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Retention of Rhine water in the Rijnstrangen to mitigate drought

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SWECO

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by

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Cover image: Impression of the Rijnstrangen, photo taken May 2021.

Preface

Dear reader,

The world around us is changing rapidly and with a changing climate we are facing a wide variety of challenges regarding our water management. This changing world intrigues me. With this thesis I only touch upon a very small part of this global challenge, but I still hope that it can be of impact and that this idea can be an inspiration for other projects.

Working on this thesis has taught me how much I have learned already, but also how much there is still to explore. I am proud of the final product that you are reading right now, as well as of the process that has led to this thesis. This would however not have been possible without the help of many people that were willing to take the time to be part of my graduation and learning process. I really enjoyed how many people wanted to share their passion about their field of work and help me with all sorts of questions and suggestions during meetings and excursions.

In particular, I would like to thank my committee for sharing their expertise with me, both from the TU Delft and Sweco. First of all, I thank Martine for her weekly dose of suggestions, questions and feedback, Remko for the elaborate feedback on my reports and Joep for diving into a subject that may have been further away from your field of expertise than expected. Also, I thank Roel for the regular feedback and discussions, and Kees for diving into groundwater modelling with me. It has been a pleasure to work with all of you!

Besides the guidance for the more technical questions, I had a lot of support from my family and friends. Especially the covid-situation that forced us all to work from home made it extra valuable to have their support. The daily cappuccinos on the balcony with my (former) roomies, the calls with my parents, working on the campervan on the weekends with Maarten and the dinners, talks and sports activities with friends have certainly made my graduation process easier. I want to thank all of you for your part in my graduation process and your endless support.

Enjoy reading!

Laura de Vries
Delft, September 2021

Abstract

Over the last years the Netherlands has often had to deal with droughts and water shortages during summer. This problem is caused by long periods without rain but with high evaporation rates and is enhanced by groundwater extraction for drinking water. Due to climate change, these droughts are expected to occur more often and become more severe. A possible strategy to mitigate drought in the eastern part of the Netherlands is to scale down the groundwater extraction, thereby limiting the groundwater depletion. In this case however, an alternative drinking water source has to be created. This research explores the option to use the former river bed of the Rhine near the Dutch-German border, the Rijnstrangen, to create this alternative drinking water source, answering the following question: How can retention of Rhine water in the Rijnstrangen contribute to drought mitigation in the eastern part of the Netherlands?

Due to the low elevation of the Rijnstrangen, water from the Rhine can be let into the area via a weir, when the Rhine water levels are high. This way a retention reservoir is formed, demarcated by the old river dikes of the Rhine. To see whether constant drinking water extraction from the Rijnstrangen can be guaranteed, a water balance of the area is set up consisting of four elements: Rhine inflow, precipitation, evaporation and groundwater flow. The drinking water extraction is part of the groundwater flow, as the water is extracted from the groundwater. The stored volume of water in the basin is a result of these fluxes.

Datasets from January 1960 to December 2009 of the Rhine water levels, evaporation and precipitation are used in the water balance, presenting the dynamics of the basin for varying input parameters. These varied parameters are the weir height, the weir width, the maximum volume in the basin and the groundwater extraction volume. Furthermore, four climate scenarios are investigated in the water balance as variable by using adapted time series of the Rhine water level, evaporation and precipitation. It is found that the parameters with the highest impact on the water balance are the extraction volume, the maximum allowed volume in the basin and the weir height. The weir width only starts to influence the outcome of the calculation if it is under 100 m wide, whereas the landscape allows for a weir over 1 km wide. The climate scenarios have a relatively small effect on the water balance calculations, compared to the impact of the other parameters.

With the water balance calculations, it is shown that the Rijnstrangen realistically can contribute up to 100 Mm^3/y to the drinking water production in the region. This is up to 75% of the drinking water production of the Dutch province Gelderland, in which the Rijnstrangen is located. The exact maximum extraction volume from the Rijnstrangen depends on policy choices such as the maximum accepted water level in the Rijnstrangen and the maximum accepted average extraction from the region around the Rijnstrangen.

From a water quantity point of view, the maximum extraction volume of up to 100 Mm^3/y indicates that utilizing the Rijnstrangen as a retention reservoir is a promising option to contribute to drought mitigation in the eastern part of the Netherlands. Therefore, further investigation of this idea is relevant. In further research, interesting topics to explore include the use of a stepwise filling of the Rijnstrangen, to allow for multiple parallel types of land use and types of nature at low water levels in the basin. Moreover, the option to use the Rijnstrangen for a combination of drought mitigation with flood risk reduction of the Rhine would be interesting to investigate, as this combination could be more attractive than the individual options, for example from a financial point of view. Lastly, topics such as water quality, costs, stakeholder involvement, consequences for nature and management strategies should be studied before final conclusions can be drawn about the over-all feasibility of the Rijnstrangen as a retention reservoir.

List of Figures

List of Tables

Contents

1 Introduction

1.1. Incentive: a mismatch of available water

Over the last years the Netherlands has often had to deal with droughts and water shortages during summer. This caused severe implications for, amongst other things, agriculture, drinking water production, shipping and nature. These shortages may be something one can hardly imagine in winter, when fresh water of good quality seems abundant. This mismatch of available water resources will only grow due to the already changing climate.

In the East of the Netherlands, the (inter)national problem of a changing climate has become clearly visible over the last years. Despite many rivers and countless small streams and channels dissecting the landscape, the area largely relies on precipitation and some transboundary inflow of surface water from Germany for its groundwater recharge (Witteveen+Bos, 2007a). Besides that, the top layer in the area is generally sand, which has a poor water holding capacity. The combination of these factors makes the area one of the driest regions in the Netherlands (Cloin, 2021).

In response to the drought of 2018, the Dutch meteorological institute (KNMI) looked into the effect of climate change on droughts (Van der Wiel, K., 2020). This research showed that a clear trend towards more extreme droughts can be expected for the inland area of the Netherlands. In this region however, drought related problems are already occurring. For example, one can think of nature deterioration due to water shortages, which is enhanced by water extraction for drinking water production and irrigation. Therefore, it is time to take action and look into mitigation strategies to adapt to a future climate that is more arid with heavier precipitation- and discharge peaks, and longer periods of water shortage.

1.2. A promising idea: using the Rijnstrangen

A possible strategy to adapt to an arid climate lies within local and regional (re-)development of water diversions and water storage. A promising location to implement this strategy is the Rijnstrangen (see Figure 1.1). This is a low-lying area near the Dutch-German border that consists of the former flood plains and river bed of the Rhine. This research explores the possibility to divert Rhine water into the Rijnstrangen to form a retention reservoir. Groundwater that is extracted close to this reservoir could then be used during the year for multiple purposes. For example, drinking water and water for irrigation can be produced from the retained water. This could allow for the scaling down of (ground)water extraction locations in the region that face declining groundwater tables due to the changing climate. A groundwater extraction location near the formed reservoir would not face this problem, as here water from the reservoir would recharge the groundwater levels. Furthermore, the water from the retention area may be able to recharge the groundwater levels in a broader area.

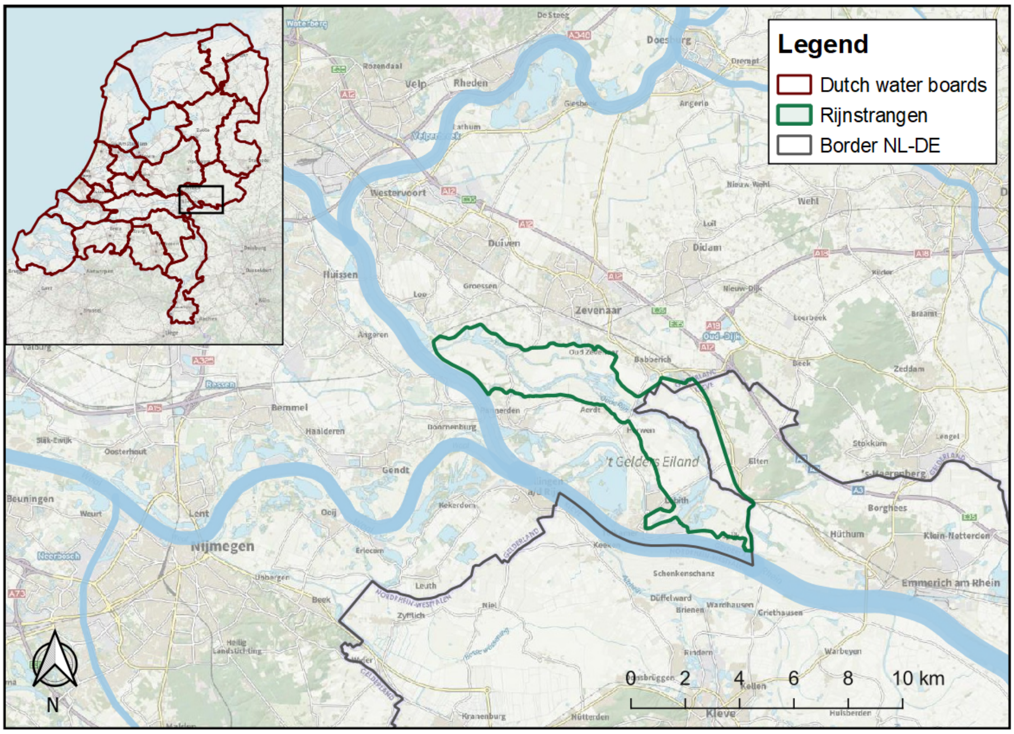


Figure 1.1: Location of the Rijnstrangen. The river widths are not to scale to visualise them clearly.

The plan to use the Rijstrangen as retention area is already under consideration in the Dutch Delta Program, where the Rijnstrangen is reserved as a potential buffer area for peak discharges in the Rhine (CSO, 2013). This plan entails that, during extreme discharge peaks (> 16 000 m^3/s, occurring less than once in 1000 years), some of the river water can be diverted into the Rijnstrangen. The area would buffer around 70 million m^3 of water, thereby reducing the water levels in the Waal by 15 cm and in the IJssel by 5 cm. The water is released after the discharge peak has passed. When timed correctly this reduces the flood risk of downstream areas.

Clearly, the focus of the plan for the Rijnstrangen in the Delta Program is on flood prevention, whereas this research focuses on drought mitigation. Still, the plans do not necessarily contradict or compete, they may even go hand in hand.

1.3. Research scope

Before drought mitigation plans for the Rijnstrangen can be implemented, their feasibility needs to be investigated from a technical, financial, governmental and societal perspective. Also, it needs to complement existing spatial plans, land use (change) and future plans. In this research the technical feasibility of using the Rijnstrangen for water retention is assessed, answering the following research question:

How can retention of Rhine water in the Rijnstrangen contribute to drought mitigation in the eastern part of the Netherlands?

This research is limited to the water quantity related aspects of using the Rijnstrangen as retention area. One can think of river in- and outflow, precipitation, evaporation, groundwater flow and water use. Water quality determines the possibilities of using water for drinking water production, agriculture and nature. However, the quality aspects will not be covered in detail in this thesis. Also stakeholders, governmental aspects, value for nature and costs are out of the scope of the research.

This research is an important step in the exploration of adaptation strategies to a more arid climate with higher peak discharges and drier summers. By gaining insights in ways to use retention of river water to mitigate drought related problems, water boards and water utilities in the region will learn about a possible solutions. Besides the local interests, the findings of this research will be valuable for other water boards, water utilities and comparable local and regional committees responsible for the water management that are coping with similar problems, nationally as well as internationally.

1.4. Reading guide

To start with, Chapter 2 describes the history of the Rijnstrangen, followed by a description of the Rijnstrangen as it is now. Together, this highlights the possibilities and limitations that have to be dealt with when re-designing the area. This analysis is used in Chapter 3 to present the concept of the Rijnstrangen as retention reservoir. This chapter shows how the reservoir would fit in the landscape, where elements like the inlet would be placed and what volumes of water can be stored at what inundation levels.

In Chapter 4, the methodology of this research is described, presenting the water balance used to gain insight in the dynamics of the Rijnstrangen as retention reservoir, including its four fluxes: Rhine inflow, precipitation, evaporation and groundwater flow. Also, in this chapter the methodology to include climate change scenarios in the water balance is presented, as well as the criteria to evaluate the feasibility of the outcomes of the water balance calculations.

The results of the performed calculations are presented in Chapter 5. First of all, the validation of the groundwater model and the sensitivity of the groundwater model to its parameters are presented. Furthermore, the results of the water balance calculations are presented, showing the behaviour of the Rijnstrangen as retention reservoir over time for varying parameter values.

Chapter 6 discusses the consequences and limitations of the results found in the research, as well as suggestions for implementation and further research. Chapter 7 closes off the thesis, presenting the conclusions that are drawn from the research.

2

Area description

In this chapter a variety of aspects about the Rijnstrangen area is presented, highlighting the possibilities and limitations that have to be dealt with when re-designing the area. To start with, a brief overview of the history of the study area is presented in Section 2.1. The subsequent sections discuss the current situation in the area and its surroundings. These aspects give context to the presented plans and form the basis for the further research.

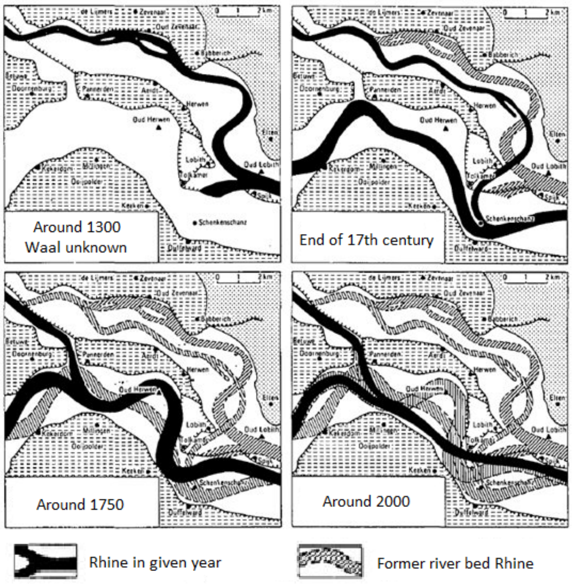
2.1. History of the Rijnstrangen

This section is written based on the work of Buro Noord (2020a) and Buro Noord (2020b) and can be divided in three parts. First of all, ice and water formed the landscape in the eastern part of the Netherlands, after which humans started to interfere with the water. Lastly, man-made changes in the river regime near the Rijnstrangen formed the situation we know nowadays.

Formation of the landscape by ice and water
The formation of the Rijnstrangen starts with the shaping of the landscape by the ice of the ice ages. An example of this is the Montferland, which is formed by the driving force of the ice of the second most recent ice age (370.000 - 130.000 years ago). From the Holocene (11.000 years ago) the Rhine has had its route approximately where it is now. It deposited sediments like clay, sand and gravel while meandering through the landscape, altering its route over the years, as can be seen in Figure 2.1a.

Start of human interference with the water
From the time of the Roman empire onward, humans have started to interfere with the highly dynamic water. For the Romans the Rhine was the ideal transportation route of goods and military troops. However, this required enough water in the Lower Rhine. The construction of a dam at the bifurcation of the Waal and the Lower Rhine (currently known as the Pannerdensche Kop) managed this. The area around the river flourished.

In the early middle ages (8^{th} - 11^{th} century) the river banks started to naturally form dikes due to sedimentation and settlements formed on the high embankments and river dunes. Every now and then a dike would breach, allowing for exchange of river water with the swamps behind the dikes and river dunes. Around the 10^{th} century a battle against the water started as the agricultural fields could flood from the swamps nearby. Quays were build to protect fields and livestock from the high water. The first permanent reclamation of land from the meandering Dutch Rhine was probably in the end of the 13^{th} century, when local quays were connected into one regional dike. This resulted in a new landscape with permanent chances for agriculture. With this new dike however, the storage capacity of the rivers decreased and, together with the effects of sedimentation, dike breaches started to occur frequently. Dikes had to be raised over and over while at the same time seepage became a big problem.



(a) Historical river courses of the Rhine around Lobith. Retrieved from WRIJ (n.d.-b).

(b) Operative Spijkse Overlaat before its closure in 1959. Retrieved from SPGS (n.d.).

Figure 2.1: Historical Rijnstrangen.

Forming of the current river regime: drastic man-made changes
The situation from the middle ages with some serious floods remained until the 18th century, when national interest required the redevelopment of the rivers in the area around the Rijnstrangen. The Pannerdensche Kop, the Pannerdensch Channel and the Bijlandsch Channel were constructed. The Rijnstrangen was kept functional as river bed as a relatively low spillway allowed water of the embanked Rhine to enter the Rijnstrangen at high water levels. This spillway is the Spijkse Overlaat (Spillway at Spijk), as shown in Figure 2.1b. The Rijnstrangen flooded on average 8 days per year (SPGS, n.d.).

From 1900 onward the Spijkse Overlaat has been a point of discussion for decades. Closing the spillway permanently would allow to use the Rijnstrangen without regular floods, while the spillway also helped with water safety of the Rhine. This discussion took until 1959, when the spillway was permanently closed and the Rijnstrangen became the area it is today.

2.2. Dikes and elevation

Based on the elevation map as presented in Figure 2.2 the dikes in the Rijnstrangen are visualised in Figure 2.3. Like in Figure 2.2, all heights in this study are indicated relative to NAP (Normaal Amsterdams Peil or Amsterdam Ordnance Datum). The study area is demarcated by the old river dikes and the former floodplains are still surrounded by the old summer dikes. The old dikes may need maintenance before they can safely protect against the water again, as piping is currently a risk (Kurstjens et al., 2013).

The elevation in the Rijnstrangen ranges from about 10 m +NAP at the wetland areas to around 18.5 m +NAP at the primary river dikes. The southern old winter dike has an elevation of around 15.5 m +NAP, which is the elevation most of the mounds have as well, whereas the northern winter dikes are around 16.5 m +NAP. The old summer dikes vary in height between 12 m +NAP and 14 m +NAP. To the east of the Rijnstrangen the elevated Montferland is clearly visible.

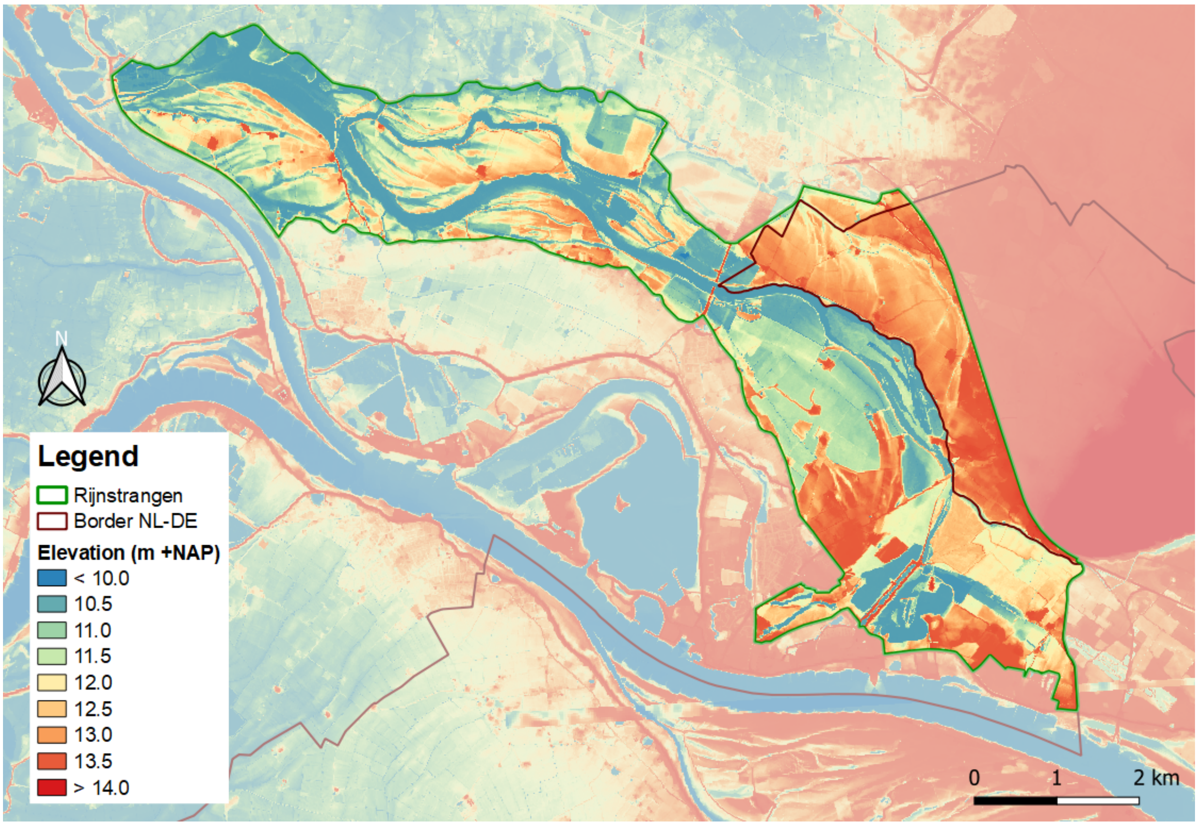


Figure 2.2: Elevation of the Rijnstrangen.

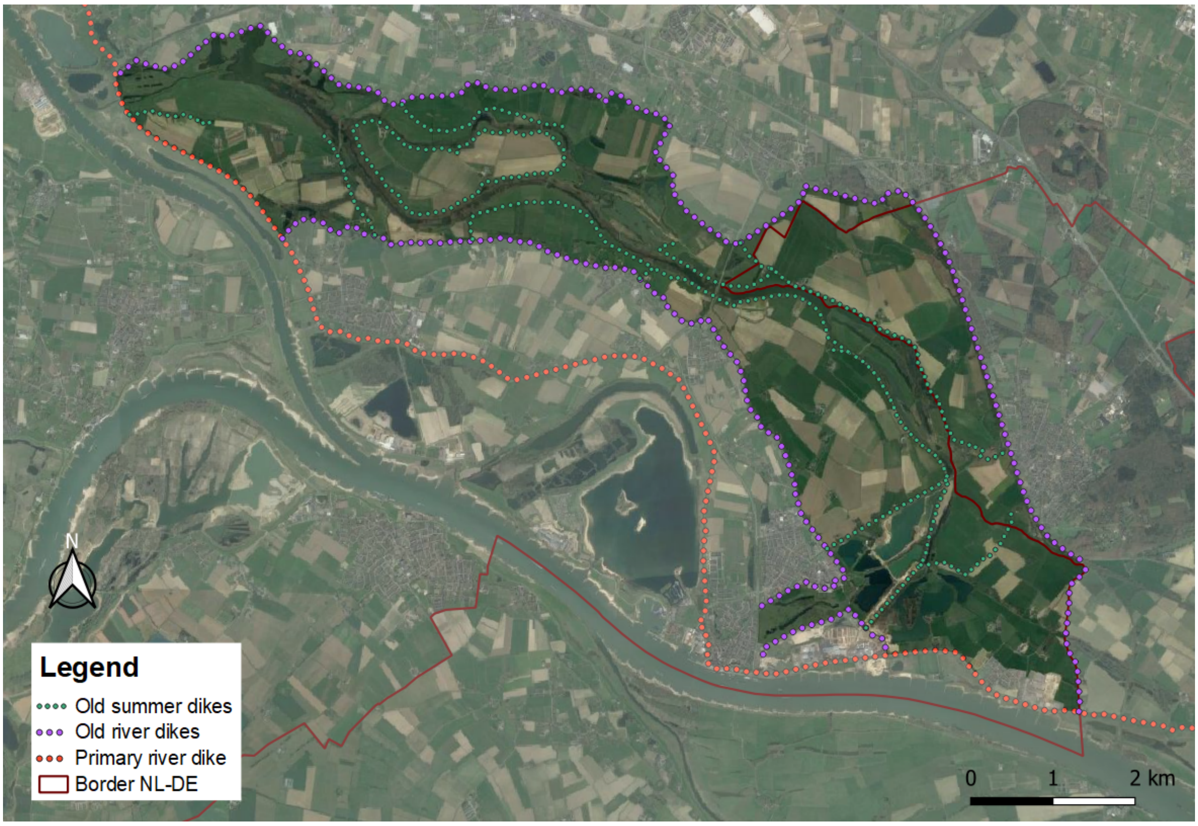


Figure 2.3: Dikes in the Rijnstrangen.

2.3. Natura 2000

Most of the Rijnstrangen is Natura 2000 area, as is shown in Figure 2.4. These areas are designated under the EU Habitats and Birds Directives and the goal of the status is to protect flora and fauna and their habitats (European Environment Agency, 2020). The Natura 2000 rules impose that changes in the area may not lead to deterioration of nature in the area. Only when the measures are of big public interest, they can be implemented under strict conditions. Besides the standard conservation goals, for some areas development goals are defined. For the Rijnstrangen, the main development goal is to increase the area and quality of reed marshes (Witteveen+Bos, 2007a). Additional to the consequences for allowed changes in the area, the Natura 2000 status has consequences for the farmers in the area, as a maximum nitrogen emission is allowed. Also, noise disturbance should be reduced and water quality has to be protected (Rijksoverheid, n.d.).

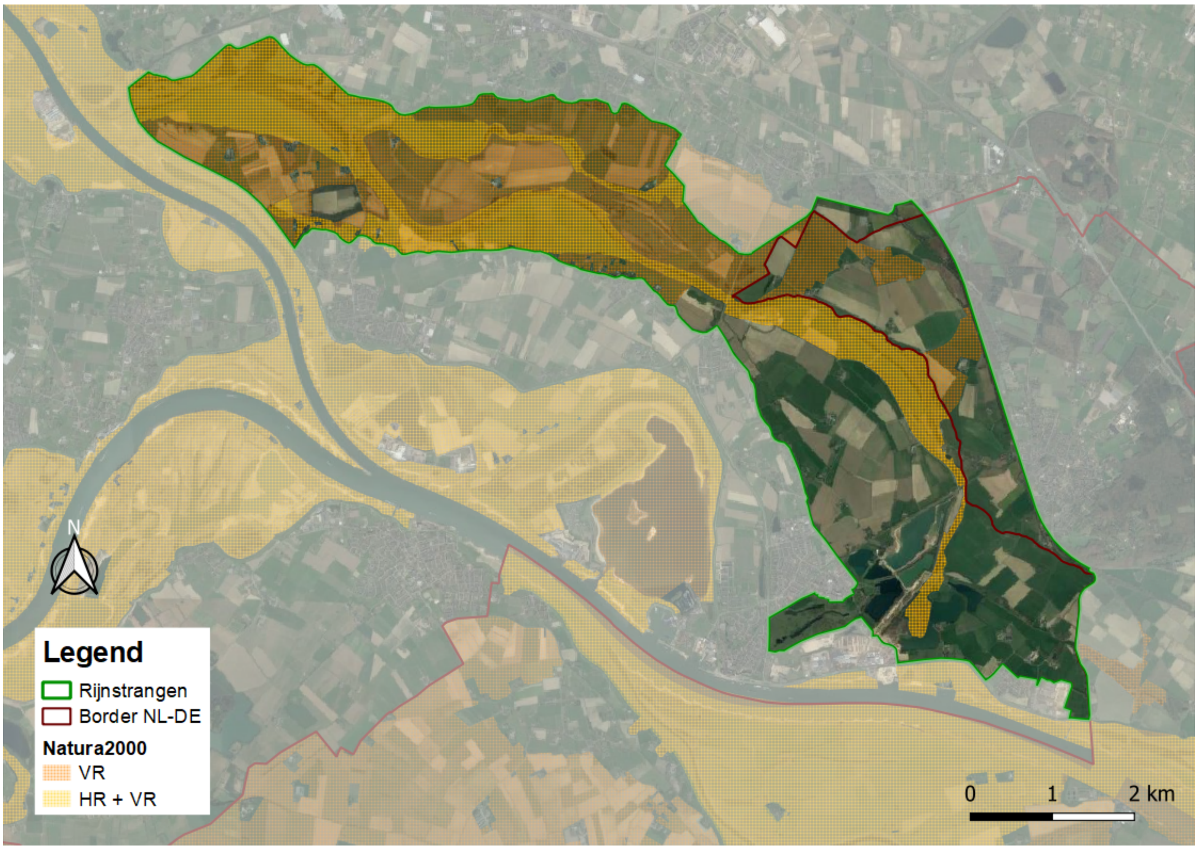


Figure 2.4: Natura 2000 area in the Rijnstrangen. VR indicates the Birds Directive areas. HR indicates the Habitat Directive areas.

2.4. Land use

The old river courses, that are now the low-lying parts of the Rijnstrangen, are wetland areas full of reed, bushes, grassland and wide, shallow streams with very low flow velocities. The area is home to many birds, insects and small animals and partially open for recreation (ARK Natuurontwikkeling, n.d.). A map with the functions in the area is shown in Figure 2.5.

The main function in the area is agriculture. Some buildings like homes and farms are located within the old river dikes as well. Most of these properties are located on mounds to protect them from high water, however there are also properties that are located lower. Figure 2.6 shows the properties within the study area and their elevation, which indicates their safety when the area is flooded. Behind the old winter dikes, the concentration of villages with farms and properties is much higher.

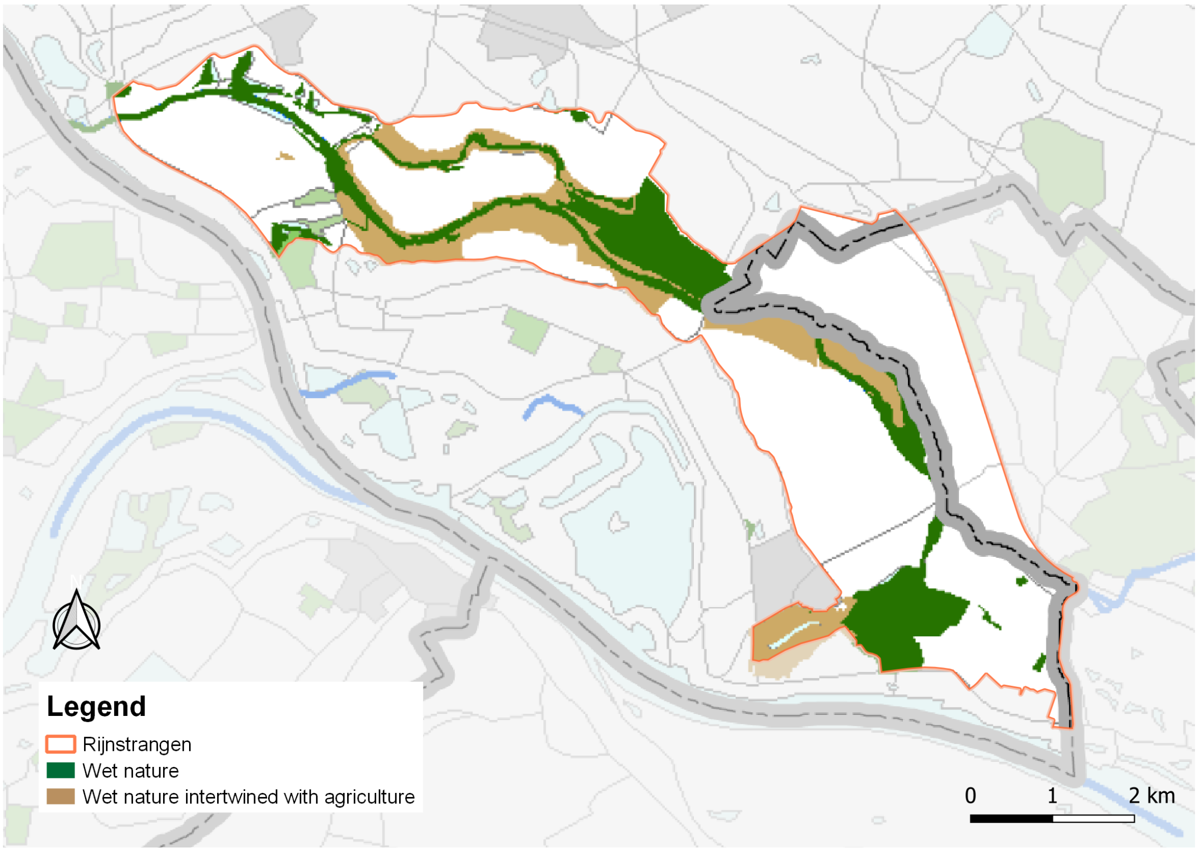


Figure 2.5: Land use in the Rijnstrangen as indicated in the Functiekaart Water of Gelderland. The white area in the Rijnstrangen indicates agricultural land.

