a simplification of the real river system, but this schematization is calibrated and maintained by Rijkswaterstaat and the errors introduced are in the order of 0.004 m (Berends, 2013). For the Waal river the errors are at most 0.024 m for low Rhine discharges. The discharges that are considered in this study are lower than the calibration values (Rhine discharge of 2700 m^3/s), so the difference could be greater. This is not expected to significantly alter the results of this study.

Chapter 9

Conclusion and recommendations

In this chapter the key findings are given and an answer to the research question is formulated. In the second section of this chapter recommendations are made for future research.

9.1 Key findings

In this section an answer will be formulated to the main research question: **In what way can the placement of a permanent water barrier in the Rijnmond help in restoring groundwater levels in the east of the Netherlands?** This will be done by briefly recapping the sub-questions and its sub-conclusions, after which the conclusion on the main research question will be formulated.

1. *How does climate change influence the occurrence of droughts in the east of the Netherlands and the Rhine river system?*
   Due to climate change, the occurrence rate of droughts is expected to increase. A higher probability of meteorological drought combined with higher temperatures in the summer cause an increase in precipitation deficit in the Netherlands. The driest climate scenario projects an increase in evaporation of 16% and a decrease in precipitation of 20% in 2050, and this may be doubled in 2100. This affects the groundwater levels in the east of the Netherlands, and multiple consecutive dry summers could create a deficit of groundwater which can take up to 8 years to restore by natural means. The Rhine river system is also changing under the effects of climate change, becoming more dependent on precipitation and less on snow melt. This causes a change in the river regime of the Rhine, creating higher flood peaks in the winter and lower discharges in the summer. On average, the yearly discharge is projected to be reduced by 5 to 8% because of climate change in 2050. The changing climate is projected to cause a severe water deficit in both surface and groundwater every year in 2050 for the most extreme climate scenario. The river system is also affected by the sea level rise, as the storm surge barrier at the Meuse river mouth must be adapted to higher sea levels. A solution is to replace the Maeslantkering with a permanent water barrier, including sea locks.

2. *What is the hydrodynamical behaviour of the Rhine river system during dry spells?*
   The Rhine river system is currently adapted dynamically to the occurrence of droughts through the river management of the system. The weirs of the Nederrijn are adjusted below a Rhine discharge of 1500 m^3/s to discharge as much water as possible through the IJssel river. Above this discharge, the IJssel is kept at a discharge of 285 m^3/s. As the IJssel flows into the IJsselmeer, this discharge adds to the largest fresh water buffer in the Netherlands. The northern part of the Netherlands is dependent on the fresh water out of the IJsselmeer for fresh water demands. The bulk of the water available is discharged through the Waal river. To prevent the salt wedge from the North Sea from propagating too far inland that the fresh water inlets are compromised by

saline water, a minimum of about 1000 m^3/s is aimed to be discharged through the Nieuwe Waterweg. To prevent reaching the Waal river traffic limit, 800 m^3/s has to be discharged through the Waal. When Rhine discharges are low (below 1700 m^3/s), the Haringvliet sluices are closed gradually to store as much fresh water as possible in the Rijnmond area.

3. *How can surface water be used to restore groundwater levels in the east of the Netherlands and how much water is needed in a dry summer?*
   River water can help in decreasing the strain on the groundwater levels during droughts by supplying water to the drought-stricken area. Instead of pumping groundwater to irrigate the crops during the dry months of the growing season, surface water can be used if the streams in the area are supplied with water, which would require 12.6 m^3/s. The water that does not evaporate infiltrates through into the groundwater, increasing the buffer. The capacity of the streams in the study area which are used to convey the river water is 45 m^3/s, divided into 27.5 m^3/s through the Twentekanalen and 17.5 m^3/s through additional infrastructure, which has not been installed. The additional infrastructure as proposed in this thesis are extraction from the IJssel, or extraction from the Rhine or a canal out of Germany. The direct infiltration from the streams to the groundwater requires a discharge of 0.18 m^3/s, which is not substantial. Extra measures are needed to distribute the river water, which could provide a buffer of 100 mm in the unsaturated zone in 124 days for the whole area.