Figure 2.6: Properties within the dikes in the Rijnstrangen and their elevation. The elevation of the properties indicates their safety when flooding the area.

2.5. Geohydrological situation

A representation of the geohydrological situation in the Rijnstrangen is shown in Figure 2.7 for the cross-sections as indicated in Figure 2.8. A top layer between 2 m and 6 m thick forms the first layer of the Rijnstrangen subsurface (indicated in green in Figure 2.7). The IJssel and Rhine cut through this top layer, connecting them with the underlying first aquifer of about 20 m thick (indicated in pink in Figure 2.7) (Witteveen+Bos, 2007a). The bottom of this aquifer is formed by a clay aquitard (indicated in dark red in Figure 2.7). Under the Rijnstrangen this layer reaches over 40 m thick, whereas in the east of the Rijnstrangen this layer can be as thin as 5 m. As explained in Section 4.1.5, in the groundwater model for the Rijnstrangen this first clay layer forms the geohydrological base due to its very high hydraulic resistance. Below this aquitard a second aquifer (indicated yellow in Figure 2.7) is located, which only connects with the first aquifer via a complex layer in the southeast of the Rijnstrangen. Below the second aquifer a thin clay layer forms the aquitard between the second and third aquifer. Locally, the second and third aquifer are mixed with thin clay layers (Witteveen+Bos, 2007a).

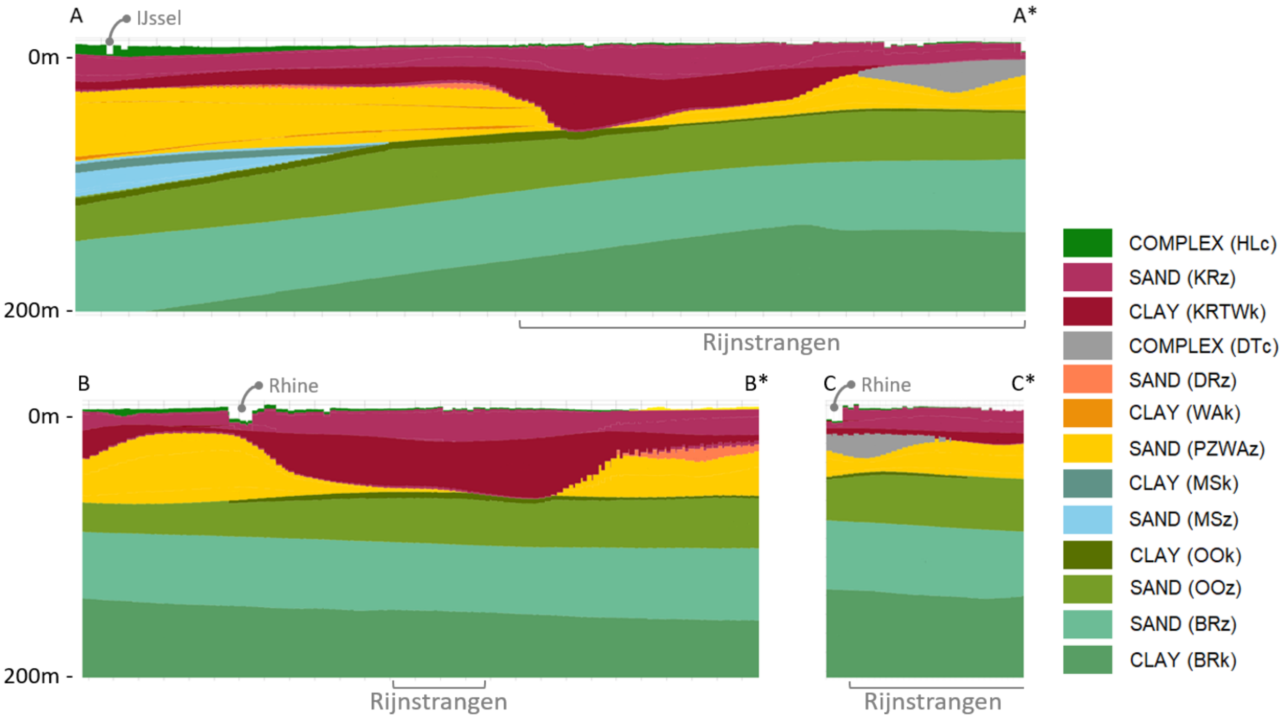


Figure 2.7: Geohydrological situation in the Rijnstrangen region along three cross sections. Adapted from TNO Geologische Dienst (2021).

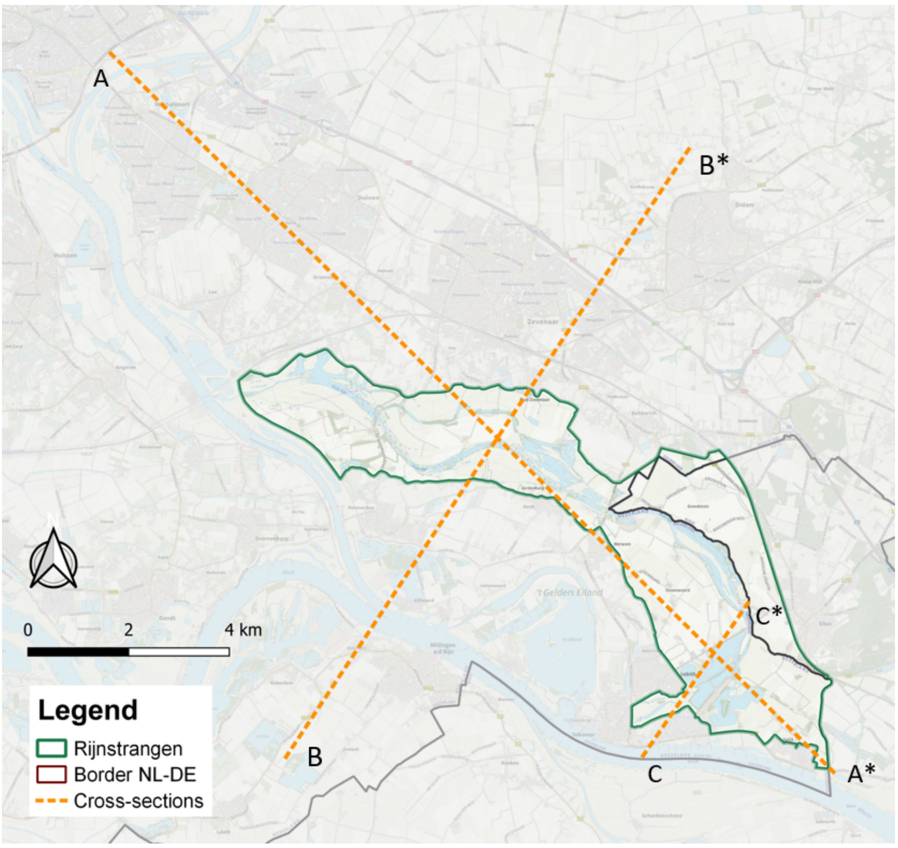


Figure 2.8: Cross-sections as referred to in Figure 2.7.

2.6. Managed water level

Since the closure of the weir at Spijk in 1959, the water levels in the Rijnstrangen can be closely managed. Currently the area has a constant winter and summer water level that is only changed in leap years for the conservation of the reed marshes. The water level is managed using four areas, as shown in Figure 2.9. This is done using a series of small dams, weirs and pumping stations. The water levels are managed according to the Peilbesluit, in which the water levels in the area are defined. Pumping station Kandia is the main means to control the water levels in the Rijnstrangen. Here water can be exchanged with the Pannerdensch Channel. In the rest of the region only a target water level (streefpeil) is used to manage the water levels (WRIJ, n.d.-d).

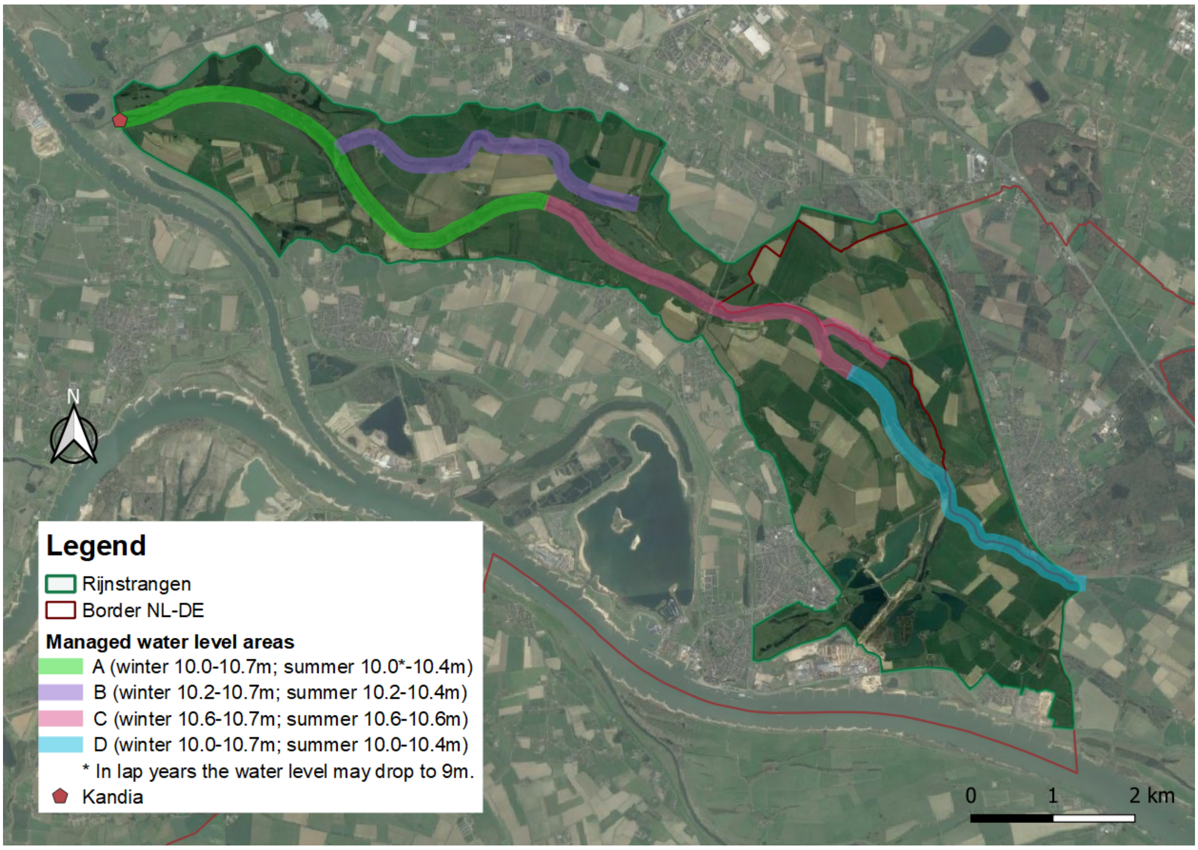


Figure 2.9: Managed water levels in the Rijnstrangen according to the Peilbesluit.

2.7. Drinking water production and water use

In the Dutch province Gelderland, in which the Rijnstrangen is located, groundwater is the first choice for drinking water production. This source is clean, as the water is already filtered by the ground, and therefore costs are low. Drinking water company Vitens has 40 extraction locations in Gelderland that are responsible for a yearly extraction of 134 million m^3 of water. Of this water 85% is for household purposes, the other 15% goes to businesses like hospitals and agriculture (Provincie Gelderland, 2019). The Dutch extraction locations in the region of the Rijnstrangen are shown in Figure 2.10.

Besides the 134 million m^3 of extracted water Vitens has permission to extract another 34 million m^3 of water (in total 168 million m^3). This capacity is needed for emergencies, peaks in the water use and adaptation to growth scenarios (Provincie Gelderland, 2019). On top of this, the province is searching for additional drinking water extraction locations. This may be needed as Van der Aa et al. (2015) calculated that by 2040 the the water use in the Netherlands may have increased with 30%. Together with increasing precipitation shortages in summer, this increase in demand asks for mitigating strategies and alternative solutions.

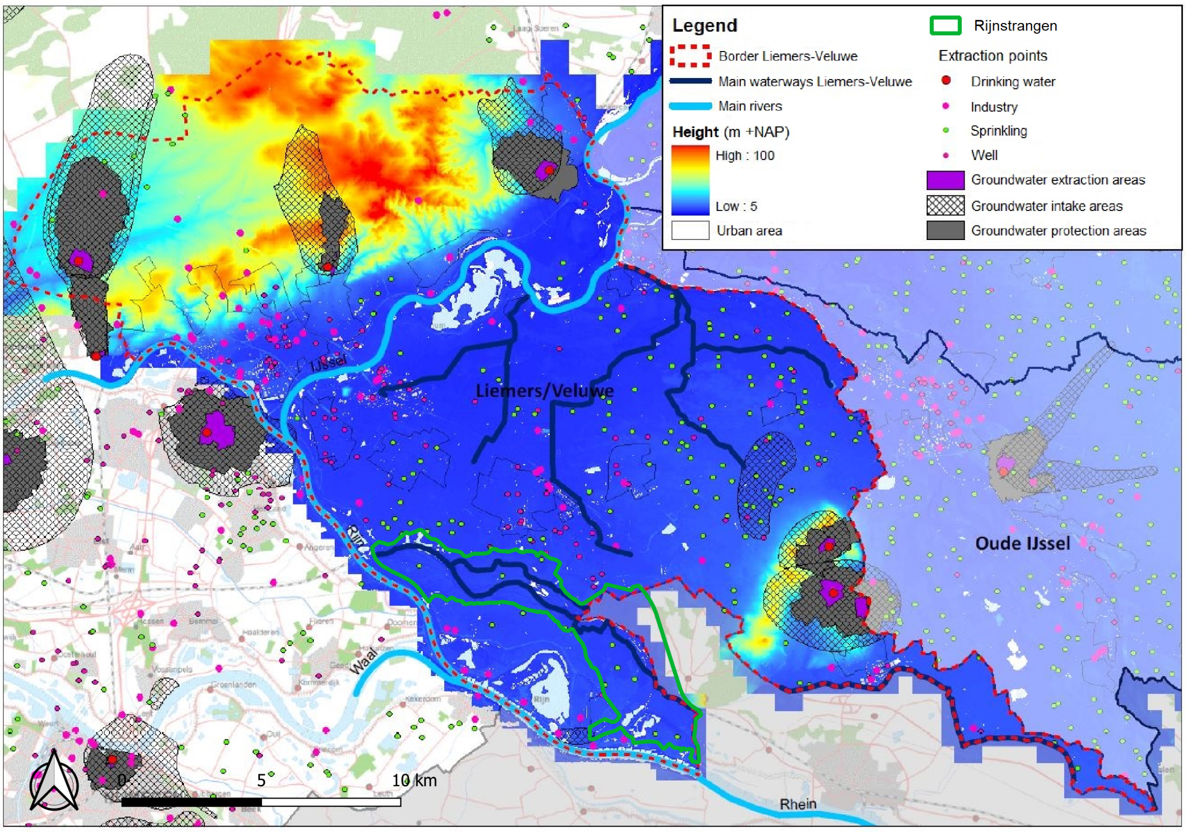


Figure 2.10: Groundwater extraction locations in the Liemers-Veluwe management area. Adapted from WRIJ (n.d.-a).

3

Concept: the Rijnstrangen as retention area

In this chapter the concept of using the Rijnstrangen as retention reservoir is presented. Section 3.1 shows how the plans fit in the landscape and how the surface water would flow through the area. Section 3.2 presents how the groundwater system under the Rijnstrangen would behave.

3.1. Surface water

As a retention area the Rijnstrangen would become a wetland area throughout the year. A map of this concept is shown in Figure 3.1. The area is demarcated by the old river dikes of the Rhine and covers 28.6 km^2, crossing the Dutch-German border. The old river dikes would have to be reinforced where necessary. At Spijk, three possible locations for inlets have been identified (widths from west to east 530 m, 500 m and 180 m, respectively). These would allow water from the Rhine to enter the Rijnstrangen. An outlet at the current location of pumping station Kandia, at the downstream end of the Rijnstrangen, would help to regulate the water levels and the flow through the area.

Figure 3.2 shows the relation between different water levels in the Rijnstrangen and the extent of inundated land and stored volume of water. This relation is retrieved using inundation maps generated in QGIS. From this figure it becomes clear that up until a water level of around 13.0 m +NAP every next water level step inundates new land. This relation is more or less linear between 10 and 11 m +NAP and between 11 and 13 m +NAP. This shows that here the elevation of the land increases gradually. The added volume of water storage per water level step is not yet very high up until this water level.

From 13.0 m +NAP up, the inundated area does not increase linearly anymore. Here the added area starts to decline and the added volume starts to increase drastically. A more or less linear relation between the water level and stored volume is present here. In this stage a significant stored volume is added per water level step. This shows that here the land is relatively steep, at most locations the dike is reached and the water can only go up instead of inundating new land. Some new area is still added in this stage, yet this does not add enough volume to disturb the linear volume-water level relation. Figure 3.2 is presented up to 15.5 m +NAP, as this is the height of the crests of the southern dike.

Figure 3.3 shows the effect of different water levels in the Rijnstrangen in the landscape. Here the relation that was shown in Figure 3.2 is also visible: up until 13.0 m +NAP in every step new land is inundated. From that water level onward most of the area is already blue, which means that an increase in water level does not add a lot of inundated area, however it adds a lot of stored volume. The figure shows flooding of the area as if it were filled up by rain, neglecting the effect of the old summer dikes (see Section 2.2).

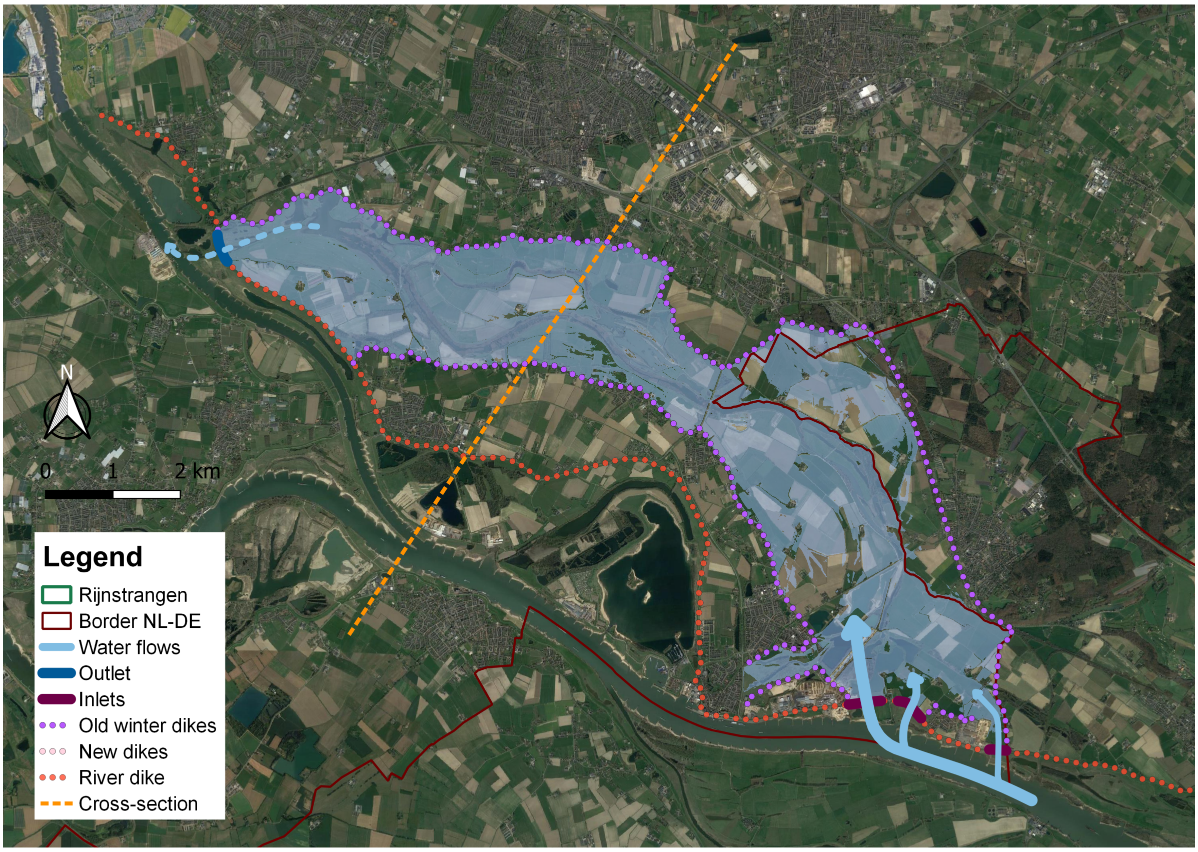


Figure 3.1: Concept of the Rijnstrangen as retention area. Here the water level is set to 13.0 m +NAP as an example. The cross-section is referred to in Figure 3.4.

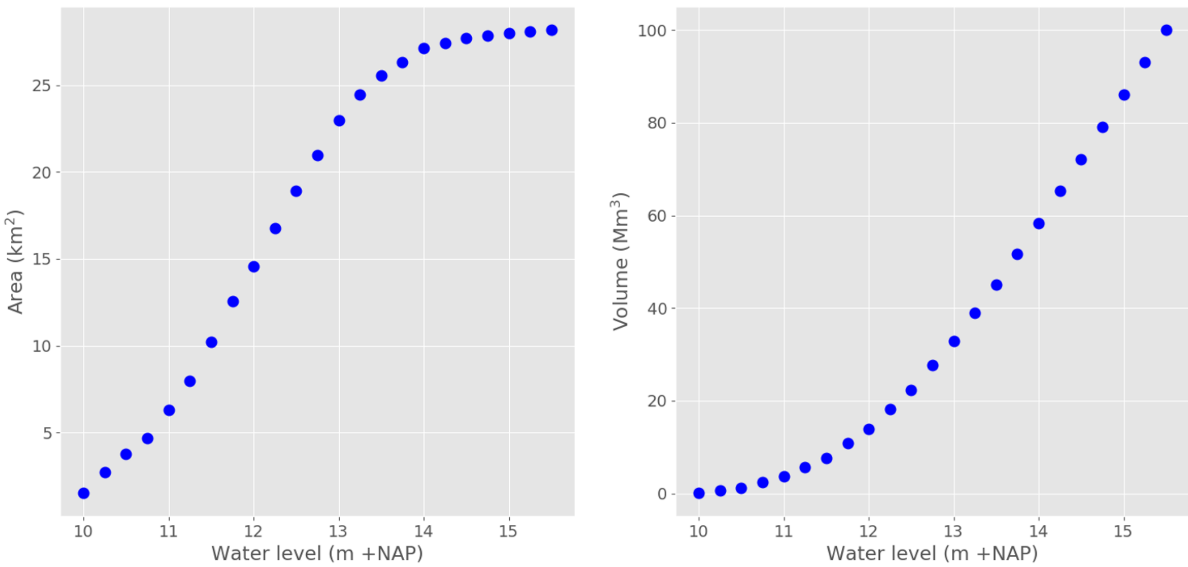


Figure 3.2: Stored volumes of surface water and inundated area for different water levels in the Rijnstrangen.

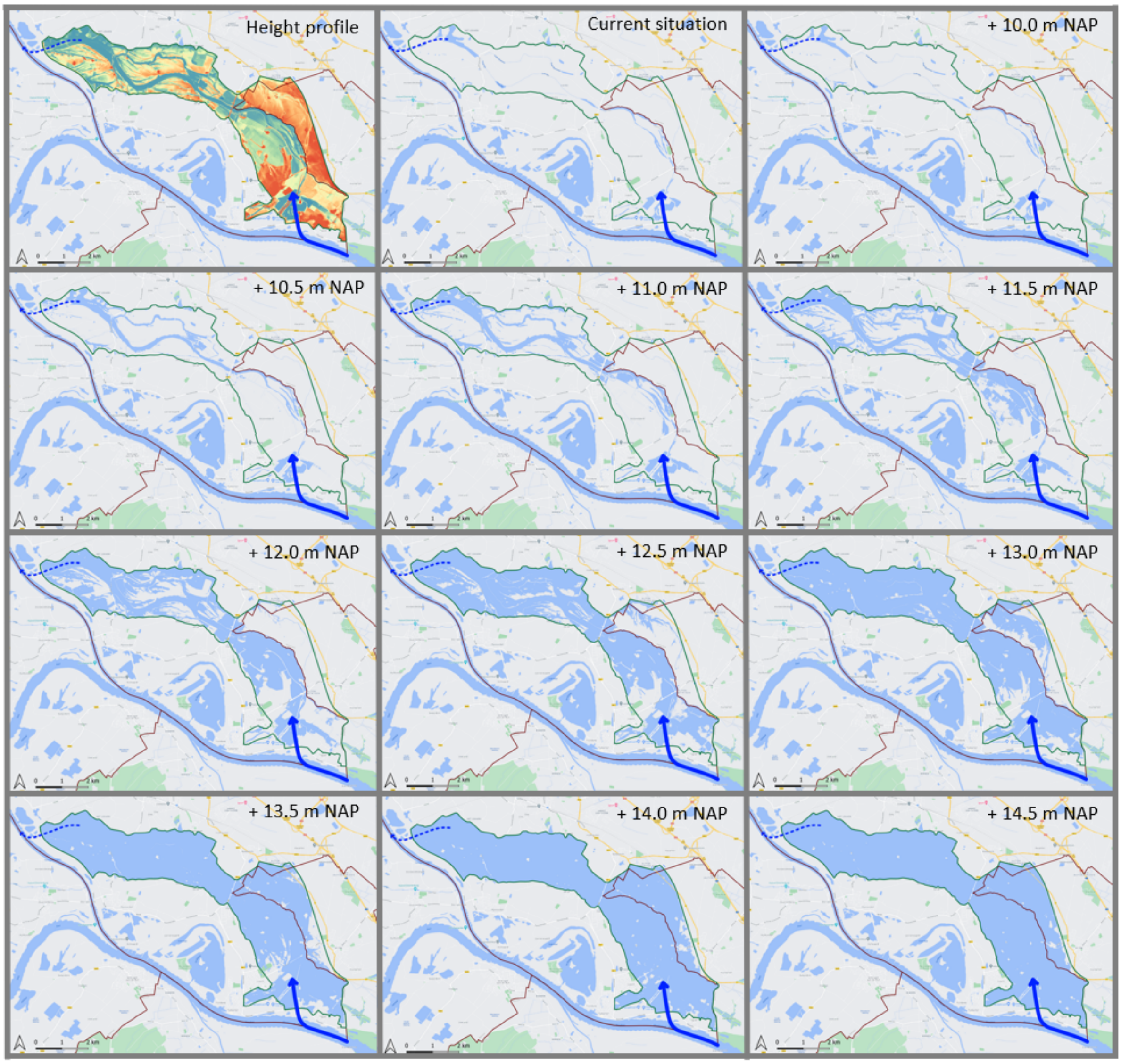


Figure 3.3: Visualisation of different water levels in the Rijnstrangen. The figure shows flooding of the area as if it were filled up by rain, neglecting the effect of the old summer dikes.

3.2. Groundwater

The surface water in the Rijnstrangen and its surroundings interacts with the groundwater in the first aquifer. Therefore, the groundwater table and the direction of flow of the groundwater in the region are influenced by the surface water levels, for example the surface water levels in the Rijnstrangen, the Rhine and the IJssel. There is hardly any interaction with the deeper aquifers, as there is a thick clay layer separating the first aquifer and the deeper layers. A schematization of the sub-surface is shown in Figure 3.4. This is the cross-section as shown in Figure 3.1, which corresponds with cross-section B - B* of Figure 2.7.

Around the Rijnstrangen, groundwater extraction locations would be constructed that produce drinking water. This would allow for the scaling down of other drinking water extraction locations in the region that cause or have problems, for example with their water quality or water shortages for nature. The new extraction locations would be located along the borders of the new reservoir, as at this location mostly infiltrated water from the reservoir would be extracted. The percentage of the extracted water that originates from the reservoir and from the groundwater of the surrounding region will be studied, as described in Section 4.3.3. The water would be extracted from the first aquifer, as this aquifer would be recharged by the reservoir. Extraction directly from the reservoir would also be possible, however then the advantage that the filtering effect of the ground has on the water quality would not be made use of.

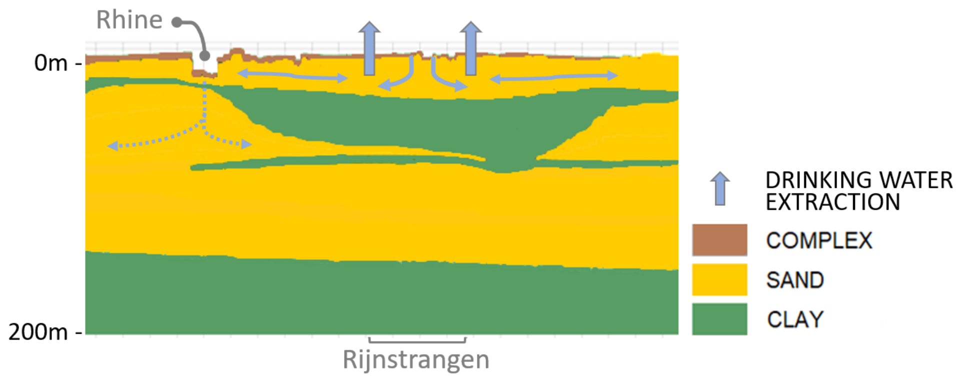


Figure 3.4: Concept of the Rijnstrangen as retention area visualised in a cross-section (indicated in Figure 3.1). The pattern of clay and sand is based on cross-section B - B* as presented in Figure 2.7, but only indicative.

4 Methodology

A water balance of the study area and a set of evaluation criteria are used to test whether and how water retention in the Rijnstrangen can contribute to drought mitigation in the eastern part of the Netherlands. In Section 4.1, the setup and elements of this water balance are presented. Subsequently, Section 4.2 discusses how projected effects of climate change are implemented in the water balance calculation to test it for potential future situations. Also, it presents what datasets are used for this. Lastly, in Section 4.3 it is discussed what parameters are varied to test a variety of reservoir-configurations, together with the evaluation criteria to measure the effectiveness of the Rijnstrangen as retention area.

4.1. Water balance of the Rijnstrangen as retention reservoir

A water balance with four main fluxes is used to provide insight into the dynamics of the Rijnstrangen as retention reservoir. Before going into detail on the separate elements of the water balance of the Rijnstrangen, the general setup of the water balance is discussed in Section 4.1.1. Then, the four main fluxes of the water balance calculation are considered: inflow from the river Rhine (Section 4.1.2), precipitation (Section 4.1.3), evaporation (Section 4.1.4) and lastly groundwater flow (Section 4.1.5).

4.1.1. General setup of water balance

The study area is schematized as a bucket with fluxes into and out of the system, as shown in Figure 4.1. The water balance shows whether precipitation and inflow from the Rhine together exceed evaporation and groundwater outflow, thereby constantly maintaining a minimum water level in the basin. The water balance is set up with daily values from January 1st 1960 up to and including December 31st 2009 (see also Section 4.2). Daily values are needed to prevent losing details of the inflow from the Rhine. Calculations with smaller time steps, for example hours, would increase running times of the model and the detail this provides would not add relevant information.

The water balance is set up using Python (see De Vries (2021) for the repository), where the minimum volume of the reservoir is set to zero: if the basin is empty, no outflow is possible. The maximum volume of the basin is a variable that can be chosen based on policy. Staying within this maximum volume is guaranteed in the water balance by closing the inlet for Rhine water when the water level corresponding to the maximum volume is reached in the basin. Also, an overflow flux is present for cases when the basin is full but precipitation exceeds evaporation and groundwater outflow. It is assumed that water cannot leave the system via the inlet if the water level in the Rijnstrangen is higher than the water level in the Rhine. This is achieved by closing the inlet, similar to the situation with a full basin.

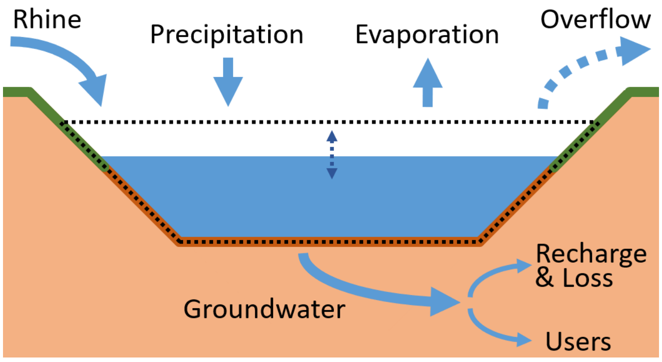
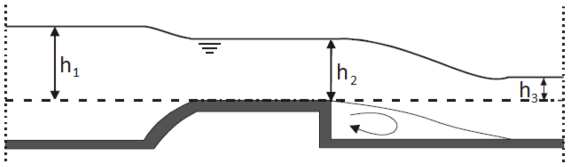


Figure 4.1: Schematisation of the water balance of the Rijnstrangen.