4. *What impact does the placement of a permanent water barrier in the Rijnmond have on the Rhine river system at average to low flows on water levels and discharges?*
   In this research, SOBEK and two river system schematizations (Rhine-Meuse estuary and Rhine branches) are used to determine the impact of a permanent barrier in the Rijnmond. This impact is contained to the water levels downstream of the Pannerdensche Kop in the Waal. The water levels at Dodewaard (Rhine kilometer 900) are increased by 0.59 m, while at Hardinxveld (Rhine kilometer 960) the water level is increased by 2.32 m for a Rhine discharge of 600 m^3/s. The impact of the permanent barrier is less for higher Rhine discharges and further upstream. The water levels at the Pannerdensche Kop are not affected by a placement of a permanent barrier in the Rijnmond, which means that the water distribution at the Pannerdensche Kop is unaffected, as well as the water levels in the Bovenrijn and IJssel river.

5. *What is the impact of river water infiltration and redistribution on the Rhine river system at average to low flows on water levels and discharges?*
   The impact of three extraction options (extraction from the IJssel, extraction from the Rhine and a canal from Germany) and two redistribution options (Using the Rijnstrangen and a canal from Germany) is computed in this study. The extraction of water from the IJssel has no influence on the water distribution at the Pannerdensche Kop and thus the water levels in the Waal, but it does have the greatest influence on the water levels in the IJssel river of the examined options, decreasing the navigation depth up to 43%. Extracting water from the Rhine does not affect the IJssel water levels as much as the extraction from the IJssel, but the water distribution at the Pannerdensche Kop is affected, causing the water levels in the Waal to be lower for the same Rhine discharge. The canal from Germany diverts the most water to the IJssel, but this affects the Waal water levels the most, requiring a Rhine discharge of 40 m^3/s more than the current situation in order to reach the minimum navigation depth in the Waal of 2.8 m.
   A redistribution of the water in the Rhine over the Waal and IJssel river is desirable for Rhine discharges between 800 and 1400 m^3/s, but using the Rijnstrangen is not efficient as a lot of water has to flow through the Rijnstrangen for a small increase in IJssel discharge (a discharge of 150 m^3/s through the Rijnstrangen for an increase of 11 m^3/s through the IJssel, an effectiveness of 7%). A canal out of Germany does change the discharge distribution, decreasing the Waal

discharge with 38-40 m^3/s while increasing the IJssel discharge with 8-10 m^3/s. This equals an effectiveness of 16-20%. The difference in discharge change is infiltrated along the course of the canal, 30 m^3/s. The navigability of the IJssel is not increased by the redistribution because the bottleneck of the IJssel for navigation is in the first 25 km of the IJssel after the bifurcation point at the IJsselkop, and the extra water flows into the IJssel after this bottleneck. The increased discharge through the IJssel increases the water buffer in the IJsselmeer.

9.2 Main conclusion

In this section an answer is formulated for the main research question:

In what way can the placement of a permanent water barrier in the Rijnmond help in restoring groundwater levels in the east of the Netherlands?

Through the construction of a permanent storm surge barrier in the Rijnmond, more control is achieved over the water levels in the Rhine-Meuse estuary. The placement has no direct influence on the discharge distribution at the Pannerdensche Kop, so the discharges of the Rhine branches (Waal, IJssel and Nederrijn) are not affected if there are no adaptations constructed in the river system. If the barrier in the Rijnmond prevents the formation of a salt wedge in the estuary, the discharge demand of the Nieuwe Waterweg is a lot less. The water demand for navigation in the Waal is reached at a Waal discharge of 700 m^3/s with a permanent barrier. Without a permanent water barrier in the Rijnmond, the biggest fresh water demand is flushing the Nieuwe Waterweg, which needs a Waal discharge of about 1000 m^3/s. This which means a different water distribution is possible with a permanent barrier if structural changes are made. More discharge through the IJssel river causes an increase in water flow to the IJsselmeer, which is a vital fresh water buffer for the northern half of the Netherlands. To restore groundwater levels in the east of the Netherlands, river water can be extracted from the IJssel or the Rhine river, e.g. by pump or by canal. The extraction option using a pumping station out of the Rhine river at Lobith is the most promising option, according to this study. A way the river water can be infiltrated in the east of the Netherlands is by distributing it over the streams, from where extra infrastructure must be constructed in order to divide it over the area. The increased infiltration can cause an increase of 100 mm in the unsaturated zone in 124 days.

There is no correlation between the construction of a permanent water barrier and the water discharge distribution at the Pannerdensche Kop. This means that the extra infiltration is not tied to the construction of said barrier, and can be implemented independently. The preferred extraction option of pumping water out of the Rhine does have an influence on the amount of water that flows into the Waal, so it can only be used if the navigation depth is sufficient. Because a permanent barrier increases the navigability of the Waal river, the extraction of water can be used more often, but it is not a requirement for implementing river water infiltration.

By providing external river water to an area of the Netherlands that is susceptible to drought, a dynamic system is created that can be adapted to the requirements of the season. Climate change in the Netherlands does not result in a consistently drier climate, but rather enhances the extremes. This means that the current moderate climate of the Netherlands will develop into wetter winters and drier summers. This requires a water system that can adapt with the changing climate, even within a single year. The land users in the east of the Netherlands must be able to deal with more extreme conditions (both wet and dry), and the current water management policy of the Netherlands is predominantly focused on managing high amounts of water. The existing infrastructure is suited for wet situations, and by supplying external water to the area the effects of extreme drought can be mitigated. By constructing a second infrastructure adapted to drought, both extremes of climate change can be dealt with.

The way a placement of a permanent barrier can help in mitigating the effects of drought on groundwater levels in the east of the Netherlands is by eliminating a fresh water demand from the river system (the need to stop the propagation of the salt wedge in the Rhine-Meuse estuary), thus providing an opportunity to rethink the discharge distribution over the Rhine branches. Because the problem of drought is a faster growing problem than the relatively slow process of sea level rise, a solution for combating drought must be implemented sooner than a solution for sea level rise. In extracting river water, a dynamic solution is presented, which can be adapted to the river discharge. The construction of a permanent barrier allows for greater flexibility in using this system.

Water in the east of the Netherlands is in short supply during dry summers, and supplying the streams in the area with water could lessen the strain on the groundwater reserves in that area. An efficient distribution network to divide the river water over the area is needed in order to profit the most from river water extraction.

9.3 Recommendations

Considering the presented conclusions and discussions, an advice is formulated. In the second section several recommendations are made for future research.

9.3.1 Advice

This study concludes 1) that the urgency to implement a way to mitigate the effects of drought in the east of the Netherlands is higher than a placement of a permanent water barrier in the Rijnmond, and 2) that river water infiltration can be implemented independently from a construction of a permanent water barrier. Therefore, it is advised to first examine the most effective way for drought mitigation in the east of the Netherlands. This should not be restricted to supplying the existing streams with water, but needs a broader approach to determine the most effective way for groundwater recharge. Once the water demands of the groundwater recharge methods are known, the effects on the water management of the Rhine river system can be determined.

9.3.2 Future research

River water infiltration
The deposition of fresh water in the east of the Netherlands is probably not sufficient to infiltrate to the groundwater, so additional measures may be needed. To determine the effect on the groundwater levels and the flow though the subsurface, additional research has to be done, for example using MODFLOW to model the groundwater flows. Also, the effect of extra groundwater on the river system can be examined in this way.

Other infiltration methods
The river extraction options considered in this study were all developed with the same method of infiltration: supplying the streams with water. However, this restricts the amount of water that can be supplied to the region to 45 m^3/s. While this is enough to supply all agriculture with water during dry months, a distribution network is needed. Other ways to mitigate the effects of drought on the groundwater can be researched on order to validate the effectiveness of the options presented in this study.

Adaption of the Pannerdensche Kop
The redistribution options as examined in this study are not effective in redistributing the river water of the Rhine. The Pannerdensche Kop is the bifurcation point where the Rhine splits into the Waal and Pannerdensch Kanaal. Adapting the bifurcation point in order to achieve a different water distribution could be studied in detail to assess the effectiveness of redistribution.

Effect on sedimentation

Closing the Rijnmond has a large effect on the water levels in the Rhine-Meuse estuary and as a consequence the flow velocities are affected. This influences the sedimentation and erosion rates in the estuary and could be of vital importance for the operation of the Port of Rotterdam. Further research is needed to assess the impact of a permanent barrier on sedimentation in the Rhine-Meuse estuary.

Effect on ecology

The ecology of the Rhine-Meuse estuary is dependent on the tidal cycle of the North Sea. A permanent barrier disrupts this cycle and affects the ecological value of the estuary. On the other hand, by allowing the Haringvliet sluices to be opened more frequently the ecology of the estuary and river system is improved. A study is advised to determine the effect of a permanent barrier on the ecology of the estuary and river.

Salt intrusion

The assumption is made in this study that the salt intrusion at the Rijnmond is stopped by implementing a permanent storm surge barrier. However, depending on the type of sea locks, salt water may intrude into the estuary and, without an open connection to the sea, may be trapped in the fresh water system. Further research is needed to determine the effect of different water barriers on the salt intrusion in the Rhine-Meuse estuary.