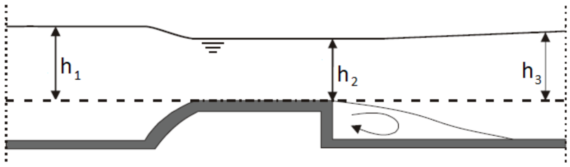
4.1.2. Inflow from the Rhine

To determine the inflow from the Rhine into the Rijnstrangen, daily water level data at Lobith is used in combination with a weir formula for free flow and a weir formula for submerged flow. The used datasets are discussed in Section 4.2.

The formula for free flow (Equation (4.1), Figure 4.2a) is used when the discharge over the weir is not influenced by the downstream water level. This is the case as long as $h_3 \leq \frac{2}{3}h_1$. As soon as $h_3 > \frac{2}{3}h_1$, submerged flow has to be used. The flow over a weir in case of submerged flow (Equation (4.2), Figure 4.2b) is dependent on both the upstream water level and the downstream water level (Bezuyen et al., 2012). The height of the crest of the of the weir is a variable that can be varied to test inflow patterns.



(a) Free flow weir.



(b) Submerged flow weir.

Figure 4.2: The two weir types, both adapted from Bezuyen et al. (2012).

$$\text{If } h_3 \leq \frac{2}{3}h_1 : \qquad Q = 1.7 \cdot c_{\text{free}} \cdot B \cdot h_1^{\frac{3}{2}} \qquad [m^3/s] \qquad (4.1)$$

$$\text{If } h_3 > \frac{2}{3}h_1 : \qquad Q = c_{\text{submerged}} \cdot B \cdot h_3 \cdot \sqrt{2 \cdot g \cdot (h_1 - h_3)} \qquad [m^3/s] \qquad (4.2)$$

In these equations the following parameters are used:

- c_{free} Discharge coefficient for a free flowing weir, 1.0 [-] (Bezuyen et al., 2012).
- $c_{\text{submerged}}$ Discharge coefficient for a submerged weir, 1.0 [-] (Bezuyen et al., 2012).
- B Width of the weir, variable with a value between 0 m and 1210 m, where 1210 m is the sum of the lengths of the weirs as depicted in Figure 3.1. This variable can be used to test different inflow patterns.
- g Gravitational constant, taken as 9.81 m/s^2.
- h_1 Upstream water level relative to the height of the crest of the weir. This is the water level in the Rhine relative to the weir crest. Daily water levels of the Rhine at Lobith are used as discussed further in Section 4.2.
- h_3 Downstream water level relative to the height of the crest of the weir. This is the water level in the Rijnstrangen relative to the weir crest.
- The crest height is a variable (see also Section 4.3.1).

4.1.3. Precipitation

The daily inflow into the reservoir due to precipitation is calculated by multiplying the daily precipitation depth with the total area of the Rijnstrangen, which is 28.6 km^2. The inundated area does not play a role in this precipitation volume, as all water is assumed to contribute to the total volume of water in the Rijnstrangen. Any delays in the runoff are neglected. The datasets that provide this daily precipitation depth are discussed in Section 4.2.

4.1.4. Evaporation

The evaporation from the Rijnstrangen is calculated based on the Makkink evaporation, which is available in the datasets of the KNMI. Since 1987 the KNMI uses the modified Makkink equation to calculate the reference evaporation. Currently Makkink's method is the most commonly used method in hydrological models in the Netherlands. Makkink's method gives the potential evaporation from grassland areas based on global radiation and air temperature (Makkink, 1957).

The total evaporation from the Rijnstrangen consists of evaporation from land and evaporation from the inundated area. The area (A) of both surfaces is dependent on the water level in the Rijnstrangen. This relation is shown in Figure 3.2. The Makkink evaporation is converted to these two types of evaporation using two correction factors (c), one for either type of evaporation. This results in Equation (4.3) for the total evaporation.

$$E_{\text{Total}} = c_{\text{land}} \cdot E_{\text{Makk}} \cdot A_{\text{land}} + c_{\text{water}} \cdot E_{\text{Makk}} \cdot A_{\text{water}} \tag{4.3}$$

The value of the correction factor for land is determined based on the study of Elbers et al. (2010) and the crop factors as defined by Feddes (1987). As most of the Rijnstrangen is covered in grass, the main vegetation correction factor is 1.0. This may be a bit higher in summer and a bit lower in winter due to cropland (Feddes, 1987). However, most of the year the actual evaporation will not reach the potential evaporation, as the evaporation will be water-limited. Therefore, a factor of 0.7 to 0.9 seems reasonable (Elbers et al., 2010). The high side of this range is chosen as there are some trees and bushes in the Rijnstrangen as well, which increases the actual evaporation (Elbers et al., 2010). Therefore, a vegetation factor of 0.85 is used in the water balance calculations (c_{land} = 0.85). For the value of the correction factor for water a value of 1.25 is used (c_{water} = 1.25), which is a common correction factor from Makkink evaporation to open water evaporation (Feddes, 1987).

4.1.5. Groundwater flow

The groundwater flow in the study area is defined as the water that is exchanged through the subsurface. Part of the water is extracted for the users, the other part is exchanged with the region surrounding the Rijnstrangen. The groundwater flow is approximated using the numerical method as described by Olsthoorn (2000).

Numerical method of Olsthoorn

The method of Olsthoorn is based on the equation of Mazure (1932), which gives a relation for stationary one-dimensional groundwater flow in a situation with one infinite aquifer that has a confining top layer and an infinite polder behind a dike with a constant surface water level. The analytical method of Mazure cannot directly be applied to the situation in the Rijnstrangen, mainly due to the assumptions of an infinite aquifer and polder. However, Maas (1986), Bruggeman (1999) and finally Olsthoorn (2000) extended the formula of Mazure to an analytical method with an arbitrary number of layers and sections, allowing for calculations along a single cross-section. This method can be applied to the situation in the Rijnstrangen.

The differential equation for one-dimensional flow in one of the aquifers of the multi-layer system is given in Equation (4.4). This equation forms the base of the analytical method of Olsthoorn.

$$\frac{d^2\Phi_i}{dx^2} = \frac{\Phi_{i-1} - \Phi_i}{T_i c_i} + \frac{\Phi_{i+1} - \Phi_i}{T_i c_{i+1}} \tag{4.4}$$

Here i is the layer number with $i = 1...N$, where N is the number of aquifers. Φ_i is the head in aquifer i in meters, T_i the transmissivity of aquifer i in m^2/day and c_i the resistance of clay layer i in days.

Equation (4.4) can be written in matrices to account for multiple layers, as given in Equation (4.5). This equation thus gives the relation for multiple layers of one section.

$$\frac{d^2\boldsymbol{\Phi}}{dx^2} - \boldsymbol{\Lambda\Phi} = 0 \tag{4.5}$$

Here $\boldsymbol{\Phi}$ is the column vector of length N with the heads in all aquifers in meters and $\boldsymbol{\Lambda}$ the system-matrix:

$$\boldsymbol{\Lambda} = \begin{bmatrix} \frac{1}{T_1c_1} + \frac{1}{T_1c_2} & -\frac{1}{T_1c_2} & 0 & 0 & ... & 0 \\ -\frac{1}{T_2c_2} & \frac{1}{T_2c_2} + \frac{1}{T_2c_3} & -\frac{1}{T_2c_3} & 0 & 0 & \\ 0 & 0 & ... & ... & ... & 0 \\ 0 & ... & 0 & -\frac{1}{T_{N-1}c_{N-2}} & \frac{1}{T_{N-1}c_{N-1}} + \frac{1}{T_{N-1}c_N} & -\frac{1}{T_{N-1}c_N} \\ 0 & 0 & ... & 0 & -\frac{1}{T_Nc_N} & \frac{1}{T_Nc_N} + \frac{1}{T_Nc_{N+1}} \end{bmatrix}$$

In this system-matrix, T is still the transmissivity of the aquifer in m^2/day and c the resistance of the clay layer in days. In this study, clay layer N is the geohydrological base, thus $c_{N+1} = \infty$. This reduces the bottom right term to $1/(T_Nc_N)$.

The analytical solution to Equation (4.5) is given in Equation (4.6).

$$\boldsymbol{\Phi} = \boldsymbol{A}e^{-x\sqrt{\boldsymbol{\Lambda}}} + \boldsymbol{B}e^{x\sqrt{\boldsymbol{\Lambda}}} + \boldsymbol{h} \tag{4.6}$$

Here $\boldsymbol{h}$ is the column vector of length N with the heads in the aquifers in meters at $x = \pm\infty$. $\boldsymbol{A}$ and $\boldsymbol{B}$ are constants of integration. These column vectors of length N are determined based on the boundary conditions of the sections. Each section forms the boundary conditions for the next section, requiring Equation (4.6) to be used for every section separately. Lastly, x is the distance along the section.

Flux $\boldsymbol{q}$ in m^2/day is given by Equation (4.7), where $\boldsymbol{T}$ is the square diagonal matrix with the transmissivity values of the aquifers in m^2/day.

$$\boldsymbol{q} = -\boldsymbol{T}\frac{d\boldsymbol{\Phi}}{dx} \tag{4.7}$$

The numerical solution is given in the Python code (see De Vries (2021) for the repository) and the paper of Olsthoorn (2000). In this study the input as listed here is used. These values are obtained as discussed in the paragraphs below and in Appendix A and correspond to the values as presented in Figure 4.6.

- c matrix with the resistance values of the top layer and clay layers of *nLay* by *nSec* in days.
  $c = \begin{bmatrix}1 & 650 & 10000 & 80 & 10000 & 250 & 225\end{bmatrix}$
- T matrix with the transmissivity values of the aquifers of *nLay* by *nSec* in m^2/day.
  $T = \begin{bmatrix}250 & 750 & 750 & 750 & 750 & 750 & 750\end{bmatrix}$
- h vector of surface water levels of length *nSec* in meters.
  $h = \begin{bmatrix}9.2 & 9.8 & 9.8 & \text{h}_{\text{Rijnstrangen}} & 9.7 & 9.7 & 9.1\end{bmatrix}$
- Q matrix of nodal injections and extractions of *nLay* by *nSec - 1* in m^2/day.
  $Q = \begin{bmatrix}0 & \text{Q}_{\text{use, left}} & 0 & 0 & \text{Q}_{\text{use, right}} & 0\end{bmatrix}$
- x vector with coordinates of the intersection points of the sections of length *nSec - 1* in meters.
  $x = \begin{bmatrix}-3100 & 0 & \text{x}_{\text{Rijnstr, left}} & \text{x}_{\text{Rijnstr, right}} & 2000 & 3000\end{bmatrix}$

Here *nLay* is the number of layers along the depth of the cross-section and *nSec* is the number of sections along the length of the cross-section. In this study *nLay* = 1 and *nSec* = 7. Therefore, the matrices have only one row. Q is in m^2/day as the calculations are performed along one cross-section (two-dimensional). To obtain Q in m^3/day, the value has to be multiplied with the length of the area perpendicular to the cross-section. In this study, all heights are indicated relative to NAP (Normaal Amsterdams Peil or Amsterdam Ordnance Datum).

Geological schematisation
To calculate the groundwater flux in the water balance of the Rijnstrangen, a cross-section from the Pannerdense Kop (southwest of the Rijnstrangen) to Didam (northeast of the Rijnstrangen) is used (see Figure 4.3). This cross-section is chosen as it is perpendicular to the length of the Rijnstrangen and more or less in the middle of the basin. As most of the water will flow out of the area crossing the long sides of the basin and most of the area has the characteristics this cross-section has (see also Appendix A), the flow along this cross-section is most representative for the main groundwater flow. The chosen cross-section is assumed to be representative for the entire Rijnstrangen.

As can be seen in Figure 4.3 the cross-section is divided in seven sections (*nSec* = 7), of which three sections (3a, 3 and 3b) have a variable width. The number and locations of the sections are based on the surface water levels, the geo(hydro)logical situation and the elements in the landscape, like the Rhine and the Rijnstrangen. The surface water levels are based on the available surface water measurements, as collected by the water board (WRIJ, 2021), and the target water levels in the different areas (WRIJ, n.d.-d). The geo(hydro)logical situation is derived from the reports by TNO Geologische Dienst (2021), Witteveen+Bos (2007a) and Witteveen+Bos (2007b).

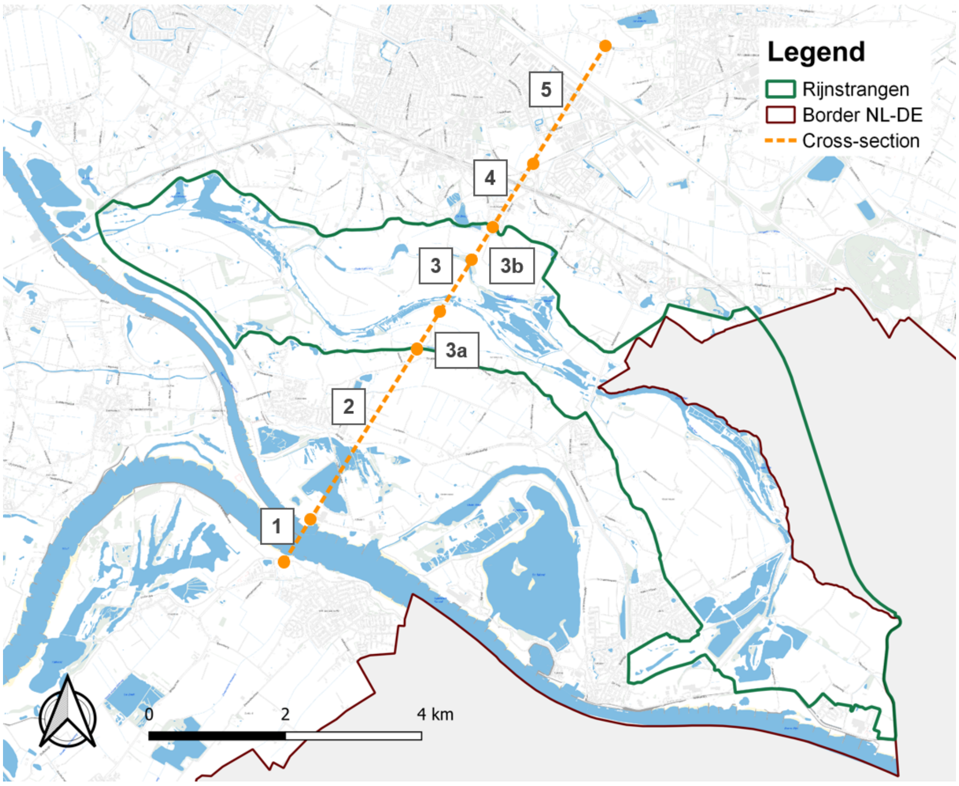


Figure 4.3: Map of cross-section chosen for the groundwater calculations. This cross-section corresponds with B - B* of Figure 2.8 and with the cross-section in Figure 3.1. It is assumed that groundwater flow along this cross-section is representative for the entire Rijnstrangen. The numbers indicate the different sections as used for the calculation of the groundwater flow.

Besides the division in sections, the cross-section is divided in horizontal layers, as can be seen in Figure 4.4. These layers can be simplified to alternating sand and clay layers, as shown in Figure 4.5. Only the top part of the cross-section is considered in the groundwater calculations as the first clay layer has a hydraulic resistance of multiple years (see Appendix A.4). Therefore, in the close surroundings of the Rijnstrangen the layer acts as the geohydrological base. Figure 4.6 presents how the top layers are translated to input values for the groundwater calculations. The analysis supporting these values is presented in Appendix A. The consequence of leaving out the deeper layers in the groundwater calculations is presented in Appendix B, together with the effect of not taking into account a longer cross-section.

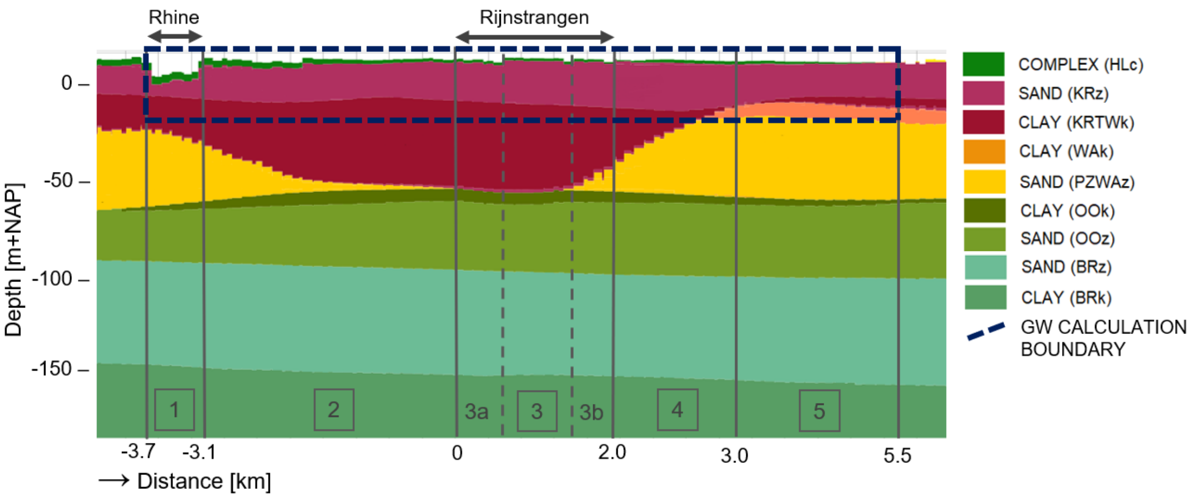


Figure 4.4: Cross-section for the groundwater calculations, as shown on the map in Figure 4.3. It is assumed that this cross-section is representative for the entire Rijnstrangen. The numbers indicate the different sections as used for the calculation of the groundwater flow. Adapted from TNO Geologische Dienst (2021).

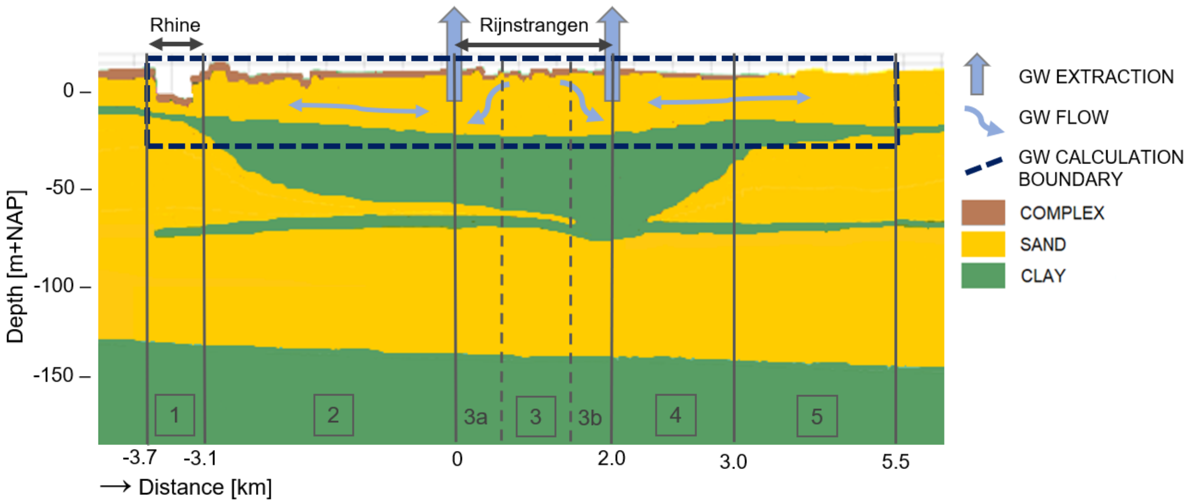


Figure 4.5: Simplified representation of the cross-section for groundwater calculations. The clay layer under the first aquifer is so thick that for this study it acts as the geohydrological base.

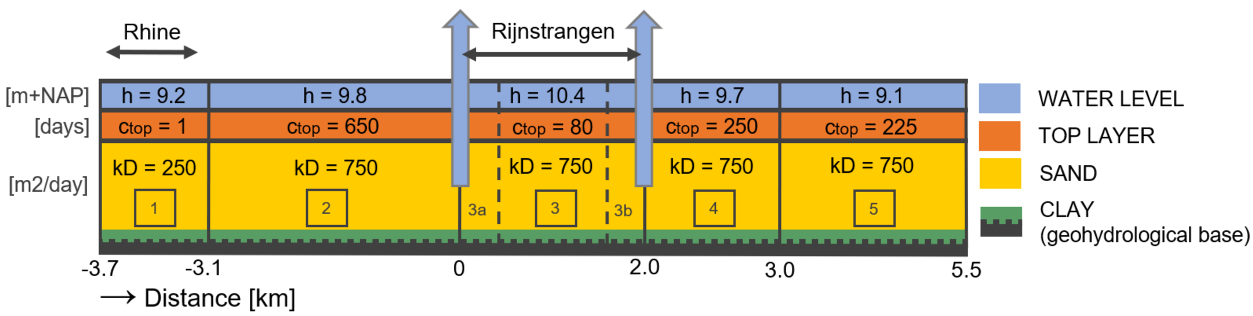


Figure 4.6: Schematization of the geohydrological situation used for the groundwater calculations. The values in this figure together form the input vectors and matrices. Sections 3a, 3 and 3b have a variable width. The hydraulic resistance of the top layer under the Rhine is very low, here the Rhine water stands in direct connection to the groundwater.

As is shown in Figure 4.6, each cell in the *nSec* by *nLay* cross-section has its own characteristics. In clay layers, where the flow is primarily in vertical direction, this is the hydraulic resistance. This resistance indicates how hard it is for water to flow through the layer, from the one aquifer to the other. For the sand layers, where the flow is primarily in horizontal direction, the characteristic value is the transmissivity. The transmissivity indicates how fast water can travel through the layer in a horizontal direction. For the top layer the characteristic value is the hydraulic resistance plus the drainage resistance, indicating how fast water can infiltrate through the top layer to the first aquifer.

Section 3a and 3b of the cross-section are introduced as the width of the Rijnstrangen varies with the water level in the area, influencing the groundwater flow. Sections 3a, 3 and 3b therefore have a variable width. The surface water level in sections 3a and 3b is set equal to the adjacent section (h_{3a} = 9.8 m +NAP and h_{3b} = 9.7 m +NAP), while the resistance of the top layer in these areas is set very high to avoid extreme seepage in the area (c_{top} = 10000 days). Therefore, there is hardly any vertical exchange between the surface water and the first aquifer here, with as result that these sections are simply passing on the water in the first aquifer from the Rijnstrangen to the surroundings. The transmissivity of the aquifer in section 3a and 3b is the same as its surroundings. In section 1, the resistance of the top layer is very low. This low resistance is taken as here the Rhine cuts through the top layer (Witteveen+Bos, 2007a), creating a direct connection between the Rhine and the first aquifer.

Groundwater extraction
A groundwater extraction component is included in the water balance to allow for the extraction of groundwater for drinking water or irrigation. This component is part of the groundwater flux and can be varied within any range to show the effect of extraction of different volumes. For example, drinking water extraction for a certain number of people can be included by multiplying the number of people by their water use.

Groundwater extraction wells in the region of the Rijnstrangen extract their water from the first aquifer (Provincie Gelderland, 2012). Due to the thick first clay layer in the Rijnstrangen region this appears to be the best option for water extraction in the Rijnstrangen as well, as this allows for the recharging of the aquifer from the retention basin. The extraction wells are therefore placed in the first aquifer on either side of the Rijnstrangen (x = 0 m and x = 2000 m). The extraction volumes are variables which can be chosen independently. This allows for the extraction on only one side of the Rijnstrangen. As the cross-section is representative for the entire Rijnstrangen, the extraction wells are located along the entire length of the Rijnstrangen.

Validation of the groundwater model
The applied method of Olsthoorn (2000) calculates the heads in the different aquifers to calculate the groundwater flow. These heads are used to validate the model by comparing the modelled head of the first aquifer for an average situation with the average measured heads in the first aquifer. If the modelled heads resemble the measured groundwater heads, the model is likely to give a good approximation of the groundwater flow as well. If the modelled heads and the measured heads do not match, the used parameters are revised. The measured heads are available via Geologische Dienst Nederland (2021).

Sensitivity of the parameters of the groundwater model
To obtain insights into the sensitivity of the groundwater model to its parameters, the model is run 1000 times while randomly varying the set of parameters within their likely range (see Appendix A for these ranges). The resulting groundwater outflows from the Rijnstrangen are plotted against the varied parameters of the groundwater model. The parameters that show a correlation should be chosen carefully, as they have a direct influence on the outflow component in the water balance. For the parameters that show a random distribution, the outcome of the model is determined by another parameter.

To find a ranking of the influence of the parameters, each time the most influential parameter is fixed to its neutral value in a next run of 1000 times to find the next most influential parameter. Also, a combination of two or more parameters can show a correlation, in that case the combination of those is of influence on the model outcome. The leakage factor ($c \cdot kD$) is tested for its sensitivity as combination of parameters.

4.2. Projected climate and available datasets

Section 4.2.1 presents what projected effects of climate change can be implemented in the water balance calculation to test it for potential future situations. Subsequently, Section 4.2.2 discusses what datasets are used in the water balance calculations for the climate change scenarios.

4.2.1. Climate scenarios

To see if the Rijnstrangen retention reservoir could be effective under a changing climate, climate change projections for precipitation, evaporation and river runoff are used in the water balance calculation. The groundwater flow is assumed to remain unchanged.

Rhine runoff
Historical time series of the daily Rhine water levels at Lobith are available via `waterdata.wrij.nl` (WRIJ, 2021). The data is consistent since January 1st 1866 and is updated daily. Projected Rhine water levels at Lobith are available via `wabes.nl`. This website is a tool from the Dutch government where water managers can see and download data regarding water resources to support well-founded decisions regarding investments and agreements. Five Rhine water level time series can be downloaded here. First of all, a reference situation for 2017 is available. This is the historical time series corrected to a time series as if it were the climate of 2017. The other four time series are also corrected historical time series, based on on the current projections for the climate in 2050. All five time series run from November 1st 1911 until November 1st 2011. The available projections for 2050 are the scenarios *Rust*, *Druk*, *Stoom* and *Warm* (free translations respectively *Rest*, *Pressure*, *Steam* and *Warm*). These scenarios account for both climate change and socio-economical changes, as shown in Figure 4.7a. The scenarios for the Rhine datasets can be linked to the KNMI'14 climate scenarios (KNMI, 2015), where the first two scenarios match the KNMI'14 climate scenario G_L and the last two scenarios match the KNMI'14 climate scenario W_H (see Figure 4.7b).

(a) Socio-economical climate scenarios.

(b) KNMI'14 climate scenarios.

Figure 4.7: Two types of climate scenarios.

Precipitation and Evaporation
A dataset with the historical daily precipitation and Makkink evaporation is available via `knmi.nl`. The dataset for the Dutch town of De Bilt is used, as the datasets for the projected climate scenarios are only available for this town. No correction for the location is needed, as shown in Figure 4.8: the Rijnstrangen falls within the *G* precipitation regime, indicating that the dataset for De Bilt is representative and no correction is needed (Buishand et al., 2009). The historical precipitation and evaporation are available from July 1st 1957 onwards.

Datasets with projected precipitation and evaporation are available via `meteobase.nl`. These datasets run from January 1st 1906 until December 31st 2014. In these datasets the historical time series for De Bilt is corrected for the current climate (2014) and future climate scenarios. The available future scenarios are G_L, W_L, G_H and W_L for both 2050 and 2085. When comparing these scenarios to the available Rhine water level scenarios, only the 2050 G_L and 2050 W_H scenario match, therefore these scenarios are used.

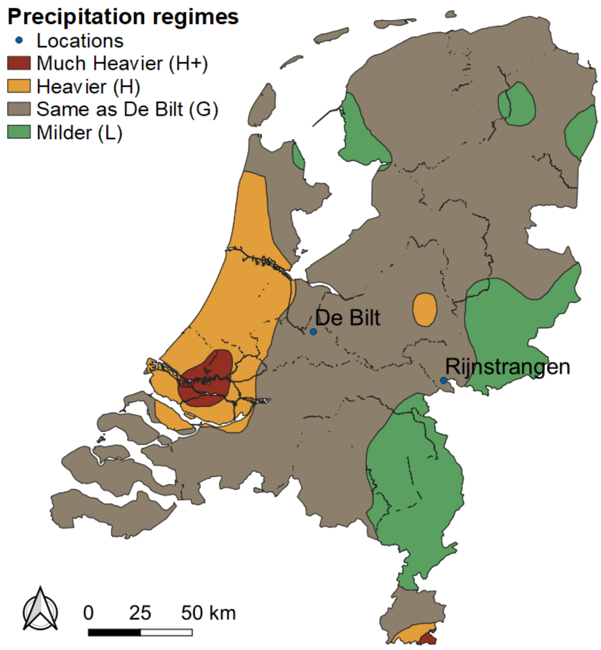


Figure 4.8: Precipitation regimes as used for the selection of the correction factor for precipitation and evaporation to go from the climate in De Bilt to the climate in the Rijnstrangen. This figure shows that the climate in De Bilt can be assumed to be representative for the Rijnstrangen. Adapted from Buishand et al. (2009).

4.2.2. Datasets

As discussed in Section 4.2.1, the following climate scenarios are selected to use in the water balance calculation:

- *Historical* Historical time series.
- *Reference* Historical time series corrected for the current climate.
- *2050 G_L* Historical time series corrected for the projected climate in 2050 for the G_L climate scenario of KNMI (2015).
- *2050 W_H* Historical time series corrected for the projected climate in 2050 for the W_H climate scenario of KNMI (2015).

For the selected climate scenarios, the overlapping time period is from July 1st 1957 to October 31st 2011, when considering both the Rhine water levels datasets and the precipitation-evaporation datasets. From this data the part from January 1st 1960 to December 31st 2009 is selected to work with in the water balance calculations. This is a time span of 50 years, which is assumed to be enough for this study as it will probably cover all sorts of combinations of water levels, precipitation and evaporation.

Rhine water levels

Figures 4.9 and 4.10 give insight in the time series of the daily water levels of the Rhine at Lobith. Figure 4.9 shows the flow duration curves for the water levels, indicating what percentage of the time the daily average water level in the Rhine at Lobith is above a certain level. For example, the figure shows that, with a weir height of 12.5 m +NAP (the neutral weir height as described in Section 4.3.1), between 5% and 9% of the time water can flow into the Rijnstrangen, dependent on the climate scenario. The detail in Figure 4.9 shows that the 2050 G_L scenario most often has high water levels, followed by the 2050 W_H scenario, the historical scenario and the reference scenario respectively. For decreasing water levels, this order changes. The jumps in the data of the historical time series are at every meter, this seems to be a flaw in the data.

Figure 4.10 presents the time series of the Rhine water levels at Lobith. The behaviour seen in Figure 4.9 can be observed in these figures as well, with the 2050 G_L scenario being the highest at the peaks and the 2050 W_H scenario being the lowest at low discharges. These low discharges however are of no importance for this study as only water levels above 10 m +NAP reach over the minimum weir height.