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Appendix A

Interviews

A.1 Drought Achterhoek

Interviewee	G. van Houweninge
Date	November 13, 2020
Topic	Drought in the east of The Netherlands

Background

Van Houweninge is a retired civil engineer living in the east of The Netherlands. Together with colleague Frank Spaargaren he coined the idea of using Plan Sluizen (the placement of a permanent water barrier in the Rijnmond) as a solution for the groundwater drought problem in the east of The Netherlands. This idea formed the basis of this study.

Interview summary

In combating the drought problem in the east of The Netherlands, Deltaprogramma Droogte (Delta program Drought) is drafted by the Delta commission. In the dry summers of 2018 and 2019 there were problems with navigation on the upstream parts of the IJssel, which led to questions about the water discharge distribution at the Pannerdensche Kop.

According to Van Houweninge, the best way to combat the receding groundwater levels is by increasing the water extraction from the IJssel at Eefde to the Twentekanalen, from which it can be dispersed over the drought stricken area. He estimated that about 6 to 8 m^3/s extra capacity should be enough to deal with the groundwater drought in the east of The Netherlands. The only current extraction point from the IJssel is at Eefde, where the current capacity is 22 m^3/s. This should be raised to 30-35 m^3/s in the future. The IJssel should also receive a greater portion of the available Rhine water to increase the discharge to the IJsselmeer and to compensate the extra extraction at Eefde. The extra water in the IJsselmeer can be used to prevent salination of the lake at the Afsluitdijk, as well as preventing salt intrusion via the Amsterdam Rijnkanaal.

The Twentekanalen needs water to be pumped up toward the higher regions of the canal in order to maintain the water levels. There are three weirs, at Eefde, Hengeloo and Enschede. Van Houweninge hypothesises that the solution for extra infiltration to the groundwater is to supply the dry stream beds with water in summer, and infiltrating and irrigate from these streams. The groundwater use for irrigation in agriculture in the east of The Netherlands is not mapped out well, and supplying water via streams to the farmers will help in conserving groundwater.

A.2 Waterschap Hollandse Delta

Interviewee	T. IJpelaar
Date	January 14, 2021
Topic	Water management Waterschap Hollandse Delta

Background

The Waterschap Hollandse Delta is situated in the Rijnmond area and covers the lands between the Nieuwe Waterweg and the Volkerrak, see Figure A.1. The water authority is responsible for maintaining the minor water ways in the work area (the major rivers and lakes are maintained by Rijkwaterstaat, the national water authority), processing waste water, maintaining water quality and checking the stability of dikes, among other things. IJpelaar is hydrologic advisor for the Waterschap Hollandse Delta.

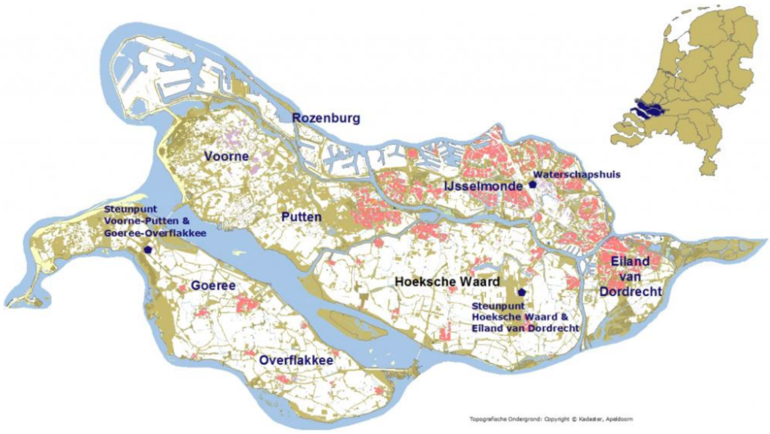


Figure A.1: Work area Waterschap Hollandse Delta (*Waterschap Hollandse Delta*, 2021)

Interview summary

The water authority is dependent on fresh water supply from the Waal and the Meuse, as the groundwater is frequently salinated by saline seepage from the North Sea. Every island lets in fresh water from the river system when a fresh water deficit occurs, and water in pumped out in case of a water surplus. The maximum water demand to counter evaporation, saline seepage and drying of ecology is 0.5 l/s/ha, which is 0.05 m^3/s/km^2. This value is the maximum demand, and is deemed to be sufficient for the water demands 30 years in the future.

To increase the ecological value of the Rhine river system, especially fish migration, the Kierbesluit precrebes the Haringvliet sluices to be open for as long as possible. When Rhine discharges are low (below 1400 m^3/s), the Haringvliet sluices are closed to maximise the fresh water buffer. An upcoming idea is to discharge a minimum of 100 m^3/s to the Haringvliet for as long as possible, in order to keep the fish migration possible.

The water buffer in the Brielse meer is used for the fresh water demand of the industry in the Port of Rotterdam, as well as supplying fresh water to the Waterschap Delfland, which lies to the north of the Nieuwe Waterweg. This water authority only has fresh water inlets in the Hollandse IJssel, and this river is heavily influenced by salt intrusion. The water management company Evides manages the water demands of the industry, Waterschap Delfland and the drinking water. The main drinking water inlets are at Berenplaat and in the Biesbosh, and uses surface water. A contact at Evides was supplied.

A.3 Waterschap Rijn en IJssel

Interviewee	G. van Houten
Date	January 15, 2021
Topic	Water management Waterschap Rijn en IJssel

Background

The Waterschap Rijn en IJssel is responsible for the water in the area between the Rhine, IJssel and Twentekanalen in the east of The Netherlands. The water authourity mainatins the waterways, provides clean surface water and manages the groundwater. Van Houten is hydrologist and maintains the data collection system for the water authority.

Interview summary

The problems with groundwater during dry spells are considerable. About 10% of the work area of the water authority can be supplied with water out of the first section of the Twentekanalen. The rest of the area is dependent on precipitation. The extraction at Eefde to the Twentekanalen is regulated by Rijkswaterstaat, as well as placing a emergency pump at Doesburg to supply the Oude IJssel with water during extreme drought. There are two problems during drought: a drying out of the surface layer of soil, which affects mostly the agriculture and shallow-rooting plants. The second problem during drought is a hydrological deficit of water in surface and groundwater, which causes ecological damage.

With the water authorities, water processing companies and Rijkswaterstaat an agreement is determined for the water demand out of the Twentekanalen during dry spells, the Waterakkoord. The water demand for Waterschap Rijn en IJssel according to the Waterakkoord is about 2-3 m^3/s, while the majority of the water pumped up at Eefde is determined for Waterschap Vechtstromen to the north of the Twentekanalen.

Extra infiltration is possible in the area. The higher regions to the east of the area, along the border of Germany, are unsuited for infiltration due to the soil. The soil there comprises out of clay and loam, and is not permeable enough to allow efficient infiltration. The region between the plateau to the east and the IJssel river consists mostly of sand, and is suitable for infiltration. The elevation of this region is on average about 6-8 m higher than the surrounding surface water sources. infiltration can be done by supplying water to the streams in the region, from where water can be used to infiltrate to the groundwater. Surface water can be used in order to maintain flow in the streams and supply the crops with water.

Most of the streams in the area originate in Germany, but there are no agreements between Waterschap Rijn en IJssel and the water authority in Germany about the water in the streams or the groundwater levels.

Another concern for the Waterschap Rijn en IJssel is the river bed erosion of the IJssel, which in 2050 amounts to a reduction of 1 meter or more.

A.4 Evides

Interviewee	B. Schaaf
Date	January 21, 2021
Topic	Water demand Evides

Background

The water processing company Evides processes the water for the southwest region of The Netherlands. It supplies drinking water and fresh water for the industry. Schaaf is process technologist for Evides.

Interview summary

Every drinking water process plant of Evides which uses surface water uses unprocessed water from the Rhine-Meuse estuary. Three big retention areas in the Brabantse Biesbosh are used as inventory and as water quality enhancement. From these retention areas the water is pumped via pipes to the production sites.

Every production site has a second supply of unprocessed water in case the pipe fails, for example by contamination or maintenance. For the Berenplaat this second inlet is out of the Oude Maas, part of the Rhine system. This inlet is only used during emergencies.

The highest peak demand of the past years has been 311951 m^3 per day, the maximum possible production discharge of the company is $1.5{\cdot}10^6$ m^3 per day. The maximum extraction from the Haringvliet is 920 m^3 per hour, so 22080 m^3 per day. The peak demand of the past years has been 21352 m^3 per day. The water in the Haringvliet consists for 85-95% of Rhine water, and 5-15% of water from the Meuse river, depending on the discharges of these rivers.

The peak water demand out of the Brielse Meer of the past years has been 55420009 m^3 per year, on average 151836 m^3 per day. The highest fresh water demand in one day was on July 26, 2019 and amounted to 168329 m^3.