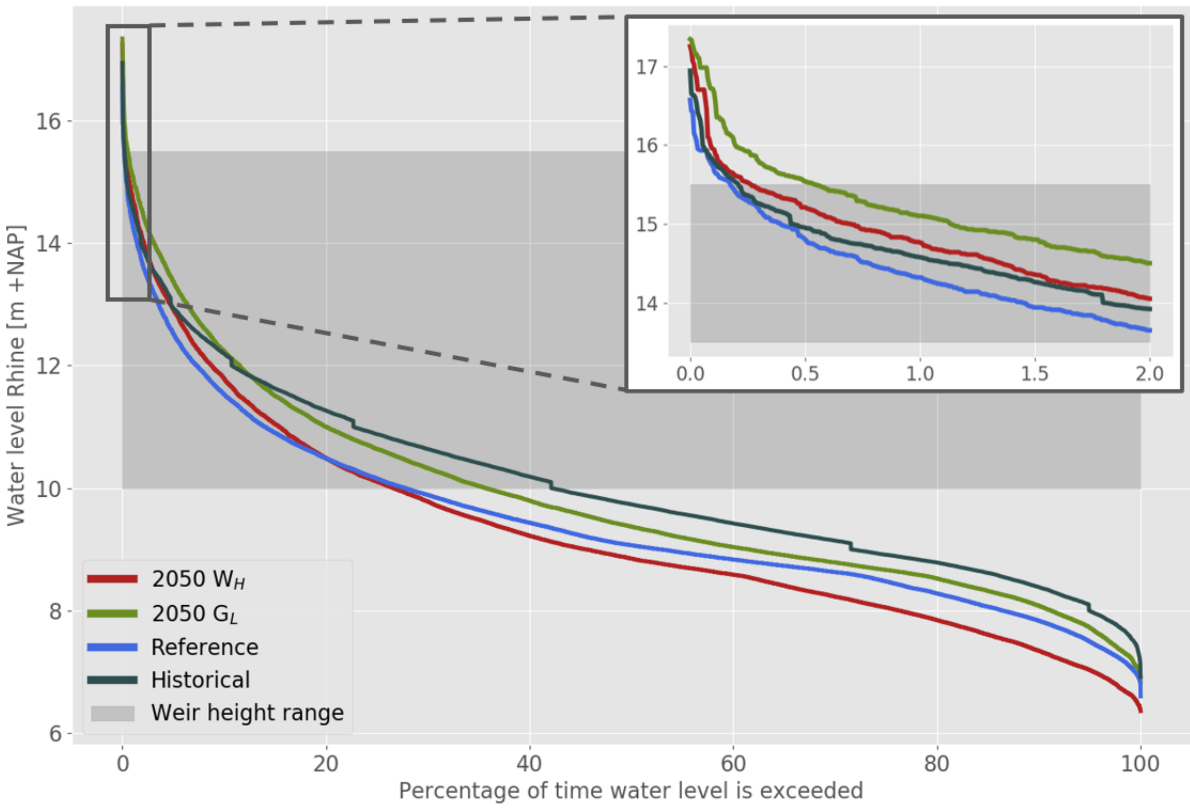
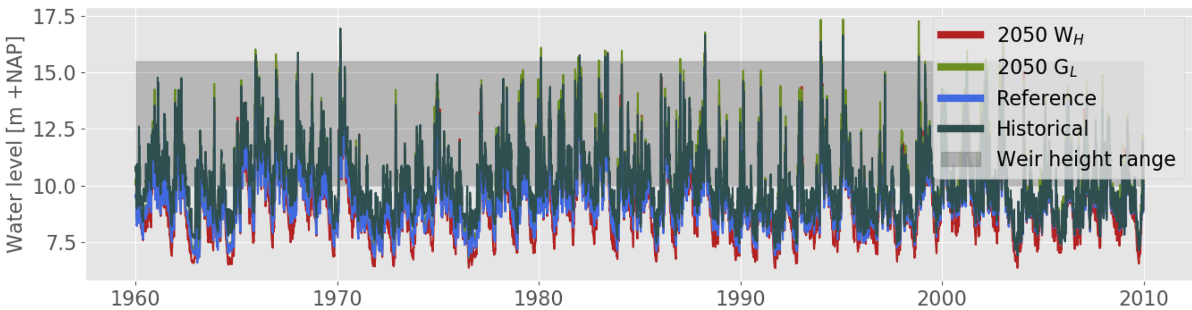
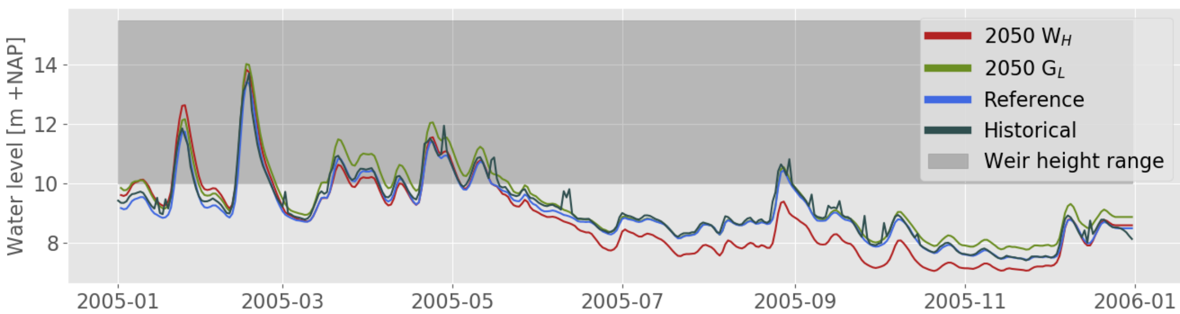


Figure 4.9: Flow duration curve of the daily average water levels in the Rhine at Lobith for the time span of the water balance calculation (1960-2009). In general the historical time series has the highest water levels, but for the peak water levels this is the 2050 G_L climate scenario. Note that this figure shows the water levels relative to NAP an thus does not show the water depths. Data retrieved from `waterdata.wrij.nl` (historical data) and `wabes.nl` (corrected series).



(a) Water levels in the Rhine at Lobith for the time span of the water balance calculation (1960-2009).



(b) Water levels in the Rhine at Lobith in 2005, as a detailed example.

Figure 4.10: Water levels in the Rhine at Lobith. The 2050 G_L time series has the highest peaks and the 2050 W_H time series the lowest lows. Note that both figures show the water levels relative to NAP an thus do not show the water depths. Data retrieved from `waterdata.wrij.nl` (historical data) and `wabes.nl` (corrected series).

Precipitation

Where the Rhine water levels show differences for the different climate scenarios, the differences between the climate scenarios seem relatively small for the precipitation and evaporation time series. For example in the precipitation data in Figure 4.11, the time series overlap so much that they can hardly be distinguished. This seemingly small difference in the precipitation is mainly due to the extreme peaks, as shown in Figure 4.12. When zooming in on Figure 4.12, the differences between the precipitation time series become more clear. In the 2050 W_H scenario the precipitation peaks are highest most often, followed by the 2050 G_L and the reference time series, which overlap. The 2050 G_L and reference scenario have the most precipitation for the higher percentages of exceedance. The historical time series has the lowest precipitation.

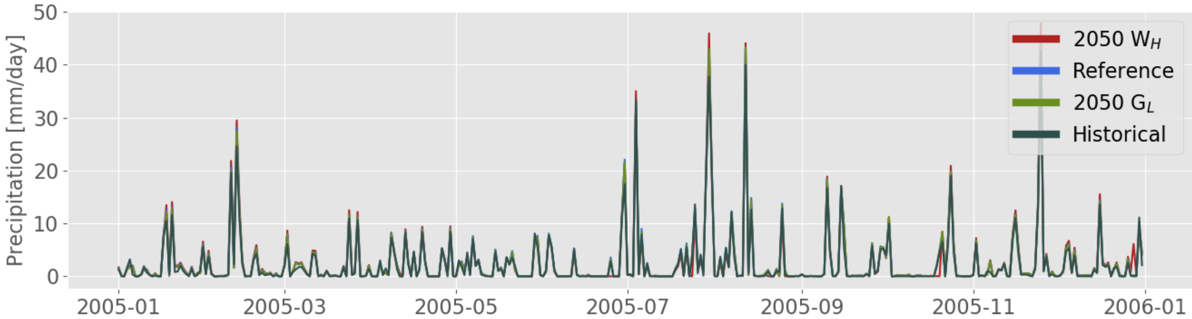


Figure 4.11: Precipitation time series in 2005 as an example of the precipitation. The figure shows that the datasets resemble each other so much that the lines are hardly distinguishable. The 2050 W_H climate scenario has the highest precipitation peaks and the historical time series has the lowest precipitation, as shown in Figure 4.12. Data retrieved from `knmi.nl` (historical data) and `meteobase.nl` (corrected series).

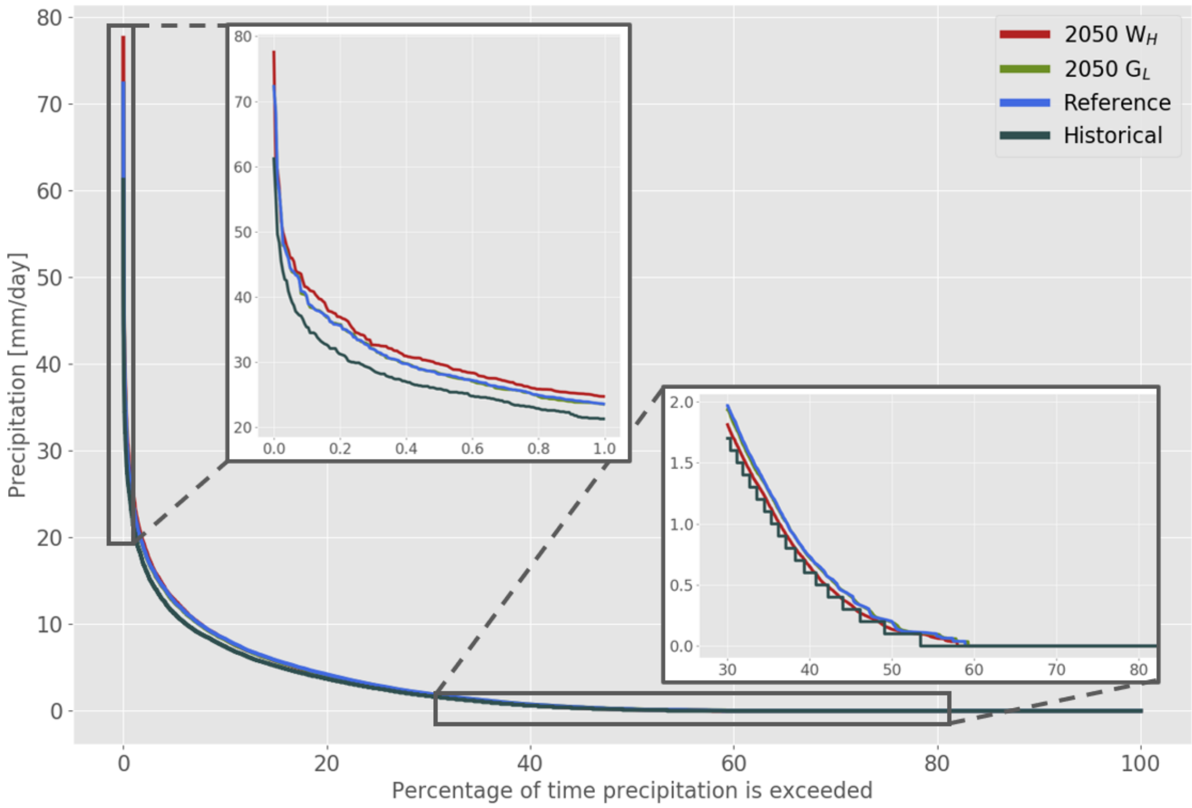


Figure 4.12: Precipitation duration curves for the time span of the water balance calculation (1960-2009). The figure shows that the 2050 W_H time series has the highest precipitation peaks and the historical time series has the lowest precipitation in general. The 2050 G_L and the reference time series are more or less the same. Data retrieved from `knmi.nl` (historical data) and `meteobase.nl` (corrected series).

Evaporation

The differences between the evaporation time series (Figure 4.13) become clear from the plot of the yearly average of the evaporation time series, as shown in Figure 4.14. The main differences between the time series occur in summer and autumn, with the highest evaporation for the 2050 W_H scenario and the lowest evaporation for the historical time series. The 2050 G_L climate scenario and the reference scenario show such a similar pattern that the line for the reference scenario can hardly be seen in the figure, due to following the 2050 G_L line.

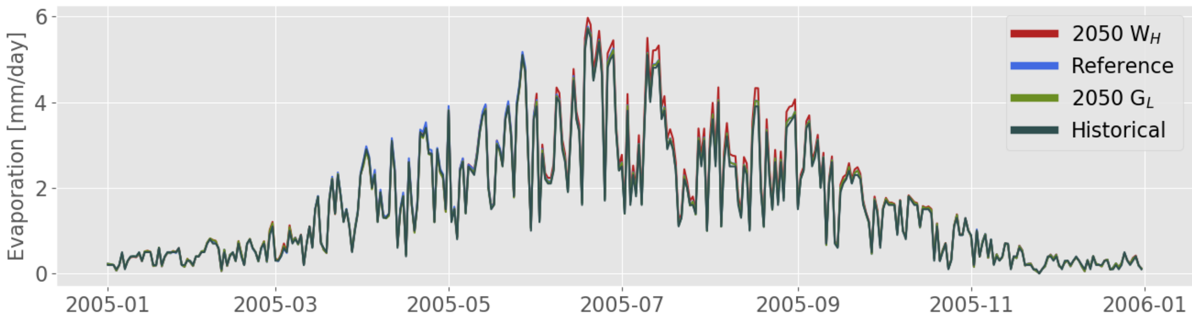


Figure 4.13: Evaporation time series in 2005 as an example of the evaporation. The figure shows that the datasets resemble each other so much that the lines are hardly distinguishable. In general the 2050 W_H climate scenario has the highest evaporation and the historical time series has the lowest evaporation, as shown in Figure 4.14. Data retrieved from `knmi.nl` (historical data) and `meteobase.nl` (corrected series).

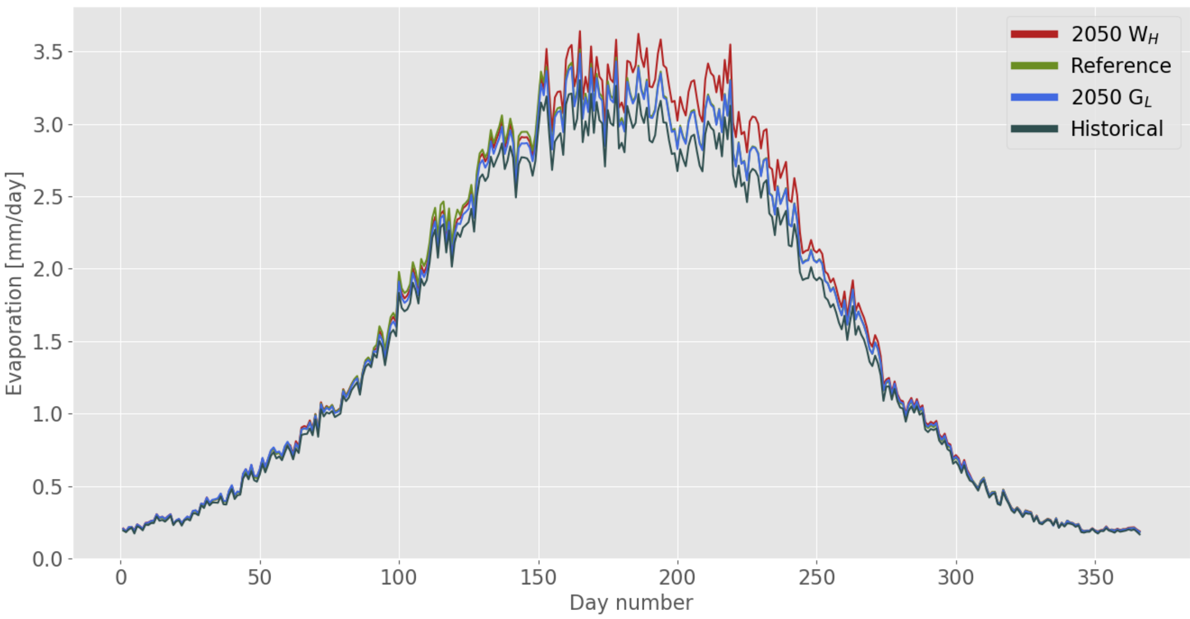


Figure 4.14: Yearly average of the evaporation time series for the time span of the water balance calculation (1960-2009). In general the 2050 W_H climate scenario has the highest evaporation and the historical time series the lowest evaporation. The 2050 G_L and the reference time series are more or less the same. Data retrieved from `knmi.nl` (historical data) and `meteobase.nl` (corrected series).

4.3. Feasibility of the Rijnstrangen as retention reservoir

Besides the water balance calculation for the different climate scenarios, different reservoir configurations can be implemented by changing the variables, such as the weir configuration. Varying these parameters gives insight in the behaviour of the basin. Section 4.3.1 discusses which parameters are varied to test a variety of reservoir configurations. Subsequently, Section 4.3.2 describes three narratives that are tested in the water balance. Lastly, Section 4.3.3 describes the criteria that are used to evaluate the feasibility of the different scenarios and parameter configurations.

4.3.1. Variable parameters

In the water balance calculation five parameters are varied to test different reservoir configurations. Table 4.1 presents these variables, their range and their neutral value. To show the effect each parameters has on the water balance calculation, every variable is varied separately within its range, while the other variables are kept at their neutral value.

Table 4.1: Variables in the water balance calculations.

Variable	Range	Neutral
Weir height	**10 m +NAP – 15.5 m +NAP** From the lowest point in Rijnstrangen (10 m +NAP) to height of crests of southern dike (15.5 m +NAP).	12.5 m +NAP
Weir width	**0 m – 1210 m** 1210 m is the sum of the lengths of the weirs as depicted in Figure 3.1.	500 m
Max. volume	**0 Mm^3 – 100 Mm^3** From no storage (0 Mm^3) to volume at water level of 15.5 m +NAP, which corresponds to the height of the crests of the southern dike. Relevant when comparing policy choices (room for nature, recreation, agriculture, etc.).	58 Mm^3
GW extraction or Q_{use}	**Any value** On both sides of the Rijnstrangen this parameter can be varied within any range independently. These values can even be negative, in which case there is an infiltration point instead of an extraction point. Examples of realistic values for this variable are given in this paragraph.	50 Mm^3/y = 2 x 25 Mm^3/y
Climate	**Historical** **Reference** **2050 G_L** **2050 W_H**	Historical

Examples of values that can be used as the groundwater extraction variable:

- 1.2 Bm^3/y — Total drinking water use of the Netherlands in 2019.
- 366 Mm^3/y — Drinking water production Vitens (drinking water company in eastern part of the Netherlands).
- 134 Mm^3/y — Drinking water production of Vitens in Gelderland, of which 85% goes to households (Provincie Gelderland, 2019).
- 3.6 Mm^3/y — Drinking water consumption in municipalities around Rijnstrangen (Zevenaar, Duiven and Westervoort), based on water use of 119 l/pers/d.

The extraction volume is expressed as a total extraction volume, but is always the sum of two extractions: one on either side of the Rijnstrangen. This is why Table 4.1 indicates 50 Mm^3/y consisting of 2 times 25 Mm^3/y. Another option would have been for example 10 Mm^3/y on the left (South) of the Rijnstrangen and 40 Mm^3/y on the right (North) of the Rijnstrangen.

A starting volume has to be chosen in the water balance calculation. A volume of 22.3 Mm^3 is chosen for this, corresponding to a water level of 12.5 m +NAP. This input value could be a variable too, however this choice only influences the first year(s) of the water balance calculation, until a Rhine peak has passed, and is therefore not chosen to be systematically varied.

4.3.2. Narratives

Besides the variation of the separate variables to get insight in the dynamics of the Rijnstrangen and the influence of the individual parameters, three narratives are tested. The three narratives are formed by balancing the extraction volume and the expected impact with a certain allowed water level for three extents. The extraction volumes and water level range as presented in Section 4.3.1 are used as guidance. Parameters that are not specified in the requirements of the narrative are the neutral situation. All three narratives are evaluated based on the criterion as described in Section 4.3.3.

Local: In this situation the interests regarding the Rijnstrangen are evaluated merely in the local surroundings of the Rijnstrangen. The extraction is for local use only and the values for recreation, agriculture and nature are of big interest. This means that the extraction volume will only be 4 Mm^3/y (2 x 2 Mm^3/y) and that the maximum allowed volume should be low to give space to these elements. A maximum volume of 7.7 Mm^3 is chosen, corresponding to a water level of 11.5 m +NAP. With the low water level, the weir height is set to 11.5 m +NAP as well and the starting volume is lowered to 4 Mm^3.

Moderate: This scenario combines a bit of the local and the regional narrative. There should be space for some agriculture and recreation, imposing a maximum volume of 22.3 Mm^3, corresponding to a water level of 12.5 m +NAP. The extraction should be of value on a regional scale, requiring an extraction of 50 Mm^3/y (2 x 25 Mm^3/y).

Regional: In this case, the main interest is the extraction of water. The maximum water level is maximized to 14.5 m+ NAP, which is 1 m below the crests of the southern dikes. This corresponds to a maximum volume of 72 Mm^3. The chosen extraction is 114 Mm^3/y (2 x 57 Mm^3/y), which allows to provide all households of Gelderland with drinking water at their current use (Provincie Gelderland, 2019).

4.3.3. Criteria for evaluation of feasibility

In this study the effectiveness of the Rijnstrangen as retention reservoir is evaluated based on one main criterion. This criterion is the volume of water that is extracted at the groundwater extraction locations along the reservoir, while taking into account the groundwater volume that is exchanged with the surroundings. The water exchange with the surroundings is defined as any water that enters or leaves the Rijnstrangen groundwater section (section 3 in Figure 4.6). This exchange with the surrounding region can be of two types. First of all, part of the extraction can originate from the surrounding region rather than from the Rijnstrangen. Alternatively, there can be a net flux from the Rijnstrangen to the surrounding region. This is the case if not all of the water that is flowing down from the reservoir is extracted. Both situations are presented in Figure 4.15. In the first situation the extraction may put pressure on the (ground)water system of the region, which is an undesirable situation. In the second situation the Rijnstrangen feeds the (ground)water system in the region, this may have positive effects, limiting drought problems during a (dry) summer. In this study there is no maximum set to the extraction from the region. The criterion is only used to compare different parameter configurations.

In the groundwater calculation (see Section 4.1.5) the direction and magnitude of the groundwater flow is one of the results. This result is used to analyse the groundwater exchange between the Rijnstrangen, the surroundings and the extraction wells. A plot of a potential groundwater flow situation is shown in Figure 4.16. This plot shows the direction and magnitude of the groundwater flow along the groundwater cross-section for a situation with $h_{Rijnstrangen}$ = 12.5 m +NAP, Q_{left} = 10 Mm^3/y and Q_{right} = 25 Mm^3/y.

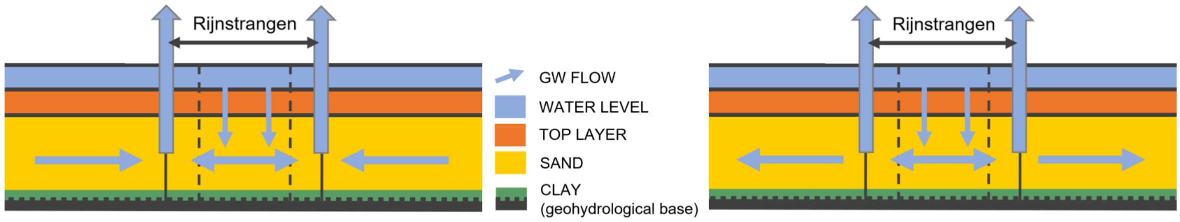


Figure 4.15: Groundwater exchange between Rijnstrangen (section 3 in Figure 4.6) and its surroundings. The left schematisation shows a situation in which the surroundings have to contribute to the groundwater extraction, which may put pressure on the (ground)water system of the region. The right schematisation shows a situation in which the Rijnstrangen reservoir contributes to the (ground)water system in the region, which may limit drought problems.

Figure 4.16 is the type of figure that can be used to analyse where the extracted water originates from. The two groundwater extractions are demarcated by the two jumps in the graph, one at x = 0 m and a second one at x = 2000 m. These jumps are equal to the extraction amount. Analysing these jumps shows where the extracted water originates from: at x = 0 m the extraction only originates from the Rijnstrangen, whereas at x = 2000 m more water is extracted, which partially originates from the surroundings. This conclusion can be drawn based on the flow direction: at x = 1 m, right next to the first extraction location, the flow is directed southward (negative value), and is thus flowing from the Rijnstrangen to the extraction well. At x = -1m the groundwater flow is still directed southward (negative value), despite the jump that is present due to the extraction location. When looking at the second well, a different situation is shown. At x = 1999 m, the groundwater flow is directed northward (positive value) and thus goes from the Rijnstrangen towards the extraction location. At x = 2001 m however, the flow is directed southward (negative), indicating a flow from the surrounding to the extraction well.

In further studies on the effectiveness of the Rijnstrangen, other criteria can play a role in the evaluation of the plans as well, which can influence the feasibility of certain parameter combinations. One of these criteria can be, for example, the value for nature. Think of bird species, vegetation or fish species that flourish under certain circumstances. Also, added value or hinder for local residents could be a criterion. Think of recreation, but also potential nuisance (flies, bad odor) due to still-standing water. Other examples are the effects of increasing the water levels in the Rijnstrangen on buildings in the area; the effects of the plans on water safety and the costs of the plan (relative to alternatives).

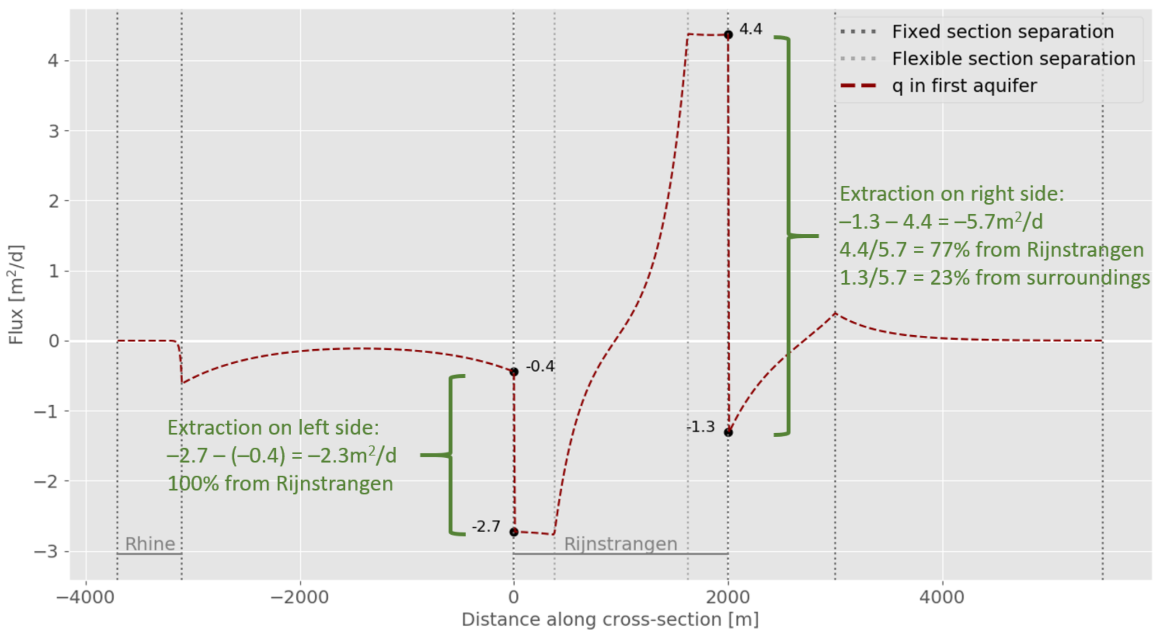


Figure 4.16: Example of a groundwater flux plot along the cross-section used for the groundwater calculations. This data can be used to analyse the groundwater exchange between the Rijnstrangen, the surrounding region and the extraction wells. A positive value indicates a groundwater flow in northward direction, a negative value indicates a southward groundwater flow.

5
Results

In this chapter the results of the study are presented. To start with, Section 5.1 presents the results related to the groundwater model. Subsequently, in Section 5.2 the results of the various water balance calculations are presented, including the results of the variation of the individual parameters. The water balances for the three narratives are presented in Section 5.3. Lastly, in Section 5.4 an overview is given of the extraction coming from the region around the Rijnstrangen for varying extraction volumes and reservoir volumes.

5.1. Groundwater model

In this section the results related to the groundwater component of the water balance calculations are presented. The result of the validation of the groundwater model is presented in Section 5.1.1. Section 5.1.2 discusses the sensitivity of groundwater model to its input values.

5.1.1. Validation of the groundwater model

Figure 5.1 shows the result of the groundwater model for the average current situation (see Appendix A for the input values) and compares it to the average observed situation (values retrieved from Geologische Dienst Nederland (2021)). If there are multiple points at one location along the cross-section, this means that there are multiple observation wells close to that location along the cross-section. The average range of heads observed is 1.5 m, where the minimum range is 1.0 m and the maximum range is over 3.0 m, at observation wells close to the Rhine. The groundwater model has a root mean square error (RMSE) of 12 cm when taking into account all average observations as depicted in Figure 5.1, this is relatively small compared to the variations in observations. Also, from a visual perspective the model resembles the observations. It is therefore assumed that the values for the groundwater fluxes are representative as well and can be used for further calculations.

Figure 5.2 shows the potential variations in heads in the first aquifer resulting from the input value ranges as presented in Appendix A. The figure shows a relatively narrow bandwidth in the area of the Rijnstrangen, but a widening range in the direction of the Rhine. This wide variety is due to the wide range of fluctuations of the Rhine water level. As the Rhine cuts through the top layer, this has a big influence on the water level in the first aquifer.

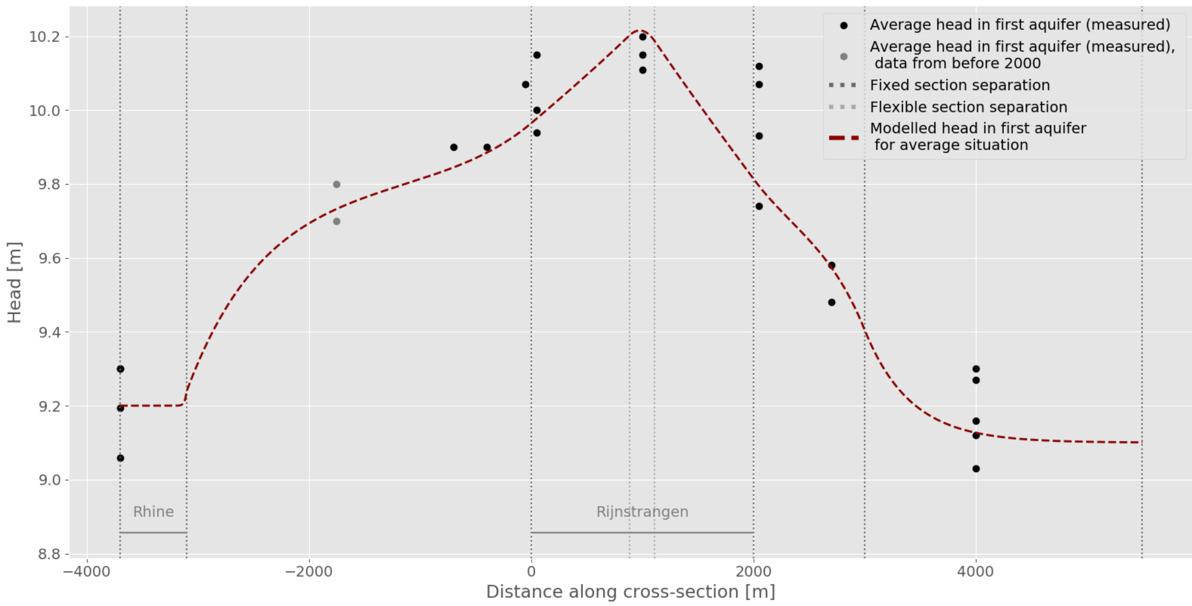


Figure 5.1: Validation of the groundwater model. With a RMSE of 12 cm and from a visual assessment it can be concluded that the groundwater model approximates reality. It is therefore assumed that the values for the groundwater fluxes will be representative as well. Measurement data for heads retrieved from Geologische Dienst Nederland (2021).

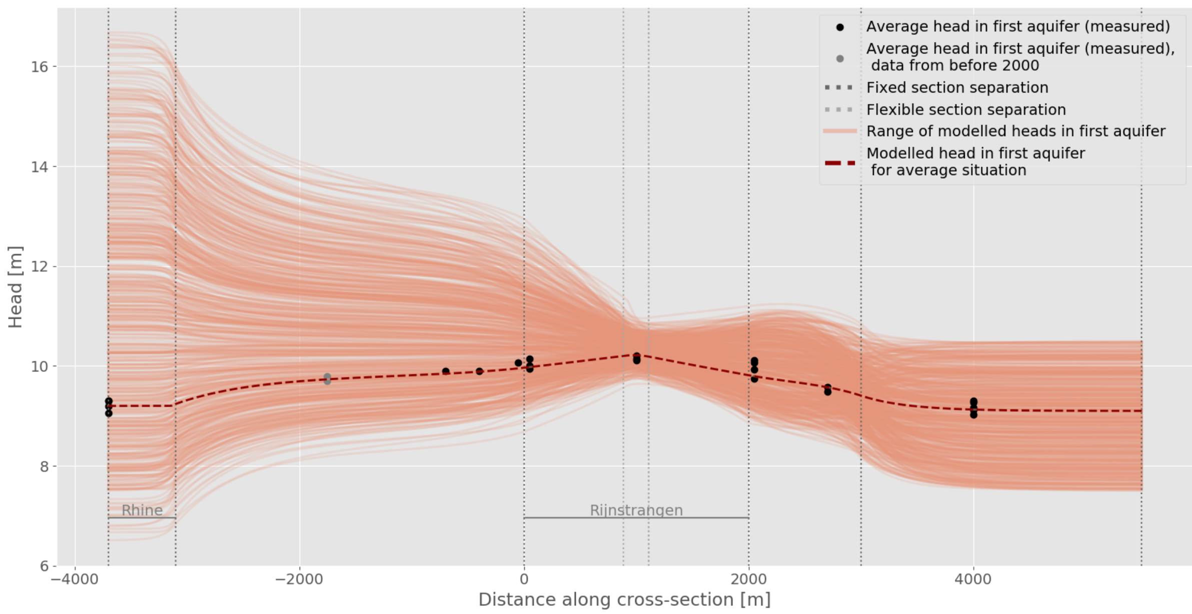


Figure 5.2: Range of modelled heads in the first aquifer, resulting from the input value ranges as presented in Appendix A. Measurement data for heads retrieved from Geologische Dienst Nederland (2021).

5.1.2. Sensitivity to the parameters of the groundwater model

The sensitivity analysis of the groundwater model to its parameters is presented in Appendix C. The analysis follows the method as described in Section 4.1.5 on page 23 and shows that the influence of the parameters on the groundwater outflow of the Rijnstrangen can be ordered. From a big to a smaller influence this ranking is:

1. Water level in the Rijnstrangen ($h_{Rijnstrangen}$ or $h_{section\ 3}$).
2. Water level (h) in section 2.
3. Water level (h) in section 4.
4. Transmissivity (kD) of sections 2, 3a, 3, 3b and 4.
5. Resistance (c) of the top layer in the Rijnstrangen ($c_{top,\ sec\ 3}$).
6. Resistance (c) of sections 2, 3a, 3b and 4, together with the water level in section 5.
7. All remaining parameters in sections 1 and 5.

The groundwater model is thus most sensitive to the water level in the Rijnstrangen, followed by the water levels in the adjacent regions (section 2 and section 4). Next most influential parameters are the transmissivity values of the sections around and under the Rijnstrangen. The resistance of the top layer in the Rijnstrangen is less important as initially expected, as its influence comes after the previously mentioned parameters. The groundwater model is least sensitive to the resistance values of the other sections and the water level in section 5.

5.2. Water balance

In this section the results of the water balance calculations are presented. To start with, the neutral water balance is discussed in Section 5.2.1. Subsequently, the results of varying the individual parameters as defined in Section 4.3 are presented and interpreted in Section 5.2.2 to Section 5.2.6. Finally, the results of the three narratives are presented in Section 5.3, as well as an overview of the extraction from the region for different parameter combinations in Section 5.4.

5.2.1. Neutral water balance

As defined in Section 4.3, the neutral situation has the following parameters:

- Weir height = 12.5 m +NAP
- Weir width = 500 m
- Max. volume = 58 Mm^3
- Q_{use} = 2 x 25 Mm^3/y
- Climate = Historical

The water balance for the neutral situation is presented in Figure 5.3, including the fluxes that are present in this water balance calculation. The figure shows the dynamics of the volume in the reservoir, as well as by which fluxes this behaviour is induced. A detailed version of this water balance is shown in Figure 5.4. In this figure it can be seen that between the start of 1975 and halfway 1976 the basin runs dry. This behaviour is also shown around 1970 and 1996 (see Figure 5.3). From this it can be concluded that if there are around 1.5 years in a row with water levels lower than the weir height, the basin runs dry with the neutral parameters.

In Figure 5.4, just before the start of 1975 the basin is fully filled by a series of days with high water levels. In the time span of running dry of the basin (1975 and 1976) the influence of the seasons can be seen. During summer the volume decreases fast, with a steep sloping line of the water volume, high evaporation and relatively few days with precipitation. During winter however, the volume of the basin stays more or less constant. Here precipitation cancels out the evaporation and groundwater outflow. After 1977, a pattern with yearly inflow from the Rhine around New Year is present. This pattern is seen in the majority of the years, as can be seen in Figure 5.3. There are also years with an inflow peak in summer as well, like in 1980 (Figure 5.4).

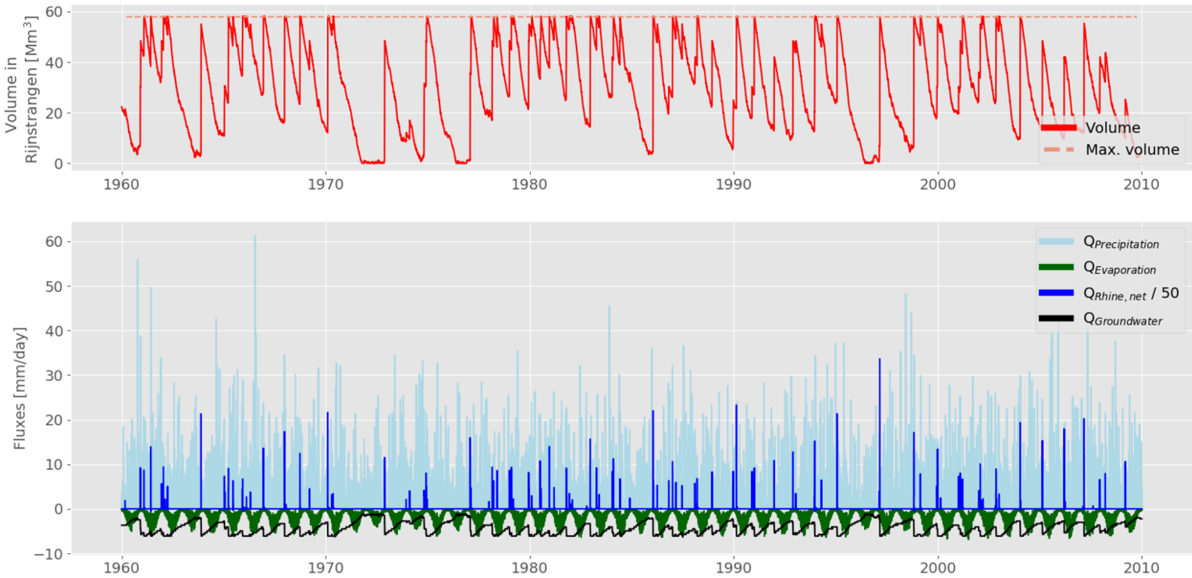


Figure 5.3: Water balance for the neutral situation. The plots show the dynamics of the volume in the reservoir, as well as by which fluxes this behaviour is induced.

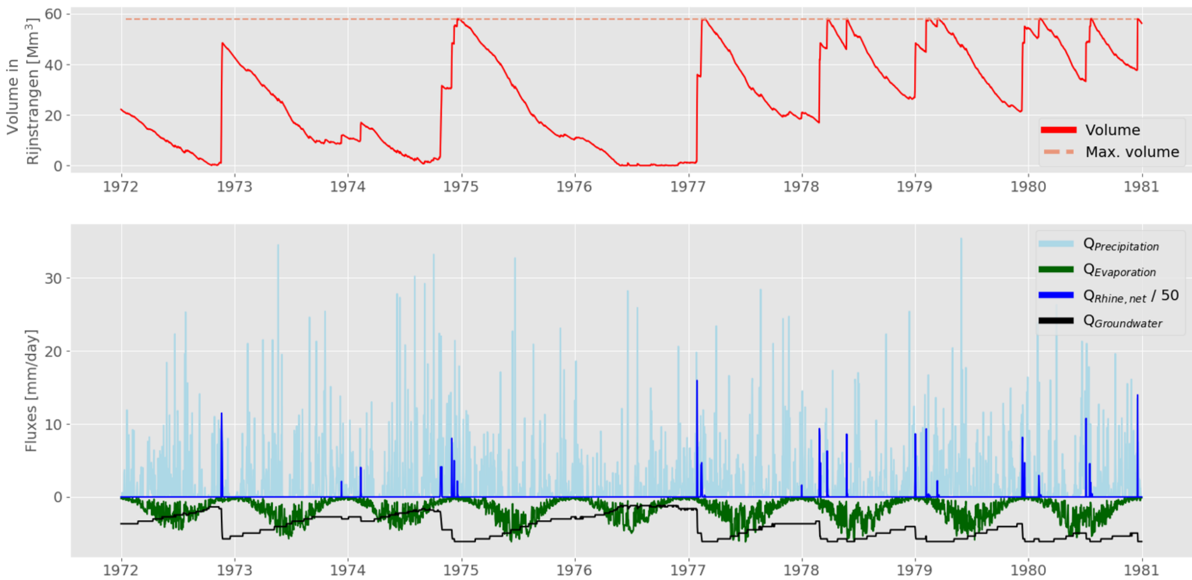


Figure 5.4: Detail of the water balance for the neutral situation, showing a dry period as well a different inflow patterns.

The water balance for the neutral situation is also plotted cumulatively in Figure 5.5, to show the total contribution of each individual component of the water balance calculation. This plot shows that none of the individual elements are dominant for the long-term behaviour of the water balance. Despite the Rhine inflow being very large per event (note the division by 50 in the plot of the fluxes), this inflow happens on average only 7.7 days per year. The same holds for the precipitation: compared to the evaporation and groundwater flux, this flux seems relatively big in the water balance plot. However, the precipitation influx is not on a daily basis, whereas the groundwater and evaporation flux are. In the cumulative plot shown in Figure 5.5 this difference becomes clear.

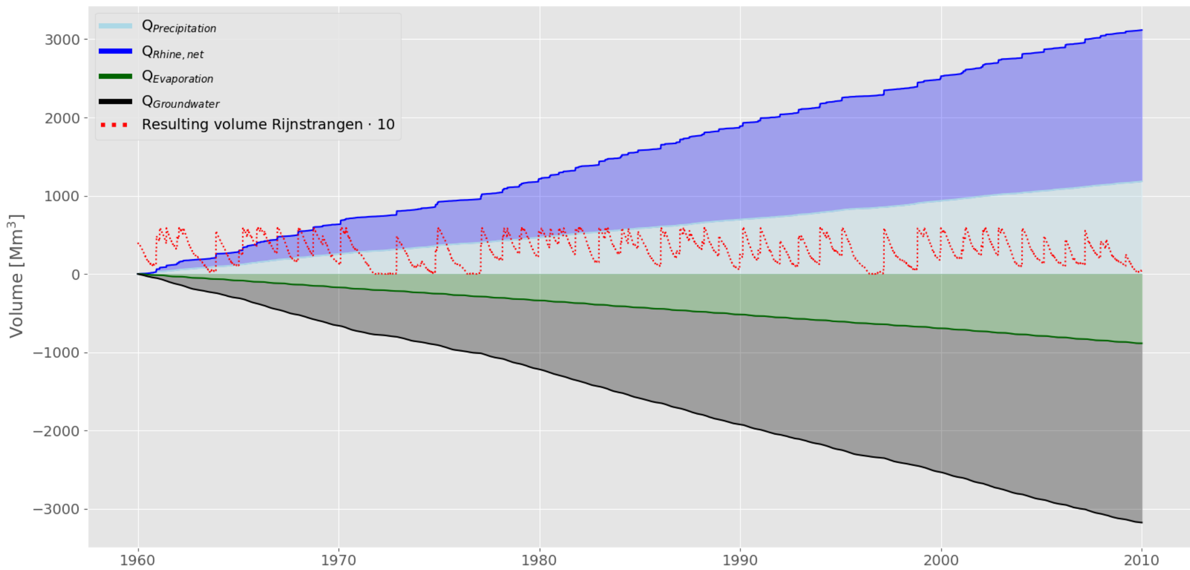


Figure 5.5: Cumulative water balance for the neutral situation, showing the contribution of each component of the water balance calculation. None of the individual elements are dominant for the long-term behaviour of the water balance.

5.2.2. Variable climate

Figure 5.6 shows the water balance for the neutral situation, but with the four climate scenarios as variable. Figure 5.7 shows a detail of this water balance. As can be seen in the figures, the effect of the climate scenarios on the outcome of the water balance is relatively limited when comparing it to the effect of, for example, a change in Q_{use} (see Section 5.2.3). Still, it is shown in Figure 5.6, Figure 5.7, and especially Figure 5.8, that in the 2050 G_L scenario the basin stays the fullest and in the reference scenario the basin volume is the lowest.

The difference between the scenarios is mostly due to the height of the Rhine water level peaks. As the basin fills up if the water level in the Rhine is higher than the weir height and the water level in the basin, the peaks in the Rhine water level determine how full the basin gets. When looking at the moments the basin is filled by a Rhine peak, the 2050 G_L scenario reaches the highest level most of the times, followed by the historical and 2050 W_H scenario and lastly the reference scenario. This pattern can most clearly be seen in Figure 5.7 in 1973. Changes in precipitation and evaporation do not seem to have a clear influence on the final water balance as the volume decline follows more or less the same pattern. These observations seem to match the patterns that are shown in Section 4.2.2.

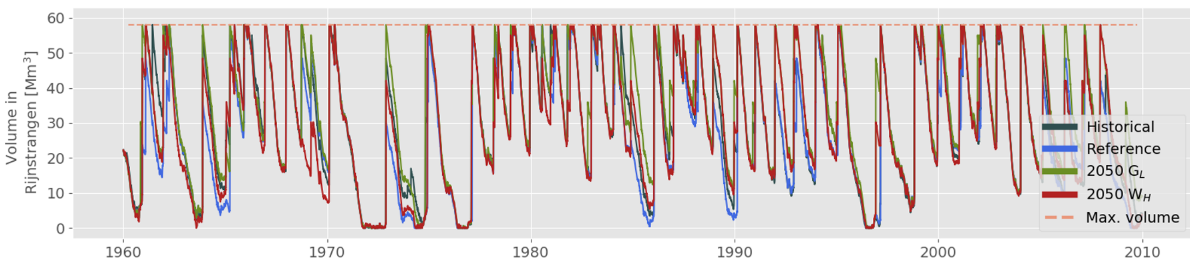


Figure 5.6: Water balance for the neutral situation, but with the four climate scenarios as variable. The historical climate scenario matches the neutral water balance (see Section 5.2.1). In general the basin is the fullest in the 2050 G_L climate scenario and in the reference scenario the basin volume is the lowest, as also shown in Figure 5.8.

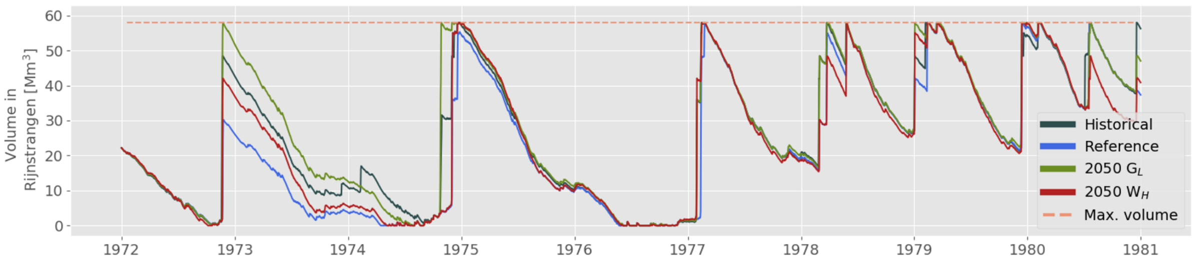


Figure 5.7: Detail of the water balance for the neutral situation, but with the four climate scenarios as variable. This detail shows the differences in filling height and timing for the different climate scenarios. In the 2050 G_L climate scenario the basin is filled highest (for example 1973 and 1979) and earlier (1975) than for the other climate scenarios.

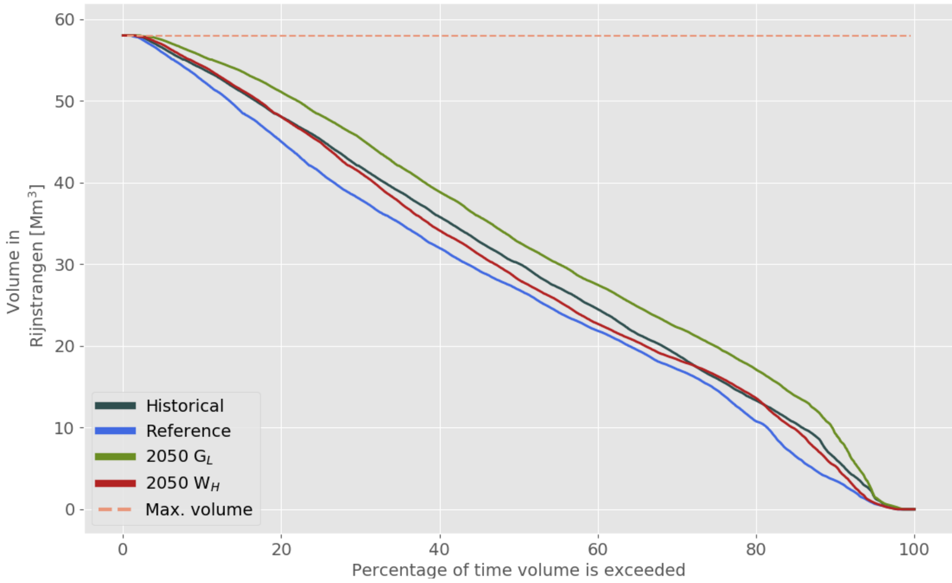


Figure 5.8: Volume duration curves for the water balance in the neutral situation, but with the four climate scenarios as variable. This volume duration curve corresponds to the water balance as presented in Figure 5.6. The basin is fullest in the 2050 G_L climate scenario and in the reference scenario the basin volume is the lowest.

5.2.3. Variable extraction volume

Figure 5.9 and Figure 5.10 show the water balance for a varying extraction volume (Q_{use}) as well as a detail of this water balance. Figure 5.11 shows the volume duration curve for the varying extraction volumes over the entire time span of the water balance. As was to be expected, the volumes in the basin are lower for higher extraction volumes.

The detailed figure (Figure 5.10) shows how the groundwater flux changes with varying water levels and extraction volumes. The groundwater outflow is high for a high extraction volume, as the extraction volume is part of the groundwater system. Also a high water level in the basin causes a high groundwater outflow due to the differences in head this causes. Yet, with high extraction volumes but low water levels in the basin, the groundwater outflow is still relatively high. This is due to the drawdown in the groundwater level that is caused by the groundwater extractions.

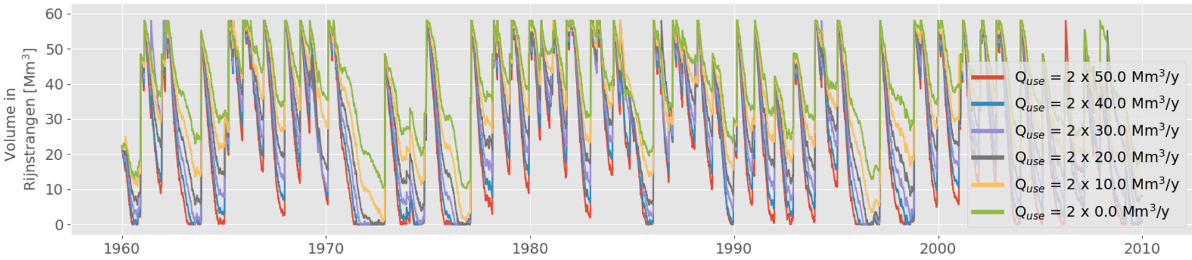


Figure 5.9: Water balance and corresponding fluxes with the extraction volume (Q_{use}) as variable.

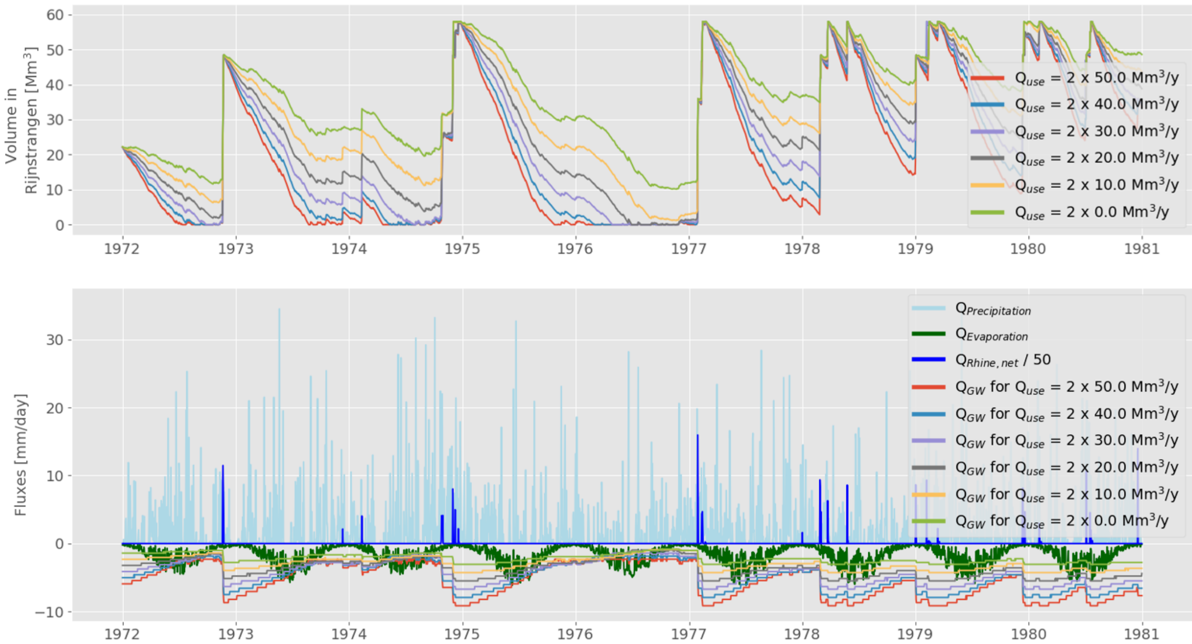


Figure 5.10: Detail of the water balance and corresponding fluxes with the extraction volume (Q_{use}) as variable. The river inflow and evaporation are given for the neutral situation.

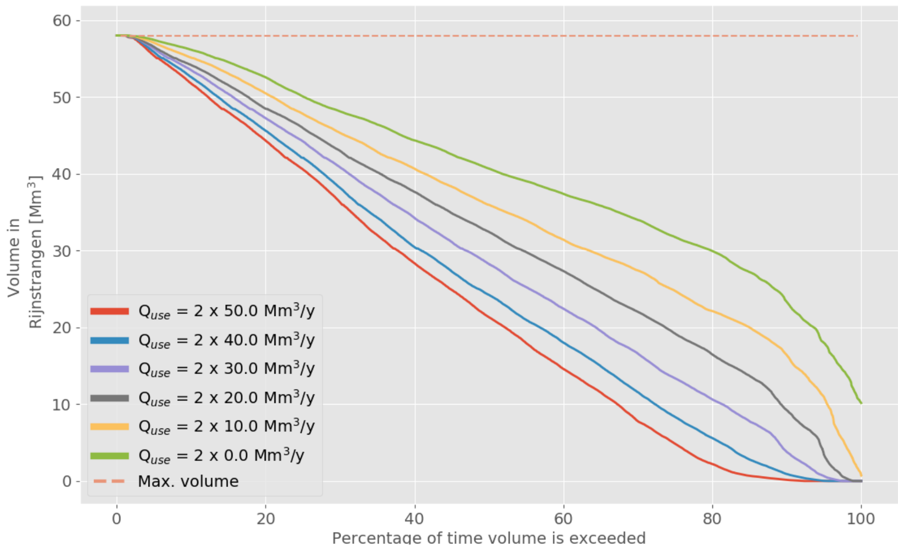


Figure 5.11: Volume duration curves for the water balance in the neutral situation, but with a varying extraction volume (Q_{use}). This volume duration curve corresponds to the water balance as presented in Figure 5.9. The volumes of the basin are highest for the lowest extraction volumes.

5.2.4. Variable maximum volume

The water balance with the maximum volume (V_{max}) as variable is shown in Figure 5.12, together with a detailed figure of this water balance in Figure 5.13. Interesting to see in these figures is that the higher the water level in the basin, the faster the decline of the volume in the basin. This fast decline is due to the coupling between the groundwater outflow and the water level. Due to this effect, even the water balances with the highest maximum volume run dry at some point. The number of dry days is reduced as shown in Figure 5.14, but dry days are not avoided with a high maximum volume. It can thus be concluded that allowing a higher maximum volume is not necessarily the solution to limiting groundwater extraction from the surrounding region. The groundwater outflow when the basin is full may however contribute to the (ground)water system of the region surrounding the Rijnstrangen.

In Figure 5.12 and 5.13 it can be seen that for a higher maximum volume the basin does not always reach its maximum level during Rhine inflow. This can be both due to a limited time interval that the Rhine water is high enough or due to the Rhine water level not being high enough at all.

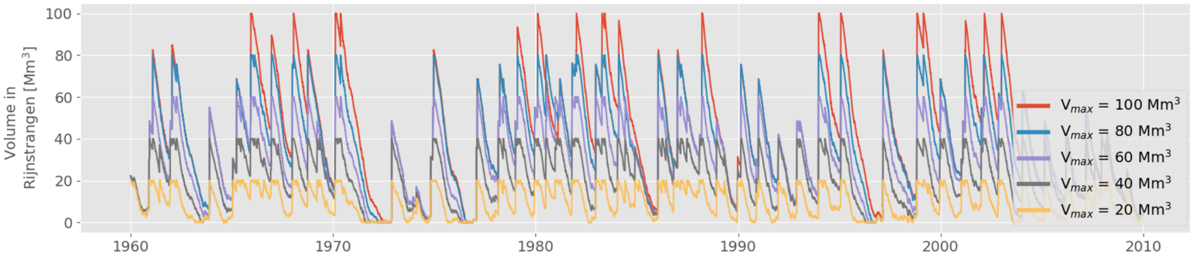


Figure 5.12: Water balance with the maximum volume (V_{max}) as variable.

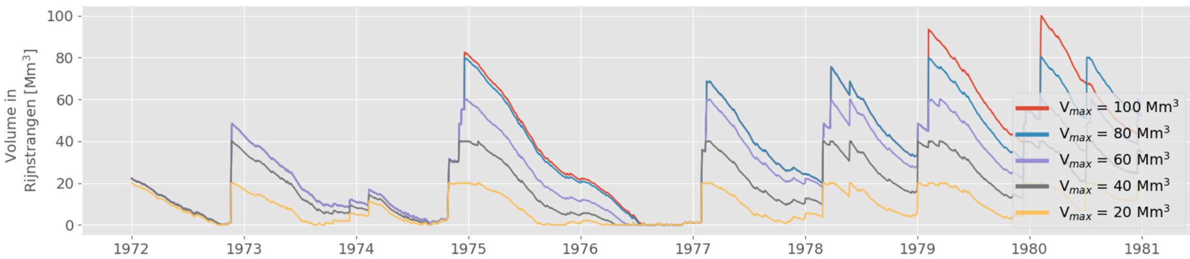


Figure 5.13: Detail of the water balance with the maximum volume (V_{max}) as variable.

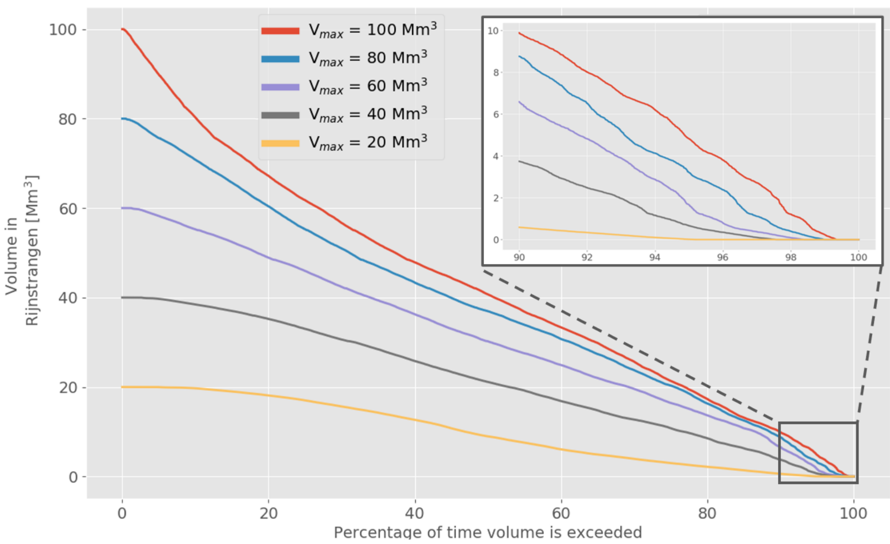


Figure 5.14: Volume duration curves for the water balance in the neutral situation, but with a varying maximum volume (V_{max}). This volume duration curve corresponds to the water balance as presented in Figure 5.12. Although this percentage is limited, also with a high maximum volume, the basin runs dry.

5.2.5. Variable weir width

Figure 5.15 shows the water balance for the weir width range as indicated in Table 4.1 of Section 4.3.1. In this figure it can be seen that the weir width in this range is not a limiting factor for the volume of the basin. Only in two cases the volume in the basin became higher due to a wider weir. Therefore, Figure 5.16 shows the effect of the weir width for a more limited range of weir widths up to 500 m. This figure shows that a weir width of around 100 m may be enough when working with the other variables in the neutral situation. This can be concluded as in most cases the line for a weir width of 100 m (purple) is the line for the highest volume, corresponding to the lines of wider weirs. This can also be seen in the detail of this water balance, which is shown in Figure 5.17. Just before the start of 1973 the difference between the various weir widths is most clear.

The finding that a weir width of 100 m is enough under the neutral circumstances is supported by Figure 5.18, which shows the duration curves for Figure 5.16. The duration curves show that the volume of the basin is almost similar for a weir width of 100 m, 250 m and 500 m.

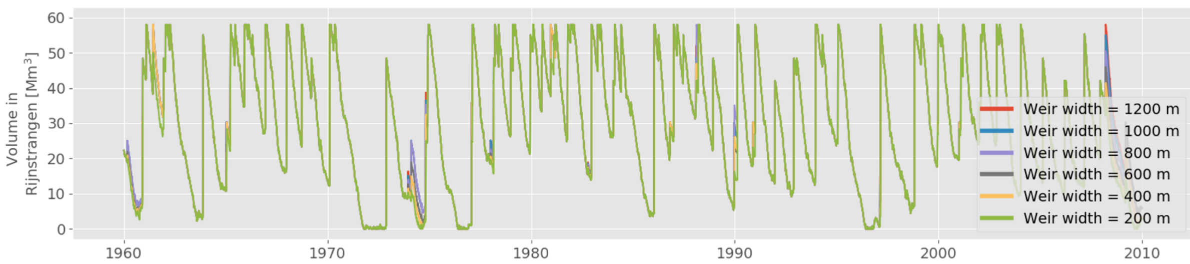


Figure 5.15: Water balance with the weir width as variable for the range of input values as defined in Table 4.1. Only two times in the time span of 50 years a weir width wider than 200 m is of added value as then the basin gets fuller with a weir width wider than 200 m.

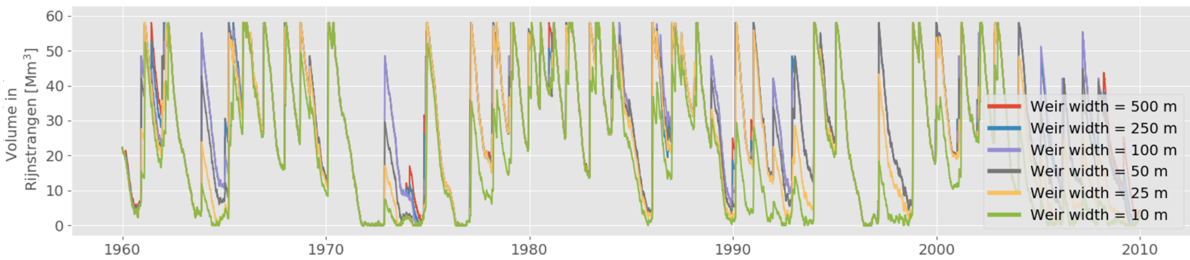


Figure 5.16: Water balance with the weir width as variable for widths under 500 m. See Figure 5.18 for the duration curves of these cases.