A.5 Groundwater Waterschap Rijn en IJssel

Interviewee	G. Roelofs
Date	April 30, 2021
Topic	Groundwater management Waterschap Rijn en IJssel

Background

The water authority Waterschap Rijn en IJssel maintains the groundwater levels in the area. Roelofs is hydrologist at the Waterschap Rijn en IJssel.

Interview summary

The groundwater in the area is used for the drinking water production for the east of The Netherlands.

In order to infiltrate naturally, a large surface area is needed. The infiltration speed from a infiltration lake is generally between 5 to 20 mm per day, depending on the soil. The average is 10 mm per day. In order to efficiently use the water in streams, a distribution network is needed to use it for irrigation. The effect of only supplying the streams with water is small, in the order of 200 m away from the streams. With an efficient distribution network the influence in the groundwater can be much greater.

There is a network of high pressure sewers in the area which may be used to distribute the water in the area.

Creating a buffer in winter by storing precipitation in the unsaturated soil is not enough, on average still 100 mm extra is needed. Storing the precipitation in the soil causes the lands to be unworkable by heavy machinery, so this is not preferred for agriculture. By supplying the water when it is needed, all demands may be met.

When creating a buffer, on average 100 mm is available in the unsaturated zone to be used as storage in the area. In order to store this water in the unsaturated zone, the water quality must be up to par, but the river water in the Rhine is relatively clean.

With a good distribution network, supplying the streams with water could have a significant effect on the groundwater levels in the area. Especially in flat areas of the land.

If river water is to be extracted, extraction out of the Rhine is preferred over extraction out of the IJssel. Ideally, a canal could be constructed to transport the water to the area under free flow, this requires cooperation with Germany. It is likely that the area on the German side of the border is also dealing with drought during dry spells, so a canal through this area could be mutually beneficial.

Appendix B

Data

B.1 Water level Hardinxveld open situation

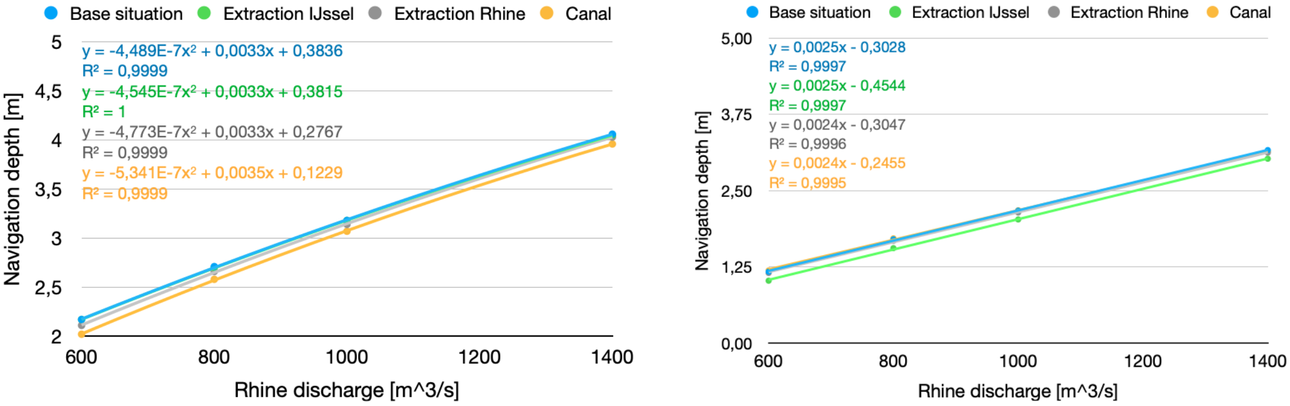
Table B.1: Water levels at Hardixveld for the open situation to be used as boundary condition [m]