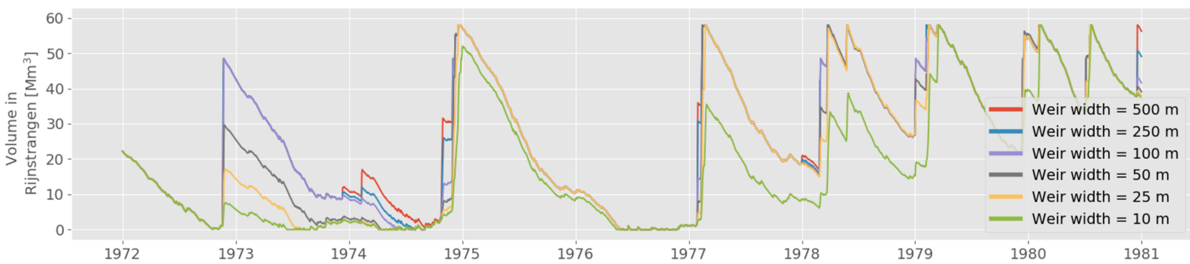


Figure 5.17: Detail of the water balance with the weir width as variable for the smaller range of input widths.

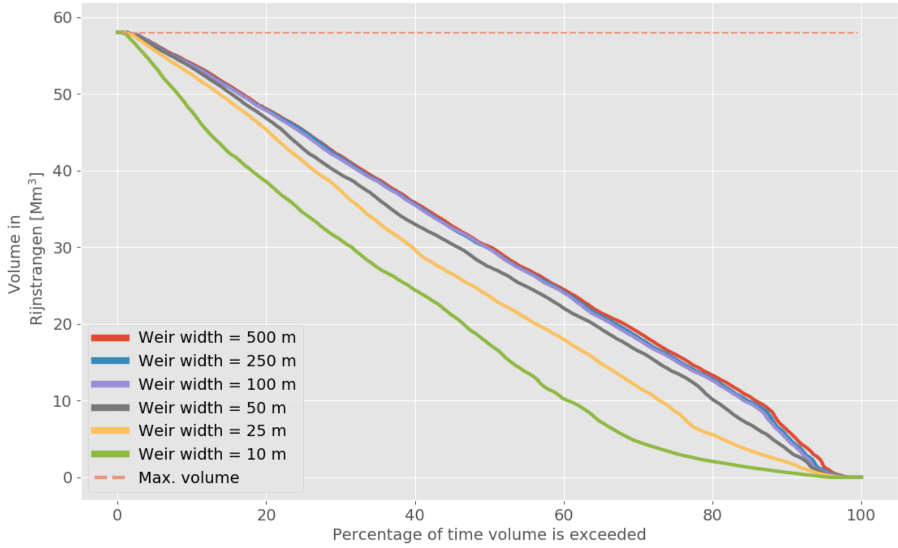


Figure 5.18: Duration curves for the water balance in the neutral situation, but with a varying weir width. This volume duration curve corresponds to the water balance as presented in Figure 5.16. The plot shows that a weir width of 100 m shows similar behaviour in terms of basin volume as a wider weir.

5.2.6. Variable weir height

The water balance for a variable weir height is shown in Figure 5.19. Figure 5.20 shows a more detailed plot of the effect of the weir height on the volume. In these figures, the volumes for a weir height of 10, 11 and 12 m +NAP are similar most of the time. The volume for a weir height of 13 m +NAP differs in some cases. Real differences start to occur for weir heights of 14 and 15 m +NAP, when inflow peaks start to pass without being able to fill the Rijnstrangen, as they do not reach over the weir. This finding is supported by Figure 5.21.

As can be seen in Figure 5.20, the timing of the peaks differs a bit per weir height, this is due to the build-up of the Rhine water level peaks, as shown in the figure as well. For example in November and December of 1974, the inflow happens first for the weir heights of 10, 11 and 12 m +NAP, a bit later the peak reaches over the weir height of 13 m +NAP and a little more later inflow for a weir height of 14 m+NAP happens. The water level never reaches 15 m +NAP, thus with this weir height the basin stays empty.

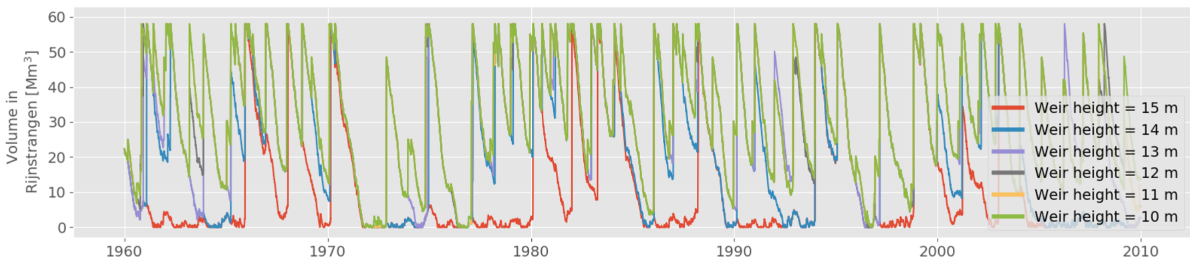


Figure 5.19: Water balance with the weir height as variable. Heights in meters above NAP.

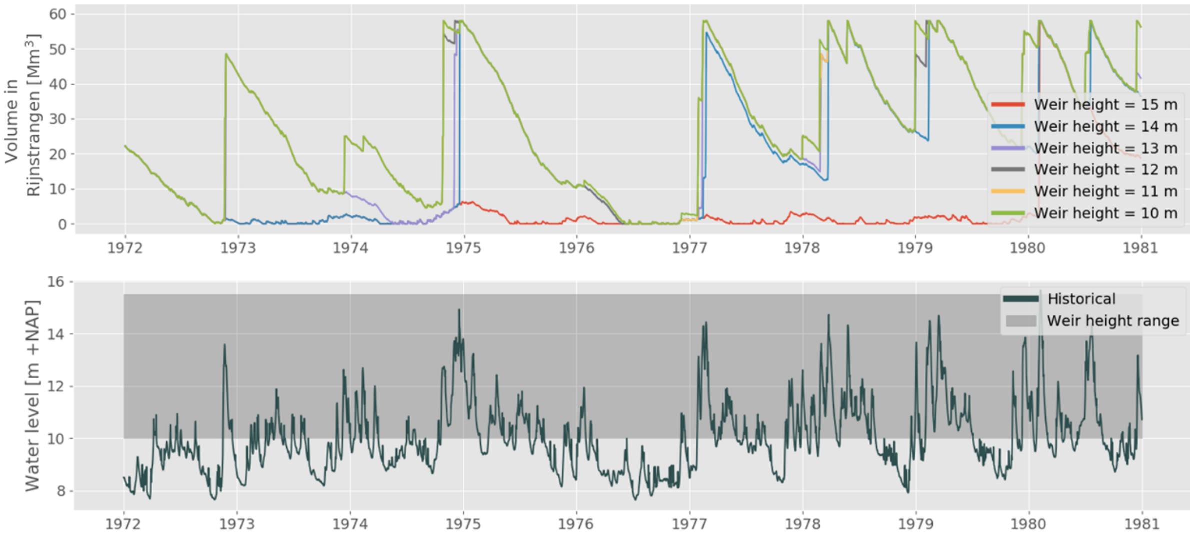


Figure 5.20: Detail of the water balance with the weir height as variable. Heights in meters above NAP. The water balance is plotted together with the water level in the Rhine to compare the inflow pattern to the water levels.

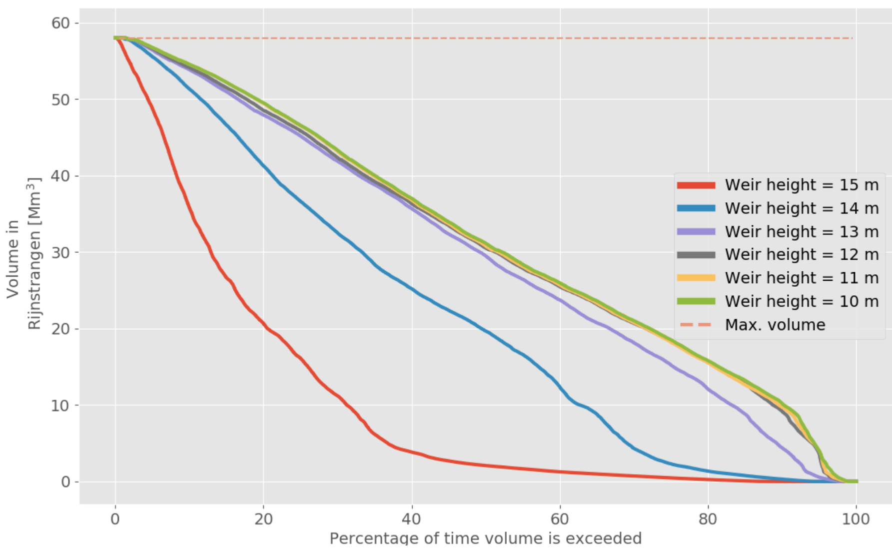


Figure 5.21: Duration curves for the water balance in the neutral situation, but with a varying weir height. This volume duration curve corresponds to the water balance as presented in Figure 5.19. The plot shows that weir heights up to 12 m show similar behaviour. With a higher weir Rhine peaks start to pass without being able to enter the Rijnstrangen.

5.3. Narratives

The water balance calculation is performed for the three narratives: Section 5.3.1 presents results of the local narrative, Section 5.3.2 those of the moderate narrative and lastly in Section 5.3.3 the results of the regional narrative are discussed. For all three calculations also the fraction of the extraction that originates from the region surrounding the Rijnstrangen is plotted. As defined in Section 4.3, this is the part of the extracted water that does not originate from under the Rijnstrangen. This part of the extraction will therefore be likely to put pressure on the groundwater system of the region surrounding the Rijnstrangen.

5.3.1. Local

In the local narrative, with a maximum volume of 7.7 Mm^3, a weir height of 11.5 m +NAP and an extraction volume of 4 Mm^3/y (2 x 2 Mm^3/y), the percentage of the extraction that originates from the region surrounding the Rijnstrangen is extremely low: only 1% of the extracted water does not originate from under the Rijnstrangen. Figure 5.22 shows the water balance for this narrative. The figure shows that in general the volume in the basin is high enough to extract all of the water from under the basin. Only when the volume in the basin drops below ± 1 Mm^3, which corresponds to a water level of around 10.5 m +NAP, part of the extraction comes from the region.

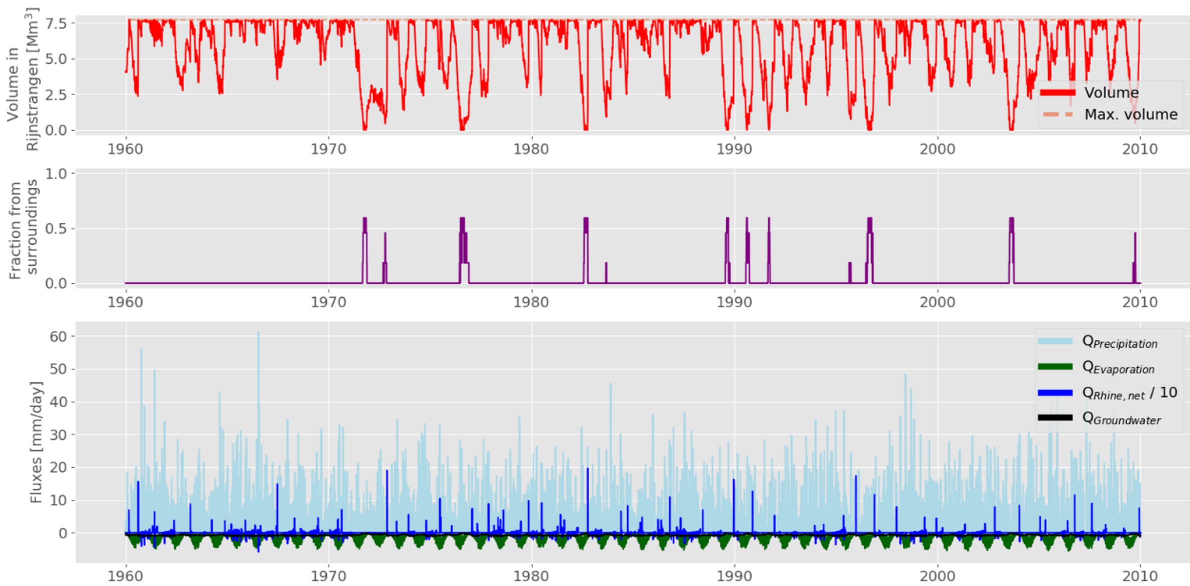


Figure 5.22: Water balance for the local narrative (a maximum volume of 7.7 Mm^3, a weir height of 11.5 m +NAP and an extraction volume of 4 Mm^3/y (2 x 2 Mm^3/y)). In this narrative over the years only 1% of the extracted water comes from the region surrounding the Rijnstrangen.

5.3.2. Moderate

Figure 5.23 shows the water balance for the moderate narrative. With a maximum volume of 22.3 Mm^3 and an extraction volume of 50 Mm^3/y (2 x 25 Mm^3/y) this narrative is very demanding when it comes to the extraction from the region surrounding the Rijnstrangen: on average 61% of the extracted water originates from the surrounding region. As shown in Figure 5.23 even with a full reservoir the extraction volume is too high to be delivered entirely by the Rijnstrangen with this maximum water level: a minimum of 30% of the extracted groundwater originates from the surroundings. At the same time, a maximum percentage from the region of around 75% can be observed. This maximum is due to the fact that a minimum surface water level in the Rijnstrangen of 10 m +NAP is maintained in the model. The result is that the water tables cannot drop enough to reach 100% extraction from the region (see also Item 2 in Chapter 6).

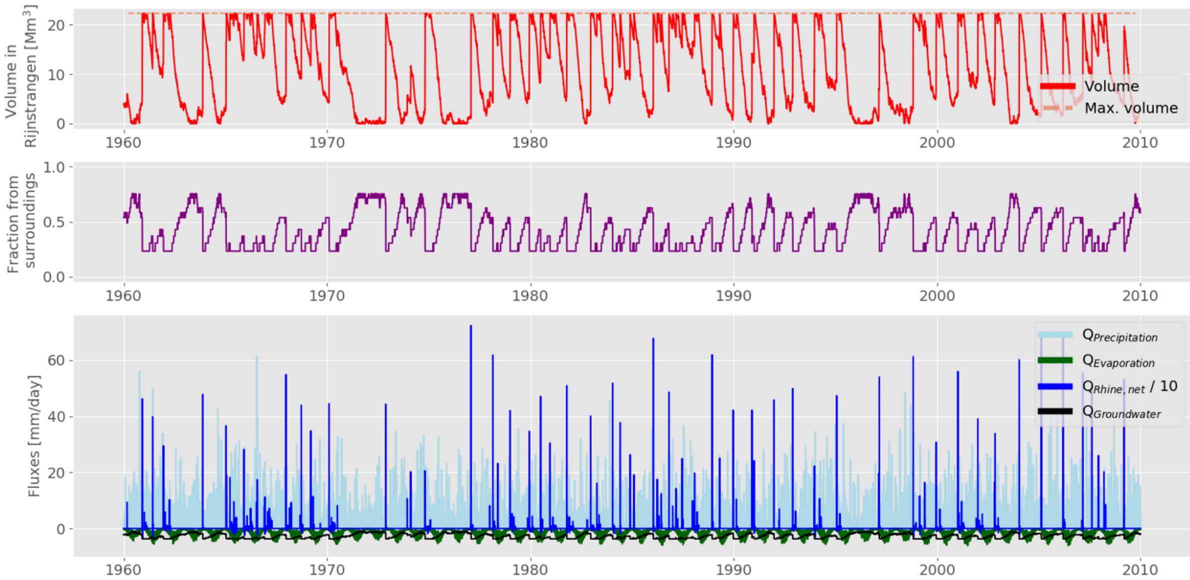


Figure 5.23: Water balance for the moderate narrative (a maximum volume of 22.3 Mm^3 and an extraction volume of 50 Mm^3/y (2 x 25 Mm^3/y)). In this narrative even a full Rijnstrangen is not able to deliver enough water for the extraction. On average 61% of the extracted 50 Mm^3/y originates from the region surrounding the Rijnstrangen.

5.3.3. Regional

In the regional narrative the maximum volume is 72 Mm^3 and the extraction volume is 114 Mm^3/y (2 x 57 Mm^3/y). In this narrative on average 65% of the extracted 114 Mm^3/y is originating from the region surrounding the Rijnstrangen. This 74 Mm^3/y (65% · 114 Mm^3/y) may put a lot of pressure on the groundwater system of the surrounding region. As shown in Figure 5.24, if the basin is full, the regional groundwater system does not have to contribute to the extraction, however as soon as the water level in the basin drops, water is extracted from the region as well.

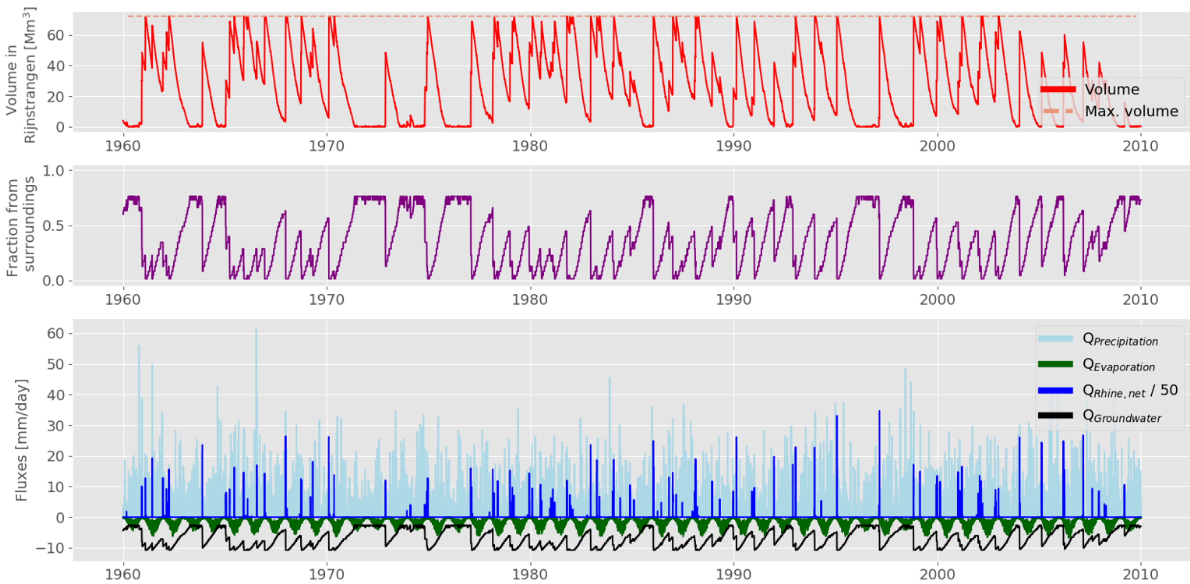


Figure 5.24: Water balance for the regional narrative (a maximum volume of 72 Mm^3 and an extraction volume of 114 Mm^3/y (2 x 57 Mm^3/y)). On average 65% of the extracted 114 Mm^3/y originates from the region surrounding the Rijnstrangen.

5.4. Extraction originating from the region around the Rijnstrangen

Besides the narratives, for every combination of parameters the average extraction percentage originating from the region surrounding the Rijnstrangen can be calculated. Figure 5.25 shows these percentages for a varying maximum volume of the basin (V_{max}) and extraction volume (Q_{use}). Here the climate scenario and weir configuration are in the neutral situation (historical time series, weir width = 500 m and weir height = 12.5 m +NAP). To obtain the absolute volume that is extracted on average from the surrounding region, the extraction volume has to be multiplied with the percentage corresponding to the parameter combination. For example, if an extraction volume of 50 Mm^3/y is requested and a maximum water level of 13.0 m +NAP is allowed, 30.8% · 50 Mm^3/y = 15.4 Mm^3/y is extracted from the surrounding region. Whether this is acceptable is not assessed in this study.

From Figure 5.25 it can be concluded that the maximum volume that can be extracted from the Rijnstrangen is a trade-off between the impact on the (ground)water system of the region surrounding the Rijnstrangen and the maximum allowed water level. The extraction volume determines how much other (problematic) extraction locations can be scaled down, whereas the extraction from the surroundings of the Rijnstrangen and the maximum water level in the basin determine the impact on, for example, local residents and nature. The maximum extraction volume thus depends on a lot of factors and an exact number can not be defined. A variety of ranges can however be given based on Figure 5.25. For example, with a range for h_{max} between 12.0 and 14.5 m +NAP and an accepted average extraction from the region of around 30% this would mean that the maximum extraction ranges from 20 Mm^3/y up to 100 Mm^3/y.

Water level (m +NAP)	10	10.5	11	11.5	12	12.5	13	13.5	14	14.5	15	15.5
V_{max} (Mm3) / Q_{use} (Mm3/y)	0.56	1.21	3.6	7.66	13.9	22.3	32.9	45.1	58.4	72.1	86.0	100.0
5.0 (2x2.5)	53.8	37.5	11.0	3.6	1.1	0.6	0.1	0.0	0.0	0.0	0.0	0.0
10 (2x5.0)	64.3	55.3	35.8	14.6	5.0	2.2	1.3	0.6	0.3	0.2	0.2	0.2
20 (2x10)	69.6	64.5	54.1	41.6	24.2	11.4	5.6	3.6	2.6	1.8	1.3	1.1
50 (2x25)	73.1	70.6	66.1	60.9	53.1	42.8	30.8	21.9	17.0	14.5	13.1	12.3
100 (2x50)	74.6	73.3	71.0	67.9	63.5	57.7	50.7	43.7	38.1	33.8	31.0	29.3

Figure 5.25: Percentages of extracted groundwater originating from the region around the Rijnstrangen for a varying maximum volume in the basin (V_{max}) and extraction volume (Q_{use}).

The overview as presented in Figure 5.25 can be made for any combination of variables and any time span. Figure 5.26 shows a simplified version of Figure 5.25 as well as the same overview for three variations. The first variation (Figure 5.26b) is a limited time span from 1970 to 1980. In the neutral water balances as depicted in Figure 5.3, as well as in the variations on the neutral water balance, in these years the water level in the basins seems low on average. This low water level is reflected in higher percentages of extracted groundwater originating from the region around the Rijnstrangen. The differences between Figure 5.26a and 5.26b reach up to 10 percentage points.

Figure 5.26c shows the percentages of extracted groundwater originating from the region around the Rijnstrangen for the time span of 1980-1990. In general, in these years the water levels in the basin are high, as shown in Figure 5.3, as well as in the variations on the neutral water balance. The differences between Figure 5.26a and 5.26c reach -10 percentage points. Lastly, Figure 5.26d shows the percentages extracted from the region of the Rijnstrangen for the entire time span of the water balance, but for the climate scenario 2050 G_L instead of the historical climate. This climate scenario is taken in the comparison with the neutral situation as Section 5.2.2 shows that 2050 G_L is the climate scenario in which the basin is generally the fullest. The differences between Figure 5.26a and 5.26d reach maximum 5 percentage points.

Water level (m +NAP)	10	11	12	13	14	15
V_{max} (Mm3)	0.56	3.6	13.9	32.9	58.4	86.0
Q_{use} (Mm3/y)						
5.0 (2x2.5)	53.8	11.0	1.1	0.1	0.0	0.0
10 (2x5.0)	64.3	35.8	5.0	1.3	0.3	0.2
20 (2x10)	69.6	54.1	24.2	5.6	2.6	1.3
50 (2x25)	73.1	66.1	53.1	30.8	17.0	13.1
100 (2x50)	74.6	71.0	63.5	50.7	38.1	31.0

(a) Neutral situation with varying V_{max} and Q_{use} for the entire time span of the water balance.

Water level (m +NAP)	10	11	12	13	14	15
V_{max} (Mm3)	0.56	3.6	13.9	32.9	58.4	86.0
Q_{use} (Mm3/y)						
5.0 (2x2.5)	54.1	15.0	2.4	0.4	0.0	0.0
10 (2x5.0)	64.5	39.3	10.7	4.0	0.2	0.0
20 (2x10)	69.8	56.3	30.9	13.5	6.5	1.9
50 (2x25)	73.3	67.4	57.3	40.8	27.7	21.9
100 (2x50)	74.7	71.8	66.6	57.5	47.1	41.3

(b) Neutral situation with varying V_{max} and Q_{use} for 1970 - 1980. In these years the water levels in the basin are relatively low compared to the entire time span of the water balance.

Water level (m +NAP)	10	11	12	13	14	15
V_{max} (Mm3)	0.56	3.6	13.9	32.9	58.4	86.0
Q_{use} (Mm3/y)						
5.0 (2x2.5)	53.8	10.2	0.1	0.0	0.0	0.0
10 (2x5.0)	64.3	34.7	2.2	0.0	0.0	0.0
20 (2x10)	69.7	53.2	17.9	0.8	0.0	0.0
50 (2x25)	73.1	65.1	48.3	20.8	7.1	6.8
100 (2x50)	74.5	70.2	59.6	42.2	27.7	20.2

(c) Neutral situation with varying V_{max} and Q_{use} for 1980 - 1990. In these years the water levels in the basin are relatively high compared to the entire time span of the water balance.

Water level (m +NAP)	10	11	12	13	14	15
V_{max} (Mm3)	0.56	3.6	13.9	32.9	58.4	86.0
Q_{use} (Mm3/y)						
5.0 (2x2.5)	53.7	10.1	0.9	0.1	0.0	0.0
10 (2x5.0)	64.2	34.8	4.2	0.9	0.0	0.0
20 (2x10)	69.6	53.3	22.7	4.3	1.5	0.5
50 (2x25)	73.0	65.4	52.3	29.1	14.1	8.6
100 (2x50)	74.5	70.6	62.9	49.4	34.7	26.5

(d) Climate scenario 2050 G_L with varying V_{max} and Q_{use} for the entire time span of the water balance.

Figure 5.26: Percentages of extracted groundwater originating from the region surrounding the Rijnstrangen for a varying maximum volume in the basin (V_{max}) and extraction volume (Q_{use}) and variations in parameters.

6

Discussion

With the water balance calculations of the Rijnstrangen, the potential contribution of the Rijnstrangen as retention reservoir for drought mitigation in the eastern part of the Netherlands is mapped. In Section 6.1, the consequences and limitations of these results are discussed, as well as remarks regarding the limitations of the methodology in general. This section is split up in Section 6.1.1, in which aspects related to the groundwater flow are discussed, and Section 6.1.2 in which points related to the evaporation, precipitation and these datasets are covered. Subsequently, suggestions for implementation and further research are presented in Section 6.2, covering suggestions for design, alternatives for low water levels in the basin and subjects to study besides the water quantity related aspects. The items are numbered for communication purposes and clarity, the numbers do not indicate a prioritization.

6.1. Limitations of the applied methodology

6.1.1. Groundwater

1. It is assumed that the groundwater (out)flow does not change under the applied climate change scenarios. This is only true if the groundwater tables remain unchanged. With drier summers however, it is likely that the groundwater tables in the region decline. This change may be minimal, as the surface water levels are managed in the area. Still, this assumption is something to keep in mind, as it is shown in Appendix C that the groundwater model is relatively sensitive to the surface water levels in the region: the water levels in the Rijnstrangen and its adjacent sections (sections 2, 3 and 4) are the top three most influential parameters of the groundwater model.
2. With the current groundwater model and input values, the extraction from the region surrounding the Rijnstrangen never reaches 100% at low water levels in the basin. This is due to the modelling choice that the basin is empty (volume = 0 Mm^3) at a water level of 10 m +NAP, corresponding to the lowest land elevation. In the model the (ground)water level can not drop further. Improving this would be one of the first things I would look into in further research, as the feasibility assessment depends on this outcome.
3. In the groundwater model, one cross-section is assumed to be representative for the entire Rijnstrangen. This assumption is probably not entirely accurate due to heterogeneity. For example variations in the top layer are present, as shown in Appendix A.2 (especially Figure A.4). This causes (locally) varying groundwater flow patterns and areas with more or less infiltration than for the average situation. Moreover, the presence of the Montferland (southeast of the Rijnstrangen) causes disturbance of the groundwater flow and direction. Around the Montferland the elevation and groundwater levels are generally higher, which causes flow in northwesterly direction from

the Montferland to the lower regions around the IJssel. In the groundwater model the groundwater flow can only occur along the chosen cross-section, which is perpendicular to the Rijnstrangen. This assumption thus is an extreme simplification.

4. As the cross-section in the groundwater model is assumed to be representative for the entire Rijnstrangen, the groundwater extraction takes place along the entire length of the basin. In practice a strip with extraction wells on both sides of the Rijnstrangen, which is around 12 km long, will be hard to realise. It is more likely that a couple of well fields will be realised. With the same extraction volume this causes larger drawdowns of the groundwater table around these wells.

5. The groundwater system is simplified to a system with only one aquifer. In reality there are two more aquifers below the thick clay layer that is taken as the geohydrological base. The results of the multi-layer system are compared to the results of the one-layer system, as shown in Appendix B. The differences in outflow between both situations are maximum 5%, whereas the variables of the water balance can cause differences in the groundwater flow well over 100% (see for example Figure 5.10). Therefore, I decided that creating the precision of the multi-layer system would not be of added value in this stage of the research.

6.1.2. Precipitation and evaporation

Precipitation

6. The daily inflow into the reservoir due to precipitation is calculated by multiplying the daily precipitation depth with the total area of the Rijnstrangen (28.6 km^2). The inundated area is not taken into account here as it is assumed that all water contributes to the total volume of water in the Rijnstrangen. In reality it may take time (more than the time step of one day) for water that falls on land to end up in the water body. This effect is not taken into account now.
On average 190 mm/year of the 826 mm/year precipitation (23%) falls on land and experiences this delay, as for the neutral situation and for the entire time span of the water balance calculation (1960-2009), the average dry area is 6.6 km^2 of the total 28.6 km^2 (23%).

Evaporation

7. In the water balance used in this study, the evaporation from the Rijnstrangen is split up in two types: evaporation from land and evaporation from open water, both with their own correction factors (see Section 4.1.4). I want to address two topics about the correction factors.

   a. Differences between the Makkink evaporation (including the applied correction factors) and the actual evaporation may be present as the reduction factors could not be validated. Differences between the theoretical and actual evaporation may for example be present due to the fact that Makkink evaporation is originally for summer situations and for energy-limited situations (enough water available). Also, (local) differences may occur due to the type(s) of vegetation as an average has been estimated.
   b. The evaporation flux could be made more precise by adding a reduction factor for dry periods. For example, when it has not rained for 10 days, an additional factor for the evaporation from land can be used, accounting for a reduction of evaporation due to a (more) water-limited evaporation. Also, the vegetation correction factor could be varied over the year, dependent on the seasonal vegetation.

   Both Item 7a. and 7b. would not be my priority in further research as I expect changes in the total water balance to be minimal with these additions.

8. The evaporation flux of the water balance is calculated based on the Makkink evaporation. The Makkink evaporation is the most common choice in the Netherlands, however recent research of Jansen and Teuling (2020) shows that Makkink is unable to reflect the actual evaporation. In a discussion I had with one of the authors of the paper (Femke Jansen, personal communication, June 8, 2021), she stated that for daily estimations of evaporation it would be best to use a method that takes into account water temperature and wind speed. A method that uses the vapor pressure gradient and wind speed could be a good alternative. The author also stated that the Makkink

method may give an acceptable result (especially on long timescales), however this is probably coincidence with the parameters instead of a correct method.
I have studied alternative methods, but for all of them crucial information is missing to apply them to the Rijnstrangen. For example the method of Granger and Hedstrom (2011) seems a good option. However, this method requires horizontal gradients (land vs lake) of temperature and vapour pressure. This data is not available and estimating it would not provide a valuable result. There are also methods (for example De Bruin and Keijman (1979)) that require water temperature (which is not available either), or coefficients that have to be estimated.

Datasets

9. As presented in Section 4.2, the (projected) evaporation and precipitation data for De Bilt is assumed to be representative for the Rijnstrangen. This assumption is made based on the work of Buishand et al. (2009). An update of Buishand et al. (2009) and the projected evaporation and precipitation datasets is presented by Beersma et al. (2019) based on the newest insights about climate change and the precipitation regimes. Here the Rijnstrangen still is in the G region, which indicates that the data for De Bilt is representative. Unfortunately, the updated evaporation data was not available and therefore the old projected data has been used in this research for both the evaporation and precipitation for consistency. In future research the new data could easily be implemented in the water balance calculation when available.