	Rhine discharge [m^3/s]					
Date	600	800	1000	1400	1700	2000
1/1/15	0.607	0.607	0.607	0.607	0.607	0.607
3/1/15	0.197	0.254	0.313	0.433	0.512	0.586
5/1/15	0.254	0.312	0.372	0.495	0.576	0.653
7/1/15	0.330	0.388	0.445	0.561	0.638	0.711
9/1/15	0.411	0.477	0.538	0.652	0.724	0.792
11/1/15	0.373	0.457	0.538	0.696	0.784	0.858
13/1/15	0.362	0.438	0.513	0.666	0.759	0.842
15/1/15	0.359	0.422	0.483	0.607	0.689	0.766
17/1/15	0.153	0.217	0.281	0.409	0.492	0.571
19/1/15	0.207	0.269	0.332	0.459	0.541	0.619
21/1/15	0.265	0.326	0.386	0.508	0.588	0.665
23/1/15	0.327	0.387	0.445	0.560	0.637	0.710
25/1/15	0.395	0.457	0.516	0.628	0.701	0.770
27/1/15	0.397	0.479	0.556	0.701	0.777	0.844
29/1/15	0.333	0.418	0.501	0.663	0.756	0.839
31/1/15	0.222	0.296	0.370	0.512	0.596	0.670
2/2/15	0.080	0.144	0.207	0.336	0.421	0.502
4/2/15	0.125	0.189	0.253	0.382	0.466	0.546
6/2/15	0.191	0.254	0.317	0.444	0.527	0.605
8/2/15	0.251	0.312	0.372	0.495	0.576	0.653
10/2/15	0.314	0.373	0.431	0.547	0.625	0.699
12/2/15	0.376	0.437	0.495	0.606	0.680	0.750
14/2/15	0.406	0.484	0.558	0.690	0.763	0.829
16/2/15	0.353	0.438	0.521	0.683	0.774	0.854
18/2/15	0.253	0.329	0.406	0.559	0.652	0.735
20/2/15	0.093	0.155	0.216	0.342	0.425	0.504
22/2/15	0.108	0.174	0.238	0.367	0.452	0.532
24/2/15	0.175	0.238	0.301	0.430	0.512	0.591
26/2/15	0.236	0.298	0.359	0.483	0.565	0.642
28/2/15	0.298	0.358	0.416	0.534	0.612	0.687

Table B.1: Water levels at Hardixveld for the open situation to be used as boundary condition [m], continued

	Rhine discharge [m³/s]					
Date	600	800	1000	1400	1700	2000
2/3/15	0.357	0.418	0.475	0.587	0.662	0.734
4//315	0.411	0.485	0.553	0.672	0.744	0.811
6/3/15	0.371	0.456	0.538	0.696	0.784	0.858
8/3/15	0.285	0.364	0.442	0.598	0.693	0.779
10/3/15	0.141	0.198	0.255	0.372	0.450	0.526
12/3/15	0.094	0.159	0.223	0.353	0.438	0.519
14/3/15	0.158	0.222	0.286	0.414	0.497	0.576
16/3/15	0.222	0.284	0.345	0.471	0.553	0.631
18/3/15	0.282	0.342	0.401	0.521	0.600	0.676
20/3/15	0.341	0.402	0.459	0.572	0.649	0.722
22/3/15	0.409	0.476	0.537	0.651	0.723	0.791
24/3/15	0.386	0.470	0.550	0.703	0.785	0.854
26/3/15	0.312	0.394	0.475	0.634	0.729	0.813
28/3/15	0.190	0.257	0.323	0.442	0.513	0.582
30/3/15	0.083	0.148	0.212	0.342	0.427	0.508

B.2 Navigation depth relation of the Waal and IJssel

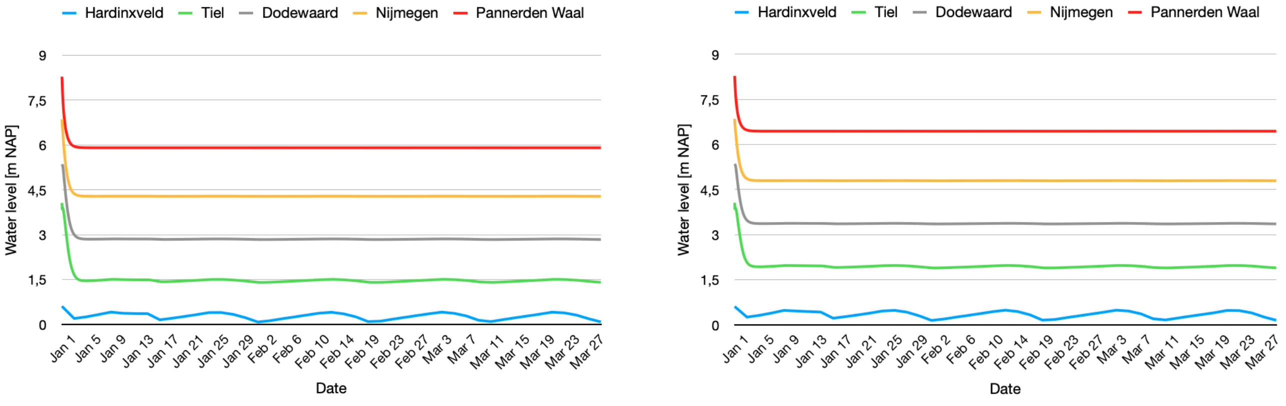


(a) Polynomial relation between Rhine discharge and Waal navigation depth

(b) Linear relation between Rhine discharge and IJssel navigation depth

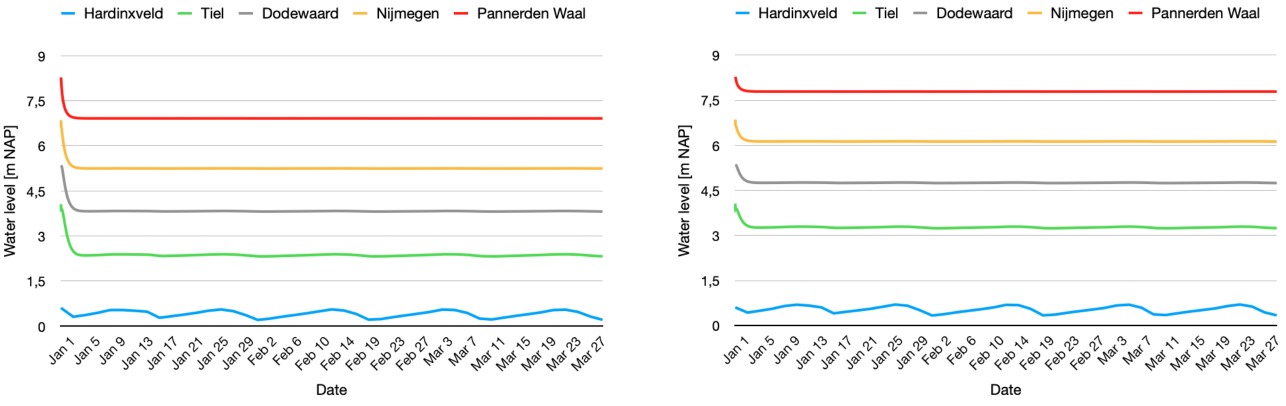
Figure B.1: Navigation depths of the Waal and IJssel for different Rhine discharges, with trendlines indicated

B.3 Water levels Waal open situation



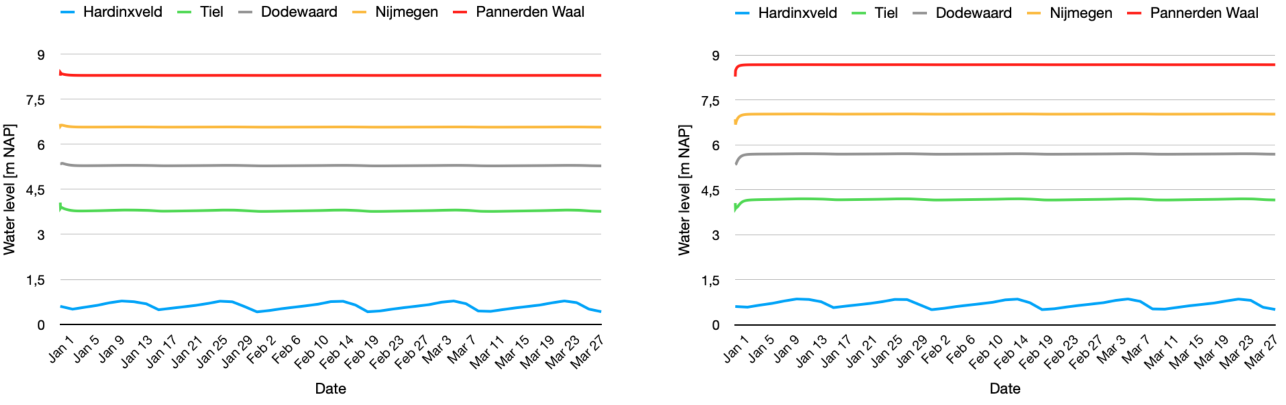
(a) Rhine discharge of 600 m^3/s

(b) Rhine discharge of 800 m^3/s



(c) Rhine discharge of 1000 m^3/s

(d) Rhine discharge of 1400 m^3/s



(e) Rhine discharge of 1700 m^3/s

(f) Rhine discharge of 2000 m^3/s

Figure B.2: Water levels of the Waal river with an open Rijnmond for different Rhine discharges at the observation points