10. Despite Buishand et al. (2009) and Beersma et al. (2019) indicating that the data for De Bilt can be assumed to be representative for the Rijnstrangen, there are differences in the historically observed data. This is presented in Figure 6.1, which shows the average evaporation and precipitation for De Bilt and the four meteorological stations surrounding the Rijnstrangen. As shown in the figure, the precipitation in De Bilt is higher than the average of the stations surrounding the Rijnstrangen (indicated as *Rijnstrangen*) and the evaporation is a slight bit lower in De Bilt than the average of the stations surrounding the Rijnstrangen. Dependent on the season, the actual precipitation in the Rijnstrangen might thus be slightly lower than is accounted for in the water balance calculation of this study.

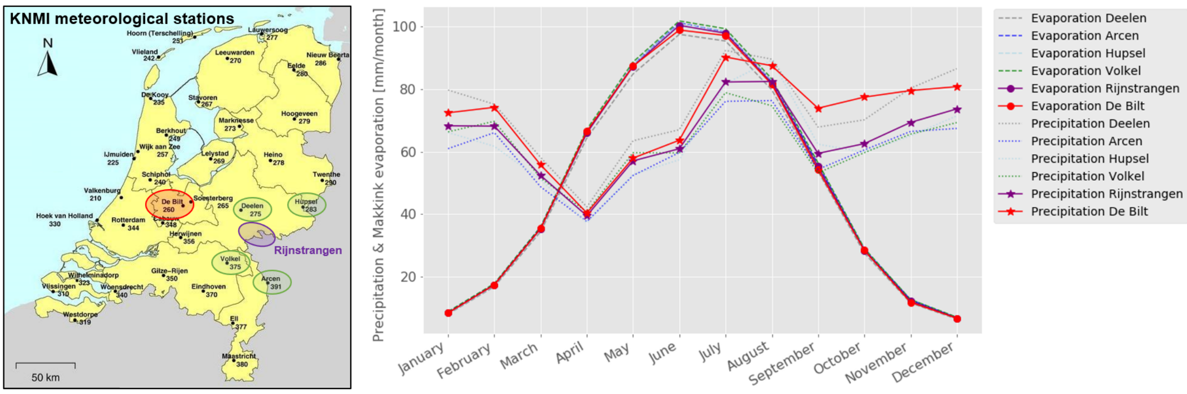


Figure 6.1: Comparison of the average precipitation and evaporation data of De Bilt and the Rijnstrangen, including the locations of the meteorological stations of the KNMI on the left. Despite Buishand et al. (2009) and Beersma et al. (2019) indicating that the precipitation data for De Bilt can be assumed to be representative for the Rijnstrangen region, the comparison of these historical datasets shows that the precipitation in the Rijnstrangen has been lower than in De Bilt. Left figure adapted from Vreeken, B. (n.d.), data for right figure retrieved from `knmi.nl`.

11. The implementation of the used datasets for the reference climate and the projected climates of 2050 are a first indication of how the basin may behave. These datasets however are adjusted historical datasets that follow the exact same pattern as the original observations, but with a correction factor. In reality, other aspects may change as well, like the duration of peaks or the timing of events. Implementing alternative methods to predict future behaviour of the basin may therefore give different insights.

6.2. Suggestions for implementation and further research

6.2.1. Design of the Rijnstrangen

Landscape

7. When making good use of the landscape that is already present in the Rijnstrangen, the plans for the retention reservoir would fit best in the landscape and the area can be used most effectively. Three suggestions for this are:

   a. Take into account the effect of the existing old summer dikes. This effect is neglected now, however these old dikes can cause shallow lakes and alternative filling patterns. This can have negative effects for the water quality or any expected flow in the area. However, it can also have positive effects, for example for infiltration and nature. These old dikes can also be made use of, as explained in Item 7b.

   b. At low water levels, it would be possible to save some areas for seasonal agriculture or recreation. This could be done by forming multiple smaller basins that can for example be formed by the old dikes. Alternatively, a system comparable to a sawas (rice fields) could be used (Twan Rosmalen, personal communication, May 20, 2021).

   c. In the southeast of the Rijnstrangen, basins are present where clay and sand have been excavated. In these areas, the resistance of the top layer will probably be very low, which reduces the effectiveness of the retention area as water leaks from the basin to the aquifer here very fast. It would be best to exclude these areas from the retention area, or create a new (natural) clay layer.

Combination of drought mitigation and flood risk reduction

8. Using the Rijnstrangen retention reservoir for a combination of drought mitigation and flood risk reduction appears to be a promising option. This would be a combination of the idea studied in this thesis and previously studied possibilities for the Rijnstrangen (see for example Pol et al. (2017)). The combination of both could make the plans more feasible, as costs are shared between the two goals. Yet, good management of the combined use of the reservoir would be essential to make optimal use of the available volume. For example, to be able to retain part of a Rhine discharge peak and thus contribute to water safety, the basin would have to be (partially) empty when the discharge peak is predicted. For optimal groundwater extraction however, the reservoir volume needs to be maximized. The management and costs of the combination of these plans would be interesting to look into in further research.

9. In the combined use of the Rijnstrangen for drought mitigation and flood risk reduction, as described in Item 8, a suggestion would be to look into the option to use the Rijnstrangen only up to, for example, 12.0 m +NAP for drought mitigation, as this allows for partial use of the area for other functions. The remaining part of the Rijnstrangen would then only be used for extreme cases of flood prevention. In this case no permanent buildings would be allowed in the region, but agriculture and nature could have space above the maximum water level for drought mitigation.

Inlet

10. In the current design of the Rijnstrangen it is assumed that the inlet is closed when the water level on the Rhine gets higher than the maximum allowed water level in the Rijnstrangen. This is mainly done for water safety. The same holds if the water level in the Rijnstrangen is higher than the inlet and the water level in the Rhine. In this case the water is kept in the basin by closing the inlet. This active management of the inlet requires further research. In this further research it would be interesting to also look into (alternative) types of inlets that could work in this situation, in combination with the desired management. For example, a system with pipes or any type of sluice could be better for this situation.

Asymmetrical groundwater extraction

11. Something that is not looked into in detail in this study, but that would be possible with the current Python script (see De Vries (2021) for the repository) is to investigate the feasibility of asymmetrical groundwater extraction. It could be feasible to extract more water on the left (southwest) of the Rijnstrangen, as here the groundwater can be recharged by the water of the Rhine. For example 75% of the total groundwater extraction could take place on the southwesterly side of the Rijnstrangen and the other 25% could come from the northeasterly side. The quality of the extraction would be something to look into in further research, as the filtering by the ground could be less effective for water flowing relatively quick from the Rhine to the extraction location.

Flow through the Rijnstrangen

12. It would be interesting to investigate the option to have flow through the Rijnstrangen area, as this flow may have positive as well as negative consequences for ecology. Also, flow through the Rijnstrangen will have an effect on the surface water quality. This effect may be positive as well as negative, as it avoids still-standing water, but the Rhine may have contamination peaks. An option would be to be able to close off the inlet if bad quality Rhine water is expected.

13. With flow through the Rijnstrangen it will be possible to (slightly) alter the water distribution at the Pannerdensche Kop, as shown in Figure 6.2. It would be a topic of further research whether bringing more water to the Lower Rhine (northward from the bifurcation at the Pannerdensche Kop) would be beneficial, for example as a solution to low water levels in the IJssel.

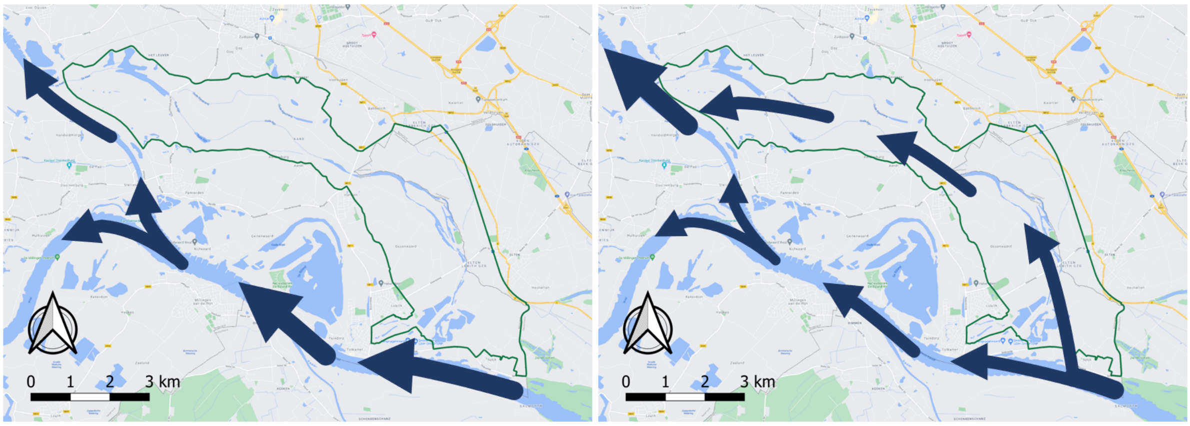


Figure 6.2: Altering the water distribution at the Pannerdensche Kop: with flow through the Rijnstrangen more water can be lead to the Lower Rhine (northward from the bifurcation), instead of the Waal (southward from the bifurcation).

6.2.2. Low water levels in the basin

Alternatives at low water levels in the Rijnstragen

14. In dry years, a big part or even all of the extracted water can come from the region surrounding the Rijnstrangen and not from the groundwater system of the Rijnstrangen itself. When this happens and how often depends on the scenario and parameters chosen. The consequences of this are not mapped it this study, but would give relevant insights. If a high extraction volume from the region around the Rijnstrangen is not desirable, the Rijnstrangen extraction volume should be lowered, requiring a variable Q_{use} in the model and extraction locations that were scaled down with the implementation of the Rijnstrangen to temporarily come into action. This may be acceptable, as the regions around these extraction locations are relieved during other periods. It would be interesting to investigate when the extraction of the Rijnstrangen should be scaled down and what the effect is of (temporarily) scaling up the other extractions.

15. An alternative to scaling down the extraction volume at low water levels in the basin, as described in Item 14, is to investigate the option to pump up water from the Rhine into the Rijnstrangen. Something similar is done in the Biesbosch, where water from the river Meuse is pumped into three basins to produce drinking water. When looking into this alternative, it would be important to keep in mind the water distribution ranking system (verdringingsreeks).

Rijnstrangen for extraction in the winter only

16. A suggestion done by a hydrologist at the Province of Gelderland is to use the Rijnstrangen only as retention reservoir in the winter (Teun Spek, personal communication, May 28, 2021). For half of the year the water level in the Rijnstrangen could then be raised to 11.2 m +NAP, which is slightly higher than the current water level of 10.4 m +NAP and a feasible water level according to the hydrologist. During this period, water could be extracted around the Rijnstrangen and nature could benefit from the high water. At the same time, this would allow the groundwater tables at the normal extraction locations to recover. During summer, the water level would be lowered again to the current level(s) to allow for the normal use of the area, with recreation and agriculture. To me this option seems promising when looking at the stakeholders in the area. However, the volumes that can be extracted at 11.2 m +NAP without putting pressure on the water system of the region are low. This balance of impact and low extraction volumes could work, but further research into this trade-off is needed to asses its feasibility.

6.2.3. Other subjects for further research

17. This study focused on water quantity related aspects of using the Rijnstrangen as retention reservoir for drought mitigation, however much more topics can be and have to be investigated before the idea can be put into practice. Suggestions of topics to study further are:

    a. **Water quality**. This determines, for example, the possibilities (and costs) of using the infiltrated Rhine water for drinking water production. The consequences of the plans for agriculture and nature depend on the water quality as well. Topics to cover would for example be the quality of the Rhine water, especially during discharge peaks, and the effect of retention and infiltration on the quality.

    b. **Costs**. A cost-benefit analysis of a variety of options will be crucial to support decision making. The suggestion done in Item 8 could make the plans more feasible.

    c. **Stakeholder involvement**. As shown in Chapter 2, the Rijnstrangen has many stakeholders like local residents and farmers and is protected under the EU Habitats and Birds Directives. Also recreation and residents of the villages nearby are important to take into account. A study into the many people, groups, organisations and governmental institutions that have their share in decision making would give valuable insights for implementation of the plans.

    d. **Water management strategies**. This includes for example the management of the inlet, any managed weirs in the basin (if present, for example as suggested in Item 7), or pumps (as suggested in Item 15). When a combination of drought mitigation and flood risk reduction is implemented, as suggested in Item 8, the management of the reservoir is very important as well.

    e. **Consequences for nature**. Dependent on the design choices and management strategy, different types of nature will thrive or disappear. Studying this would give valuable insights to support decision making.

7 Conclusions and recommendations

The aim of this study was to explore how retention of Rhine water in the Rijnstrangen can contribute to drought mitigation in the eastern part of the Netherlands. To answer this question a water balance of the Rijnstrangen as retention area has been set up. With this water balance the dynamics of the system are mapped by systematically varying the five variables of the system: the weir height, the weir width, the maximum volume in the basin, the groundwater extraction volume and the climate scenario. The climate scenarios implemented to test the system for potential future situations are the historical climate, the current climate, the climate of 2050 for the moderate KNMI'14 climate scenario (G_L) and lastly the the climate of 2050 for the high-end KNMI'14 climate scenario (W_H).

From the water balance calculations it can be concluded that groundwater extraction around the Rijnstrangen as retention reservoir can contribute a significant volume to the drinking water production in the region. This volume realistically ranges up to around 100 Mm^3/y, dependent on the accepted groundwater extraction originating from the region surrounding the Rijnstrangen, the maximum allowed volume in the reservoir and, to a lesser extent, the weir configuration and climate scenario. This maximum of 100 Mm^3/y equals 75% of the drinking water production of the Dutch province Gelderland, in which the Rijnstrangen is located. Such an extraction volume allows for closing or scaling down of other extraction locations that experience problems due to a changing climatic situation, for example increasing drought issues. As the groundwater around the Rijnstrangen is recharged by the reservoir with Rhine water, the extraction locations next to the retention reservoir will not experience these problems, or to a lesser extent. Therefore, drought related problems in the eastern part of the Netherlands can be reduced by implementing the concept of the Rijnstrangen as retention reservoir in combination with extraction locations.

From this study it can be concluded that the variables that have the most impact on the water balance calculation are the extraction volume, the maximum volume in the reservoir and the weir height. The weir width only starts to significantly change the inflow pattern when under 100 m wide, whereas a stretch of dike over 1 km is available. Furthermore, the climate scenarios have a relatively small effect compared to the other variables. This is an interesting finding, as climate change will enhance the problems the Rijnstrangen reservoir offers a solution to. With the effect of climate change on the dynamics of the reservoir being limited or even positive, the perspective of using the Rijnstrangen will become more feasible in the future.

Combining the benefits the Rijnstrangen as retention reservoir can have for drought mitigation with its added value for flood risk reduction in the Rhine appears to be a promising option for implementation. Therefore, it is advised to investigate this option in further research. By combining these two types of use of the reservoir, the costs in terms of price and nuisance are shared, which makes both strategies more feasible. When combining the use of the reservoir, a good volume management of the reservoir is essential to make optimal use of the area. This is needed as the reservoir volume needs to be maximized for the groundwater extraction, whereas the reservoir needs to be empty to take up a Rhine peak in order to reduce flood risk.

When investigating the option of using the Rijnstrangen as retention reservoir in more detail, the effect of years with a low volume in the basin should be looked into as well. If the extraction volume is kept constant, in these years a high percentage of the extraction is coming from the region surrounding the Rijnstrangen. If this is not desirable, the extraction volume of the Rijnstrangen should temporarily be lowered, requiring other extraction locations to come into action. An alternative is to investigate the option to pump up water from the Rhine into the Rijnstrangen, while considering the water distribution ranking system (verdringingsreeks).

Besides the extraction volumes, it would be interesting to consider how the volumes of water fit into the landscape of the Rijnstrangen to use the area most effectively. Especially at lower water levels, multiple functions could have space in the area when working with a stepwise filling system of separate basins or segments similar to rice fields. Another consideration would be to create flow through the area, which affects water quality and chances for nature.

It can be concluded that from a water quantity perspective the idea of using the Rijnstrangen is a viable possibility to contribute to drought mitigation in the eastern part of the Netherlands. Yet, (spatial) details of the implementation and aspects such as management strategies, consequences for nature, water quality aspects, societal support and costs should be considered before final conclusions can be drawn about the over-all feasibility of the Rijnstrangen as retention reservoir.

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A

Analysis of characteristics for the groundwater model

Each cell in the *nSec* by *nLay* cross-section for the groundwater calculations has its own characteristics. For the clay layers this is the hydraulic resistance, for the sand layers this is the transmissivity and for the top layer this is the hydraulic resistance plus the drainage resistance. Besides these characteristics each section has a surface water level on top of it. In this appendix the analysis used to determine the values as shown in Figure 4.6 is presented.

A.1. Surface water levels

The surface water levels per section are determined using the available surface water measurements, as collected by the water board (WRIJ, 2021), and the target water levels in the different areas (WRIJ, n.d.-d). The average surface water levels as used in the calculation of the groundwater flux are presented in Table A.1. Per section a brief explanation is given.

Table A.1: Surface water levels per section along the cross-section as presented in Figure 4.3. To be used in the groundwater calculations.

Section	**1**	**2**	**3a**	**3**	**3b**	**4**	**5**
	Rhine			*Rijnstrangen*			
Average surface water level [m+NAP]	9.2	9.8	9.8	10.4	9.7	9.7	9.1
Remarks	*Range: 6.9 - 16.9 m +NAP.*	*Highly dependent on Rhine.*		*Current range: 10.0-10.7 m+NAP*			

The surface water level in section 1 is the water level in the Rhine. The cross-section runs through the Pannerdensche Kop, where the water level is monitored by Rijkswaterstaat. The average water level at this location is 9.2 m +NAP.

In section 2, the surface water level is highly dependent on the water level in the Rhine. The big lake in this area, de Bijland, has a direct connection with the Rhine, which is not the case for the smaller lakes. The average surface water level taken for this area is 9.8 m +NAP, which is the average water level of the Rhine averaged with the current average water level of the Rijnstrangen (section 3), as the area is right in between them.

The surface water level in section 3 represents the situation in the Rijnstrangen. In the situation without the retention reservoir this surface water level is regulated as described in Section 2.6. The average value of these levels is 10.4 m +NAP. When adding the retention reservoir, this water level will fluctuate over time. Section 3a and 3b have the same surface water level as their adjacent sections, which are section 2 and 4 respectively. This water level is however hardly of influence, as is explained in Appendix A.2.

In section 4 and 5 the surface water level is managed, like in the Rijnstrangen. The water levels upstream and downstream of two weirs along the cross-section are available (see Figure A.1). These weirs regulate the levels in the area. The average water level upstream of weir A is taken as the surface water level in section 4, this is 9.7 m +NAP. For section 5 the downstream water level weir B is taken, which is 9.1 m +NAP. It should be noted that in sections 4 and 5 the surface water levels and groundwater levels are steadily decreasing when moving from the Montferland (East of the Rijnstrangen) to the Liemers (North of the Rijnstrangen). The surface water level is therefore strongly dependent on the location of the cross-section.

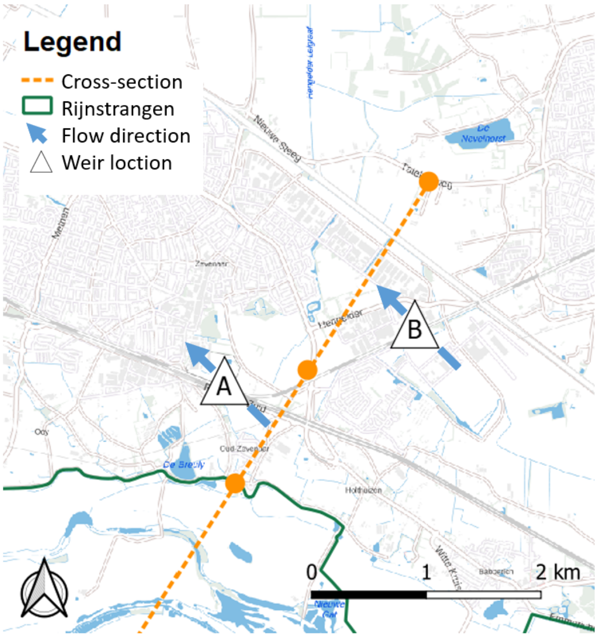

Figure A.1: Weirs on which the surface water levels in sections 4 and 5 are based.

A.2. Characteristics of the top layer

The characteristic value of the top layer that is of importance for the groundwater model is its resistance value. The resistance value of the top layer consists of the summation of the hydraulic resistance and the drainage resistance. The hydraulic resistance indicates the vertical resistance the water experiences. The drainage resistance accounts for the resistance the water experiences when flowing to the ditches. Both types of resistance and the total resistance are shown in Table A.2.

Hydraulic resistance

The layer depth of the top layer is used to determine the hydraulic resistance of this layer. Figure A.2 and Figure A.3 show the depth of the top layer. Between the Rhine and the Rijnstrangen this is around 3.0 m, in the Rijnstrangen 2.5 m to 2.0 m and to the north of the Rijnstrangen this depth decreases to 0.5 m. The hydraulic resistance values of the top layer are estimated based on these layer depths and the report of Witteveen+Bos (2007b), which gives approximations of the hydraulic resistance c of the top layer for different layer depths and kinds of top layers for the Rijnstrangen area.

The hydraulic resistance of the top layer in the Rhine (section 1) is expected to be very low, as the Rhine cuts through the top layer (Witteveen+Bos, 2007a). The resistance of the top layer in the Rijnstrangen (section 3) highly influences the outflow from the Rijnstrangen retention reservoir. It is hard to provide an exact estimate for the average resistance value in the area due to the heterogeneity in the area, as can be seen in Figure A.4. The potential resistance values in the Rijnstrangen vary from 50 days (light yellow) to 90 days (orange), with small sections with a resistance of 125 days (dark orange).

The resistance in sections 3a and 3b is set really high, as these sections only have to ”pass on” the groundwater from the Rijnstrangen to the surroundings.

Drainage resistance

The value of the drainage resistance is dependent on the groundwater table step. The groundwater table steps for the different sections are found based on the information provided by WRIJ (n.d.-c) and Aqu'Aries Advies (2014) and presented in Table A.2. These groundwater table steps are translated to drainage resistances based on the relation provided by Bot (2011), as presented in Table A.2. In sections that are filled with water, like the section with the Rhine and the Rijnstrangen when it fulfills its retention function, the drainage resistance is not applicable.

Table A.2: Characteristics of the top layer along the cross-section as presented in Figure 4.3. To be used in the groundwater calculations. The top layer plays an important role in the exchange of water between the surface water and the groundwater. Values based on Aqu'Aries Advies (2014), Bot (2011), TNO Geologische Dienst (2021), Witteveen+Bos (2007a), and WRIJ (n.d.-c).

Section	**1**	**2**	**3a**	**3**	**3b**	**4**	**5**
	Rhine			*Rijnstrangen*			
Expected hydraulic resistance [days]	1	150	10000	80	10000	75	50
Range of hydraulic resistance [days]	0 – 50	75 – 175	–	50 – 125	–	50 – 125	0 – 75
Groundwater table step	–	VII	–	–	–	V	V
Drainage resistance [days]	–	500	–	–	–	175	175
Total resistance [days]	**1**	**650**	**10000**	**80**	**10000**	**250**	**225**

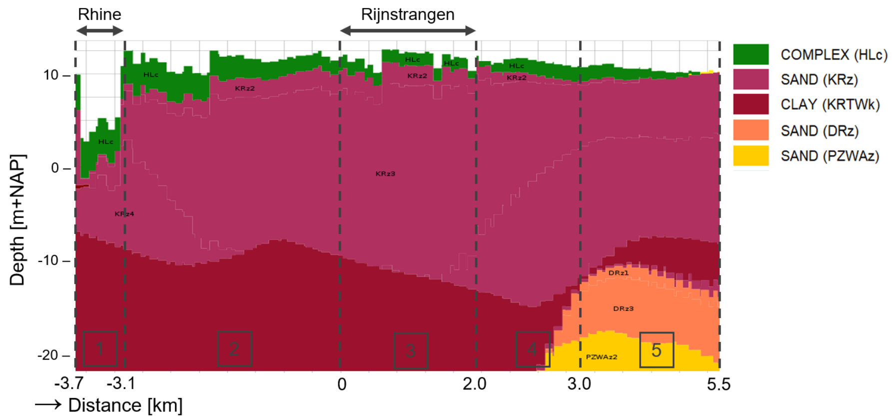

Figure A.2: Cross-section showing the depth of the top layer and the first aquifer. Adapted from TNO Geologische Dienst (2021).

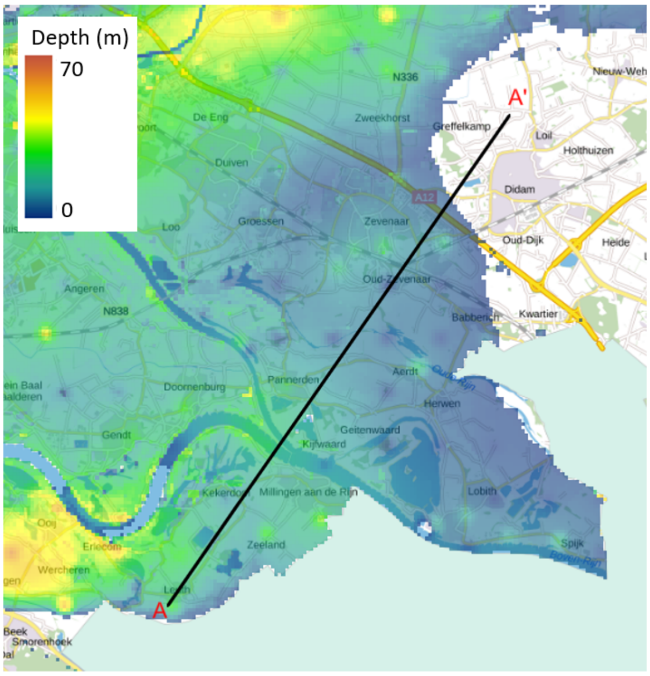

Figure A.3: Depth of the top layer. This layer depth can be use to estimate the hydraulic resistance of the top layer. Adapted from TNO Geologische Dienst (2021).

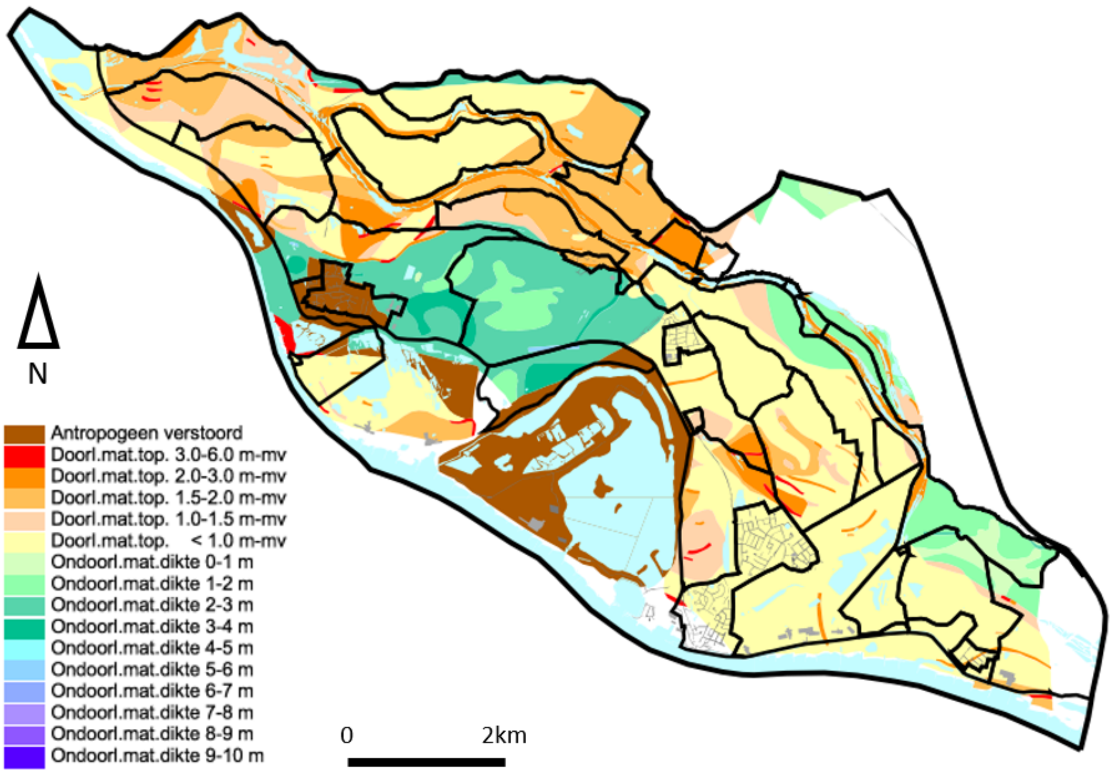

Figure A.4: Map showing the heterogeneity of the Rijnstrangen area. Adapted from Witteveen+Bos (2007b).

A.3. Transmissivity of the first aquifer

As the top layer in the Rijnstrangen area has a relatively low resistance and the Rhine cuts through the top layer to the first aquifer, the first aquifer plays an important role in the groundwater flow. It consists of two sand layers, KRz3 and KRz4, that form one aquifer. The transmissivity (kD) of the two sand layers (see Figure A.5) is summed to find the transmissivity of the entire first aquifer. The depth of the first aquifer is shown in Figure A.2. The transmissivities per section are shown in Table A.3.

Table A.3: Transmissivity values of the first aquifer along the cross-section as presented in Figure 4.3. These values are used in the groundwater calculations. This first aquifer plays an important role in the groundwater flow. Values based on TNO Geologische Dienst (2021).

Section	**1**	**2**	**3a**	**3**	**3b**	**4**	**5**
	Rhine			*Rijnstrangen*			
Expected transmissivity [m²/d]	250	750	750	750	750	750	750
Range of transmissivity [m²/d]	100 – 500	250 – 1000	250 – 1000⁺	250 – 1000⁺	250 – 1000⁺	250 – 1000	250 – 1000

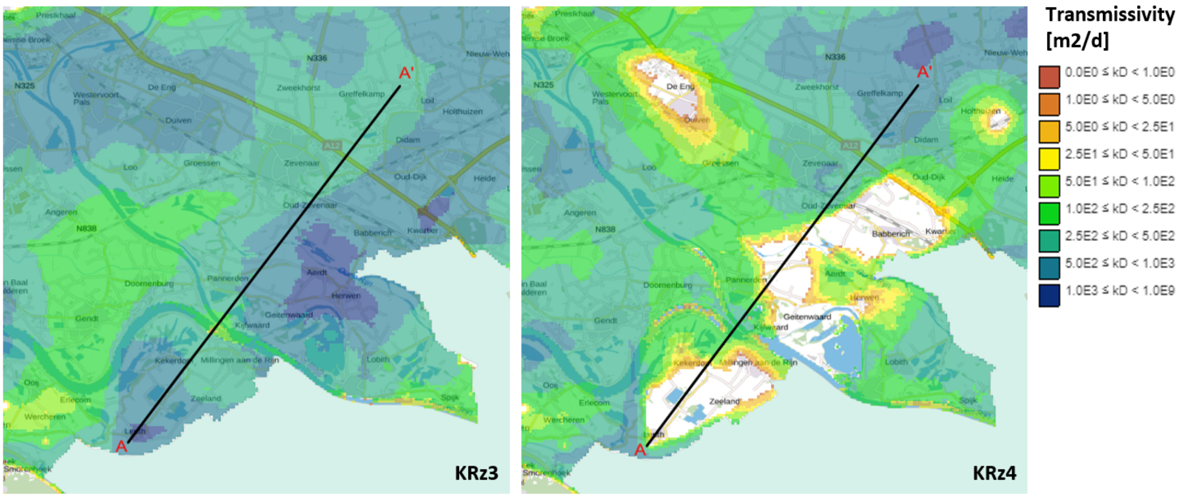

Figure A.5: Transmissivity of the first aquifer. This first aquifer consists of two sand layers: KRz3 and KRz4 of which the transmissivities are summed to find the total transmissivity of the aquifer. Adapted from TNO Geologische Dienst (2021).

A.4. Resistance of the first clay layer

The first clay layer forms a thick boundary with high hydraulic resistance between the first and second aquifer, as can be seen in Figure A.2. The layer is present under almost all parts of the study area. Under sections 2, 3 and 4 this layer is up to 30 m thick, which gives a hydraulic resistance between 10^4 and 10^5 days. Because of this very high resistance, there is hardly any significant exchange of water between the first and second aquifer. Therefore, the first clay layer forms the geohydrological base for this study.

B

Consequences of schematisation choices in the groundwater model

In this appendix the consequences of two schematisation choices of the groundwater model are discussed. These choices are: the chosen length of the cross section and the choice to take into account only one layer over depth. First, in Appendix B.1 these choices are illustrated. Subsequently, in Appendix B.2 the consequences of these choices are presented and discussed.

B.1. The schematisation choices made

Figure B.2 shows the extra sections that could have been included in the groundwater calculations. These are section 0 and section 6, one on either side of the currently used cross-section. The characteristics of these sections are shown in Figure B.1, together with the characteristics of the deeper layers. These characteristics are found similarly to the steps presented in Appendix A, based on Aqu'Aries Advies (2014), Bot (2011), TNO Geologische Dienst (2021), Witteveen+Bos (2007a, 2007b), and WRIJ (n.d.-c, n.d.-d, 2021). In Figure B.1, four rectangles are indicated. These rectangles and their colours correspond to the colours in Figure B.3 and Figure B.4, indicating the number of sections and layers included in the corresponding groundwater calculation.

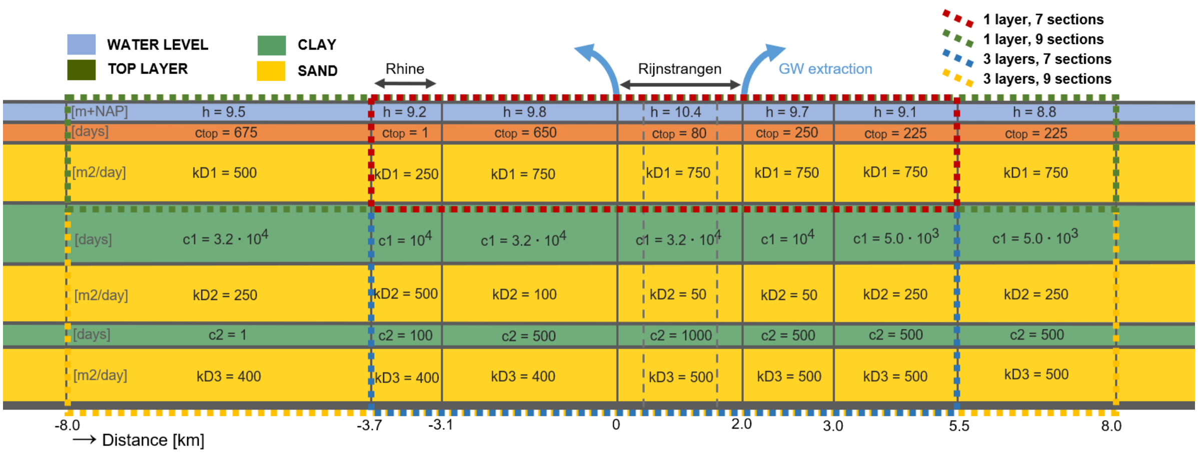

Figure B.1: Schematisation of the geohydrological situation used for the groundwater calculations with extra layers and sections.

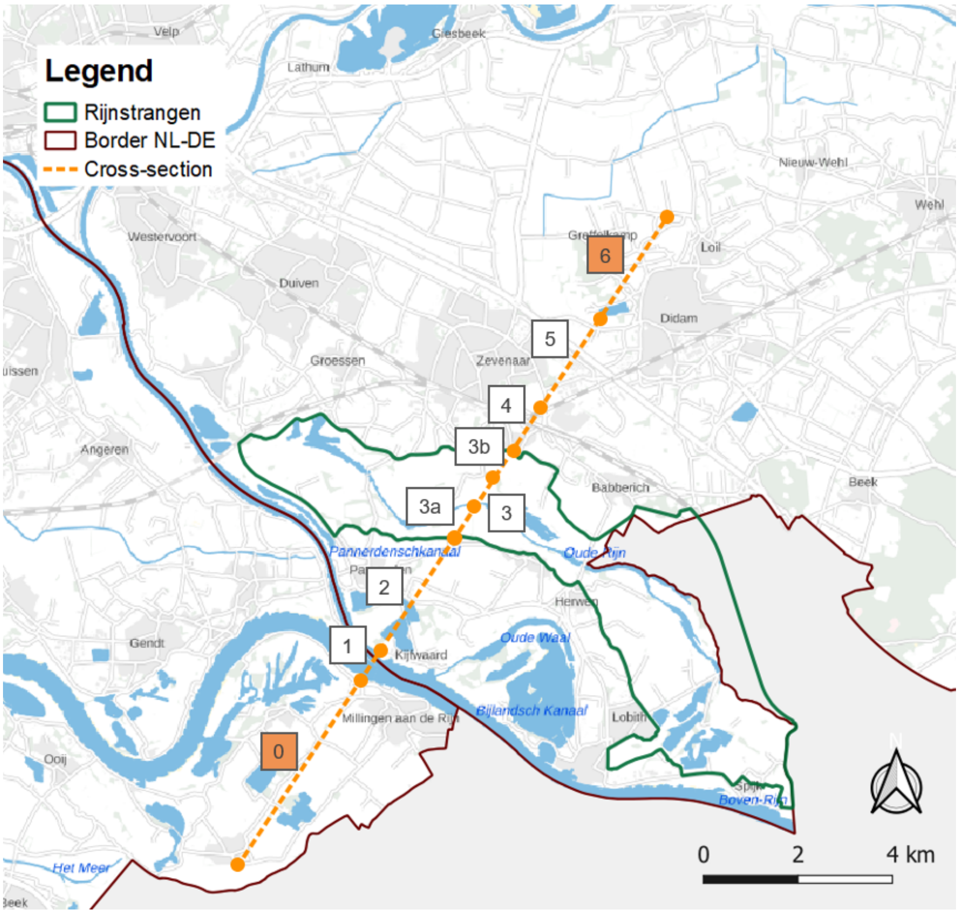

Figure B.2: Map of cross-section for the groundwater calculations, with extra sections. The numbers indicate the different sections as used for the calculation of the groundwater flow. Sections 0 and 6 are not used in the groundwater calculations performed in this study. The effect of these sections on the result of the grounwater calculations is shown in Appendix B.2.

B.2. Consequences of the schematisation choices

Figure B.3 shows the modelled heads in the first aquifer for the four different cases. The colours in the figure correspond to the colours as indicated in Figure B.1. The figure shows that the modelled heads around the Rijnstrangen are similar for the four cases, they differ less than 0.1%. This supports the choice for the simplest model with 1 layer and 7 sections, as this model takes the least calculation time and gives the same results as the more extensive models.

Figure B.4 shows the modelled groundwater fluxes for the four different cases. Like in Figure B.3, the colours in the figure correspond to the colours as indicated in Figure B.1. The thick lines in the figure indicate the total modelled groundwater flow. The thin lines show the individual flow components for the cases with multiple layers. The figure shows that the cases with multiple layers have higher flow rates, especially right (northward) of the Rijnstrangen. When analysing the individual components of the groundwater flow for multiple layers, the figure shows that the deeper layers are responsible for the differences in flow and that the flow in the first aquifer is similar for all cases. This corresponds with the finding that the heads in the first aquifer are similar for all cases as differences in head cause the groundwater flow. Despite the lines diverging slightly for the different cases, the corresponding flow rates only differ 5% when looking at the outflow from the Rijnstrangen at a water level of 10.4 m +NAP, which is the current average water level in the Rijnstrangen. This percentage drops to 3% for a water level of 13 m +NAP, as here the groundwater flow in the top layer increases more than the flows in the deeper layers.

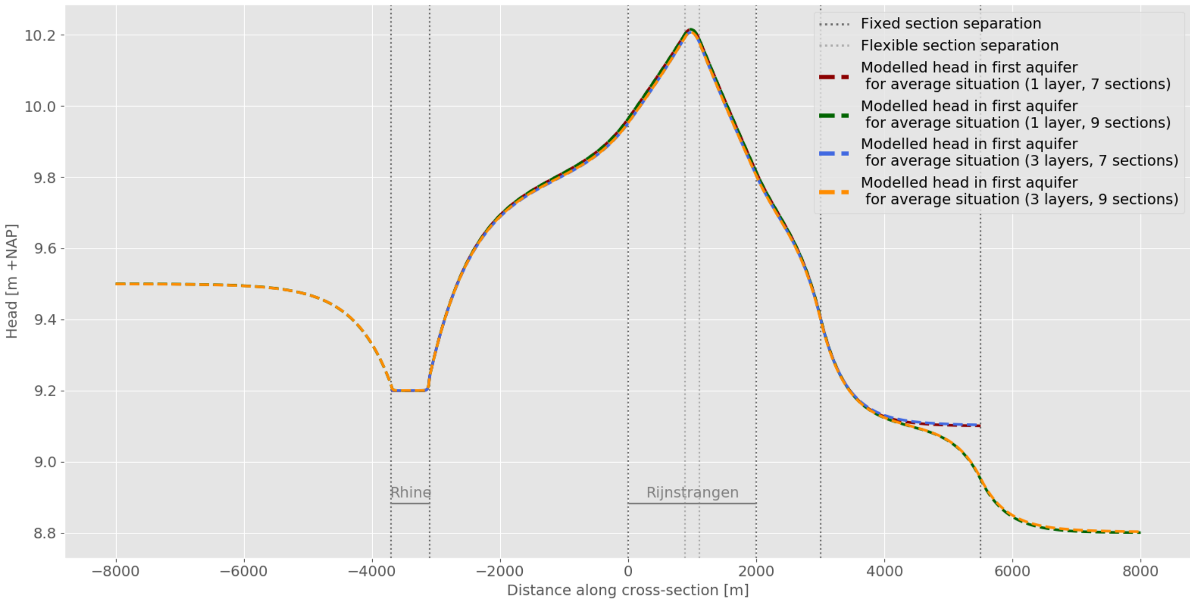

Figure B.3: Modelled heads along the cross-section for the groundwater flow calculations for four schematisations and the current average situation. This entails a water level in the Rijnstrangen of 10.4 m +NAP. The differences in head in the Rijnstrangen between the four cases are less than 0.1%.

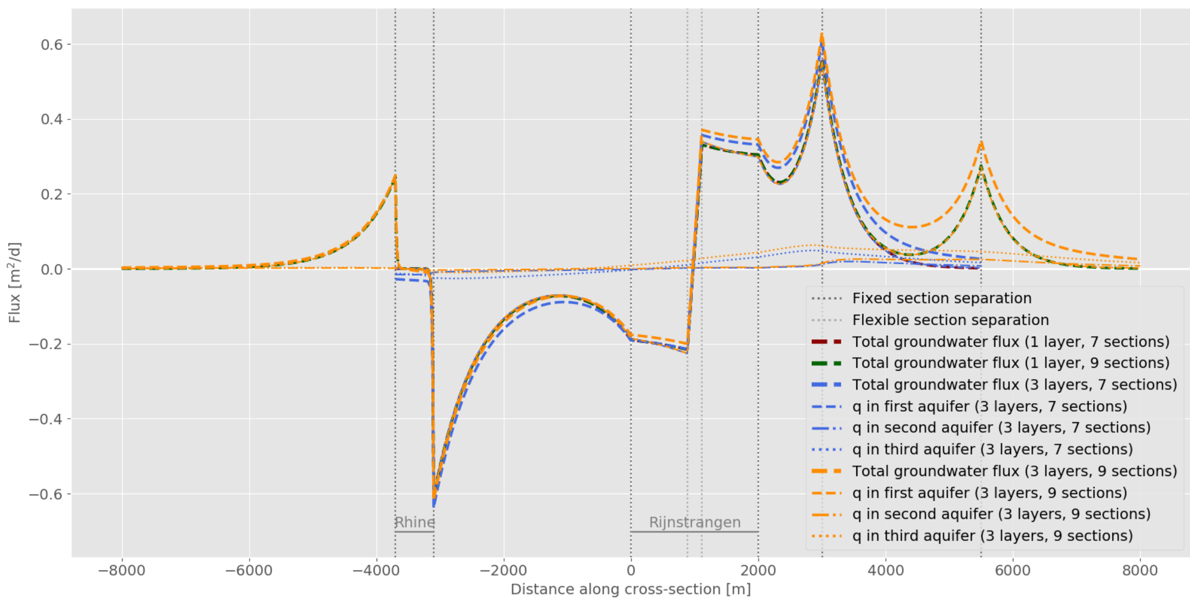

Figure B.4: Modelled groundwater flow along the cross-section for the groundwater flow calculations for four schematisations and the current average situation. This entails a water level in the Rijnstrangen of 10.4 m +NAP. The figure includes the flow in the deeper layers. A positive value indicates a groundwater flow in northward direction, a negative value indicates a southward groundwater flow. More information on how to interpret this type of figure can be found in Section 4.3.3 and Figure 4.16. The difference between the outflow with 1 layer and 3 layers is 5%.

C

Sensitivity to the parameters of the groundwater model

To obtain insights into the sensitivity of the groundwater model to its parameters, the model is run 1000 times while randomly varying the set of parameters within their likely range (see Appendix A for these ranges). The resulting groundwater outflows from the Rijnstrangen are plotted against the varied parameters of the groundwater model, as shown in Figure C.1 to Figure C.7. The parameters that show a correlation should be chosen carefully, as they have a direct influence on the outflow component in the water balance. For the parameters that show a random distribution, the outcome of the model is determined by another parameter.

To find a ranking of the influence of the parameters, each time the most influential parameter is fixed to its neutral value in a next run of 1000 times to find the next most influential parameter. Also, a combination of two or more parameters can show a correlation, in that case the combination of those is of influence on the model outcome. The leakage factor ($c \cdot kD$) is tested for its sensitivity as combination of parameters.

C.1. Sensitivity to all groundwater parameters

To start with, Figure C.1 shows the sensitivity when varying all parameters of the groundwater model for a situation without groundwater extraction. In this case, the water level in the Rijnstrangen clearly shows a strong correlation. This correlation is so strong that other parameters don't show a clear pattern. Only the water level in section 2 shows a pattern that could be a correlation. When adding extraction volumes, both symmetrical and asymmetrical, no correlations but the water level in the Rijnstrangen are present (not shown in a figure). From this it can be concluded that the water level in the Rijnstrangen is the biggest influence on the outflow of all parameters.

Figure C.2 shows the leakage factor for the situation as shown in Figure C.1. The leakage factor is the product of the resistance of the top layer and the transmissivity of the aquifer. It indicates how easy it is for water to infiltrate and flow through the subsurface. The obtained results show no clear correlation, as seen in Figure C.2.

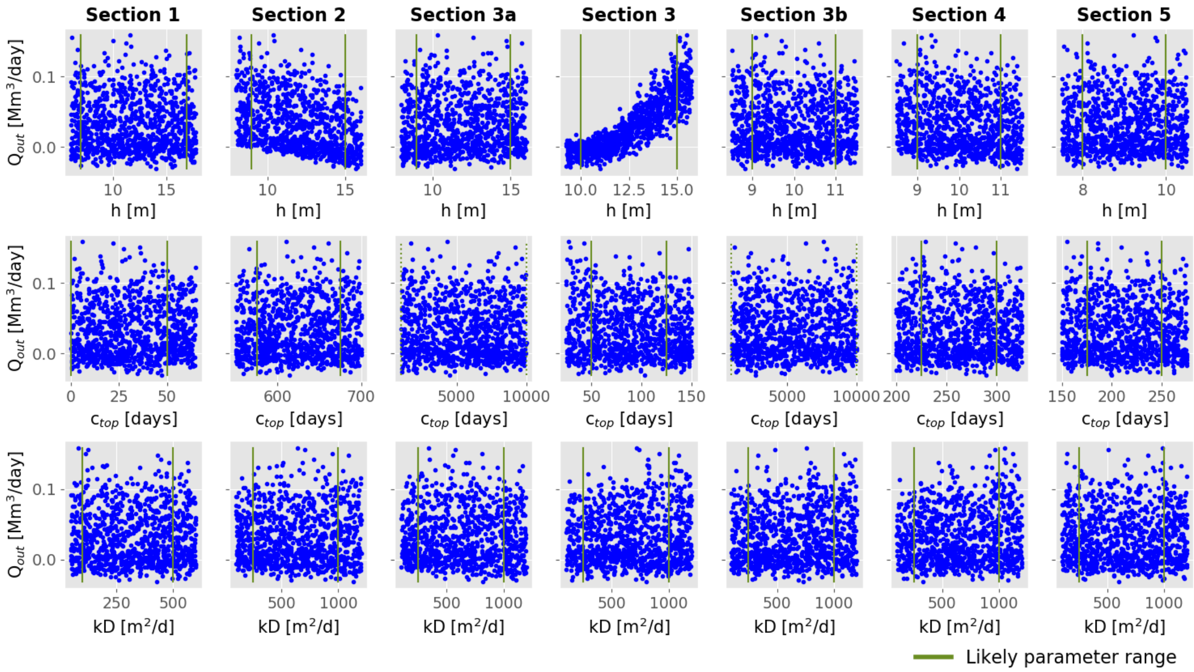

Figure C.1: Sensitivity of the groundwater model to all parameters for a situation with Q_{use} = 2 x 0 m^3/y. A strong correlation is present for $h_{section\ 3}$ ($h_{Rijnstrangen}$), as well a a slight correlation for $h_{section\ 2}$.

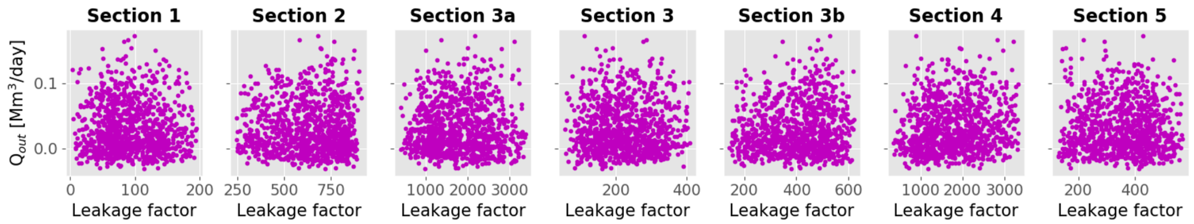

Figure C.2: Sensitivity of the groundwater model to the leakage factor ($c_{top} \cdot kD$) for a situation with Q_{use} = 2 x 0 m^3/y. No clear correlation is present.

C.2. Constant water level in the Rijnstrangen

Determining what other parameters show a correlation is done by keeping the water level in the Rijnstrangen ($h_{\text{section 3}}$) constant while varying all other parameters, as shown in Figure C.3. In this case $h_{\text{section 2}}$ shows a correlation, with a slight correlation showing up at $h_{\text{section 4}}$ as well. This means that the next parameter influencing the outflow is the water level in section 2, followed by the water level in section 4. The plots for the transmissivity of the first aquifer (kD) could be interpreted as a start of a correlation as well, however this pattern is not clear enough to draw conclusions from it.

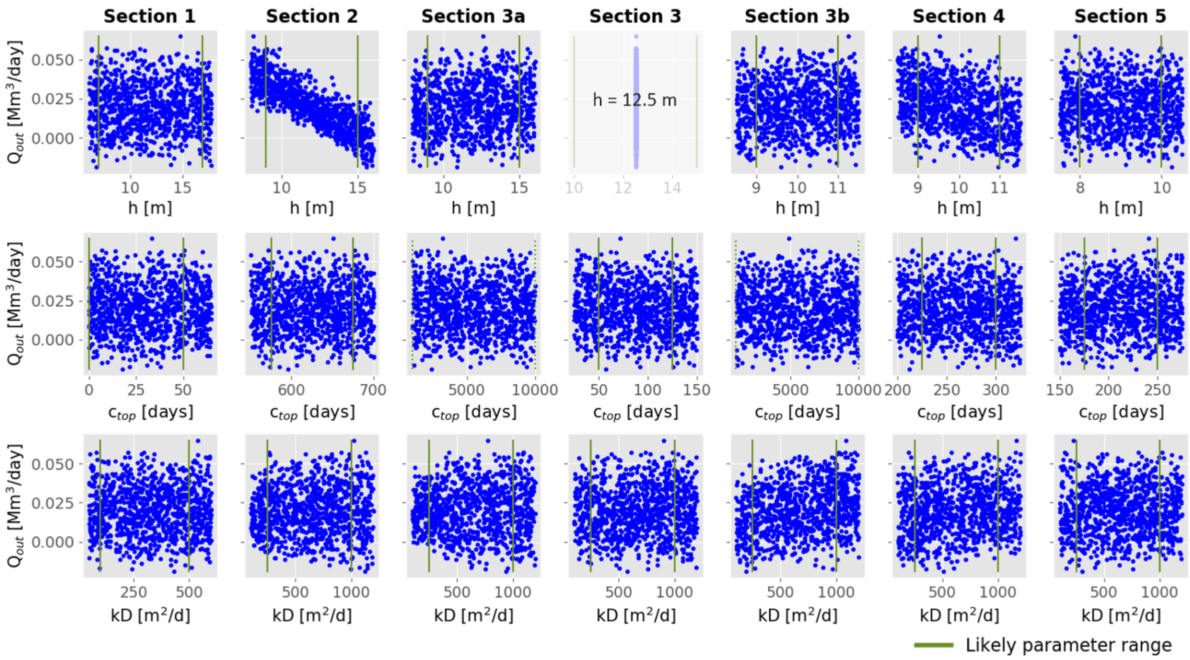

Figure C.3: Sensitivity of the groundwater model with $h_{\text{Rijnstrangen}}$ constant for a situation with Q_{use} = 2 x 0 m^3/y. A strong correlation is present for $h_{\text{section 2}}$, as well a a slight correlation for $h_{\text{section 4}}$.

C.3. Constant water levels

To see if any correlations appear when looking at the parameters of the ground only, so not taking into account the water levels, all water levels are kept constant at their values as presented in Appendix A. The result of this sensitivity analysis is shown in Figure C.4. Here a (slight) correlation is present for the transmissivity (kD) of sections 2 until 4, as well as for the resistance of the top layer in the Rijnstrangen ($c_{\text{top, sec 3}}$). The correlations of the transmissivity become more clear when adding two extraction locations, as is shown in Figure C.5. In this case, the values of the transmissivity of sections 3a and 3b are clearly of influence on the outflow. This relation is even more clear when adding an extraction on only one side, as shown in Figure C.6. When choosing the other side for extraction this figure is more or less mirrored. From this analysis it can be concluded that the transmissivity values of sections 2 until 4 are the next parameter influencing the outflow from the Rijnstrangen. These parameters are probably followed by the resistance of the top layer in the Rijnstrangen, however this correlation was not very clear in this part of the analysis.

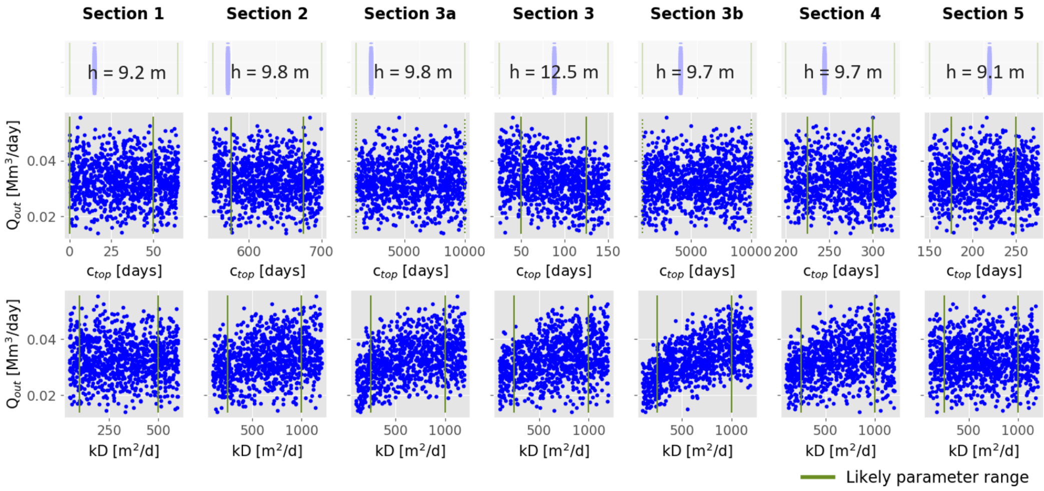

Figure C.4: Sensitivity of the groundwater model with all water levels constant for a situation with Q_{use} = 2 x 0 m^3/y. Correlations are present for the transmissivity of the aquifer (kD) and for the resistance of the top layer of the Rijnstrangen ($c_{top,\ sec\ 3}$).

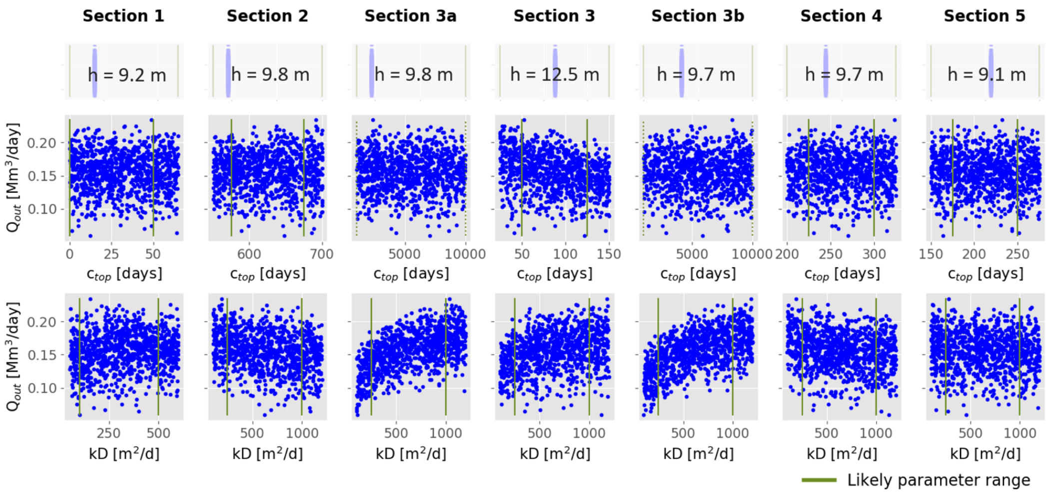

Figure C.5: Sensitivity of the groundwater model with all water levels constant for a situation with Q_{use} = 2 x 50 Mm^3/y. Correlations are present for the transmissivity of the aquifer (kD) and slightly for the resistance of the top layer of the Rijnstrangen ($c_{top,\ sec\ 3}$).

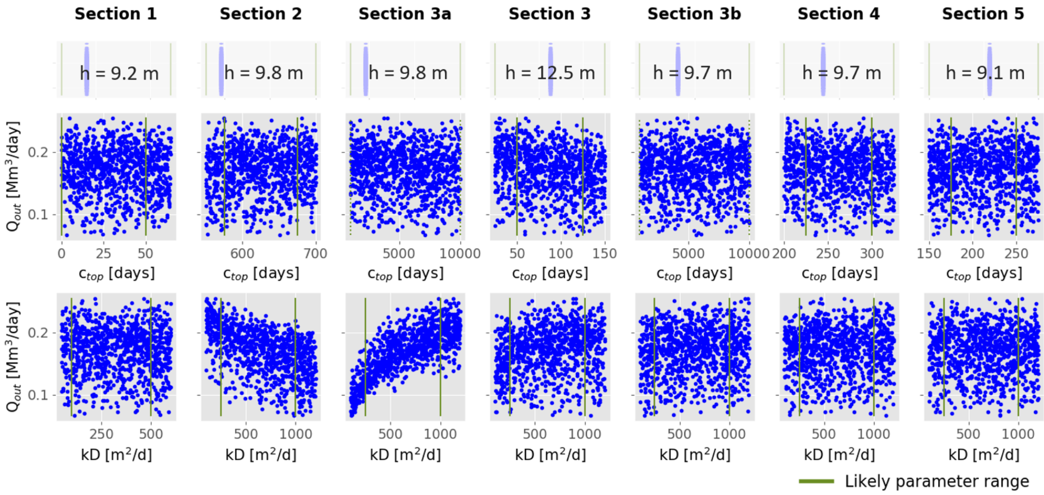

Figure C.6: Sensitivity of the groundwater model with all water levels constant for a situation with Q_{use} = 1 x 100 Mm^3/y on the left (southern) side of the Rijnstrangen. Correlations are present for the transmissivity of the aquifer (kD) in section 3 and 3a.

C.4. Remaining parameters

The sensitivity of the groundwater model to the remaining parameters, which are the resistances of the top layer and all parameters in section 1 and 5, are studied by keeping all other parameters constant. This gives the result as presented in Figure C.7, showing a clear correlation for the resistance of the top layer in the Rijnstrangen. A weaker correlation is present for the resistance of sections 2, 3a, 3b and 4, as well as the water level in section 5.

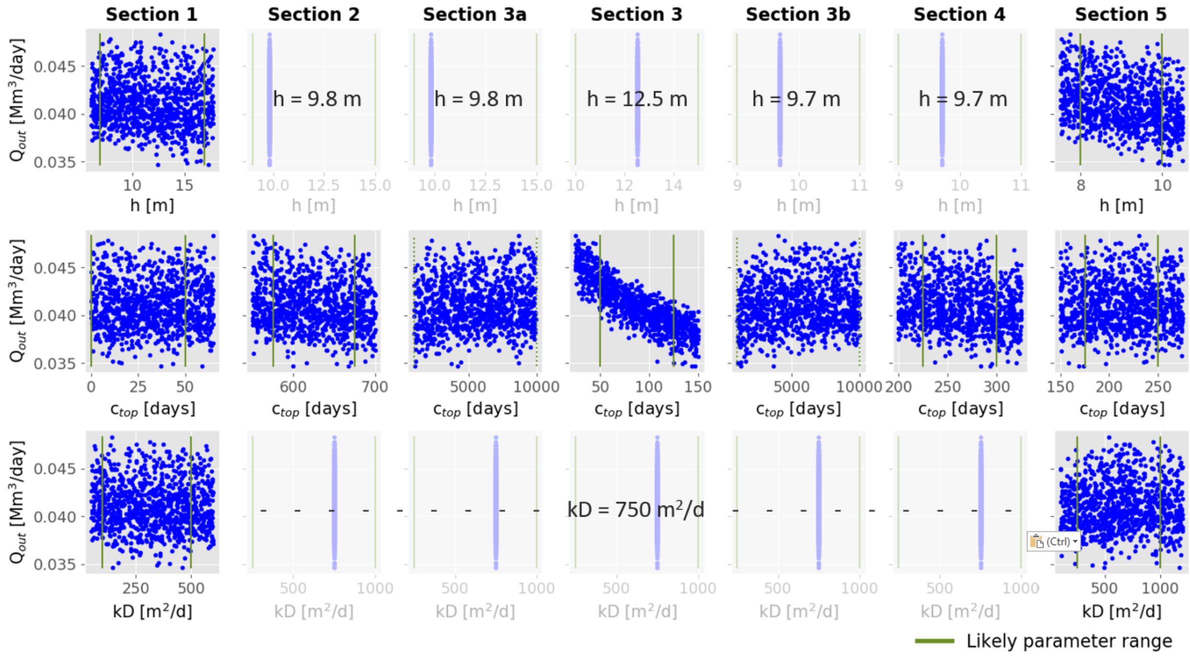

Figure C.7: Sensitivity of the groundwater model to analyse the sensitivity to the remaining parameters. Situation with Q_{use} = 2 x 0 m^3/y. A strong correlation is present for $c_{top,\ sec\ 3}$, while weaker correlations are present for the top layers in sections 2, 3a, 3b and 4 and for the water level in section 5.

C.5. Conclusions

The sensitivity analysis of the parameters of the groundwater model shows that the influence of the parameters on the groundwater outflow of the Rijnstrangen can be ordered. From a big to a smaller influence this ranking is:

1. Water level in the Rijnstrangen ($h_{Rijnstrangen}$ or $h_{section\ 3}$).
2. Water level (h) in section 2.
3. Water level (h) in section 4.
4. Transmissivity (kD) of sections 2, 3a, 3, 3b and 4.
5. Resistance (c) of the top layer in the Rijnstrangen ($c_{top,\ sec\ 3}$).
6. Resistance (c) of sections 2, 3a, 3b and 4, together with the water level in section 5.
7. All remaining parameters in sections 1 and 5.