TU Delft & Provincie Zuid-Holland

A climate proof water buffer for South Holland

Bringing back history in the future's landscape

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Colophon

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Master Thesis Report

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MSc Water Management, Water Resource Track

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Department Water Management

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Thanks for the support,

Coen

Abstract

The Province of South Holland is conducting a heritage project to explore the historical significance of barge canals and their future role in a changing climate. This thesis aims to address the water challenges posed by increased floods and droughts caused by climate change through the implementation of a water buffer system. The buffer should allow the region to serve as a drainage during storms and retain water during droughts, considering the projected climate conditions in 2100. The study focuses on a large case study area, the heart of South Holland, which is enveloped by barge canals and divided into three water boards. A water balance model, calibrated using existing pump time series, is utilized to simulate water flows at the polder level. The model demonstrates sufficient accuracy for predicting larger spatial and seasonal scales within the jurisdiction of the water boards. Future conditions are simulated in the model by incorporating KNMI scenarios. However, the scenarios underestimate the occurrence of droughts, resulting in an underestimation of polder inlet and an overestimation of outlet.

An above-average extreme climate change scenario is used to compensate for these biases. Combining the model output with long term statistical storm and drought forecasts, this leads to a more realistic buffer design capacity. If the reservoirs can be operated as prescribed, the primary hydrological purposes of the natural water buffers can complement each other. The first criterion consists of the buffering of the increased inequality of net inflow distribution throughout an average expected year, for which 20 million m^3 with an additional top layer of 115 mm would be necessary. The second criterion entails the draining of the increase of intense precipitation events. 7.5 million m^3 would be necessary to drain the extra precipitation of a 1000 year return period storm event. Thirdly, the buffers should be able to provide water, compensating for the aggravation of drought conditions. 34 million m^3 should suffice to compensate for the aggravation of droughts with a return period of 2 years and longer. As the criteria are conditionally compatible, 34 million m^3 is the net minimum required buffering capacity for the center of South Holland.

The final optimal buffering strategy entails the realization of a large buffer in the Noordplaspolder, connecting the Rotte and the Hoogeveensche Vaart, and of a smaller buffer in Schieveen. It also requires the expansion of the water reservoirs in the Eendragtspolder and Berkel. The larger buffer will feature a deeper canal, permanently submerged, linking the Rotte and the Hoogeveensche Vaart, which in turn will connect to the nearby boezem water network. The Noordplaspolder and Eendragtspolder will buffer the area of the two water boards Rijnland and Schieland and the Krimpenerwaard that are inside the case study area, Schieveen and Berkel will buffer Delfland. The Schie and the Vliet will play important roles as water carriers between Delfland and its neighboring water boards and the Nieuwe Maas. This strategy not only addresses water management but also offers recreational, historical, and ecological opportunities. It revives the functions of old barge canals, the Vliet and the Schie, and restores the connection between the Rotte and the Hoogeveensche Vaart, adding to the solution's historical value.

Contents

Glossary

Translation of terminology

Infiltration	-	Wegzijging
Level compartment	-	Peilvak
Ring canal	–	Ringvaart
Runoff	–	Afstroming
Seepage	–	Kwel
Subsurface inflow	–	Uitspoeling
Subsurface outflow	–	Intrek
Towing canal	–	Trekvaart
Water board	–	Waterschap, Hoogheemraadschap
Water level ordinance	-	Peilbesluit

Definition of terms

Boezem water
– A body of water that functions as a carrier between polder level and outer water level

Boezem pump
- A pumping station, usually with high capacity, that relieves a boezem water

Polder
– A relatively low lying area, with one or more water barriers and with an artificially controlled water level

Schieland, Delfland, Rijnland
- The parts of HHSK, HHD and HHR, respectively, that lie in the CSA

Landscheiding
- A land division in the form of an elevation or an embankment separating areas, often with different water levels

Abbreviations

CSA – Case Study Area

HHD – Water Board of Delfland (Hoogheemraadschap van Delfland)

HHR – Water Board of Rijnland (Hoogheemraadschap van Rijnland)

HHSK – Water Board of Schieland and the Krimpenerwaard (Hoogheemraadschap van Schieland en de Krimpenerwaard)

N.A.P. – Normaal Amsterdams Peil (Normal Level at Amsterdam)

Chapter 1 – Introduction

1.1 – The heritage project

For centuries, the Dutch have been in combat with water. The threat of the high sea level and the constant danger of river flooding formed great challenges for our ancestors. Recognizing the historical significance of these challenges and our unique relationship with water, the Province of South Holland has initiated a heritage project. The project aims to uncover the rich heritage associated with our ancient struggles and symbiosis with water, including the barge canals that still play a crucial role in our province's water system. These canals have now been designated as cultural heritage sites. (Erfgoedhuis Zuid-Holland, sd) One of the motivators of this study is finding out the future functions of two specific barge canals, the Schie and the Vliet. A cross reference is made to (Kuit, 2022), another thesis considering this project that investigates the redevelopment of the Hoogeveensche Vaart and the Noordplaspolder, both important components of the water system in the case study area.

In pursuit of this goal, the collaboration with TU Delft is paramount. The university shares a common drive to explore and understand the potential avenues for the future use of these canals. Now that climate change is beginning to show global effects and will likely continue to do so in the future, new challenges arise for our national water management. (IPCC, 2023) These threats consist primarily of a rising sea level and an extreme weather pattern with more intense storms and longer droughts. While a lot of attention is directed to the protection of our shorelines, we will also have to make plans to handle the consequences of climate change for our polder-boezem systems, the systems that manage the inland water quantities and qualities. The expected aggravation of droughts and storms will demand a more robust water system, which can hold on to water over rainless periods and keep our feet dry during heavy precipitation.

1.2 - Objective

As precipitation will have a more distinct pattern, characterized by softer, wetter winters and summer droughts followed by intense precipitation events, the land must be enabled to hold on to water in the form of a natural water buffer, as is philosophized by landscape architects and delta experts alike. (KNMI, 2015 (a)) (Deltares, 2019) This thesis aims to devise a way to shape the water system to become more resilient and climate proof and to find out what the functionality of the barge canals will be as a result. The goal is to quantify the minimal buffer that would enable the case study area to compensate for the effects of climate change, and to give directions to the realization of such a project. Consequently, the main research question is formulated as:

‘How can water buffering compensate for the effects of climate change on water quantity management in central South Holland in 2100?’

1.3 – Thesis Outline

The thesis will be structured as follows. Chapter 2 will describe the case study area, its history and its water system. Chapter 3 aims to produce and validate a water balance to model the water flows in the case study area. In chapter 4, this model will be used to be able to present future conditions. The results of this model are interpreted in chapter 5, where the natural buffers’ capacity will be determined. In chapter 6, the concept of buffering is applied to the case study area by considering different strategies. Finally, chapter 7 will present a discussion, conclusion and recommendations.

Chapter 2 – Introduction to case study area and polder model

This chapters' purpose is to introduce the case study area and its polder-boezem system. The area will be introduced in a general sense in §2.1. Its historic background will be described in §2.2, where both geographical and anthropogenic events will be discussed to place the system in context. §2.3 will be presenting the concept of the polder-boezem system in more technical detail and apply the concept on the case study area. See appendix A.1 for a detailed image of all the subregions, pumps and important water courses in the case study area.

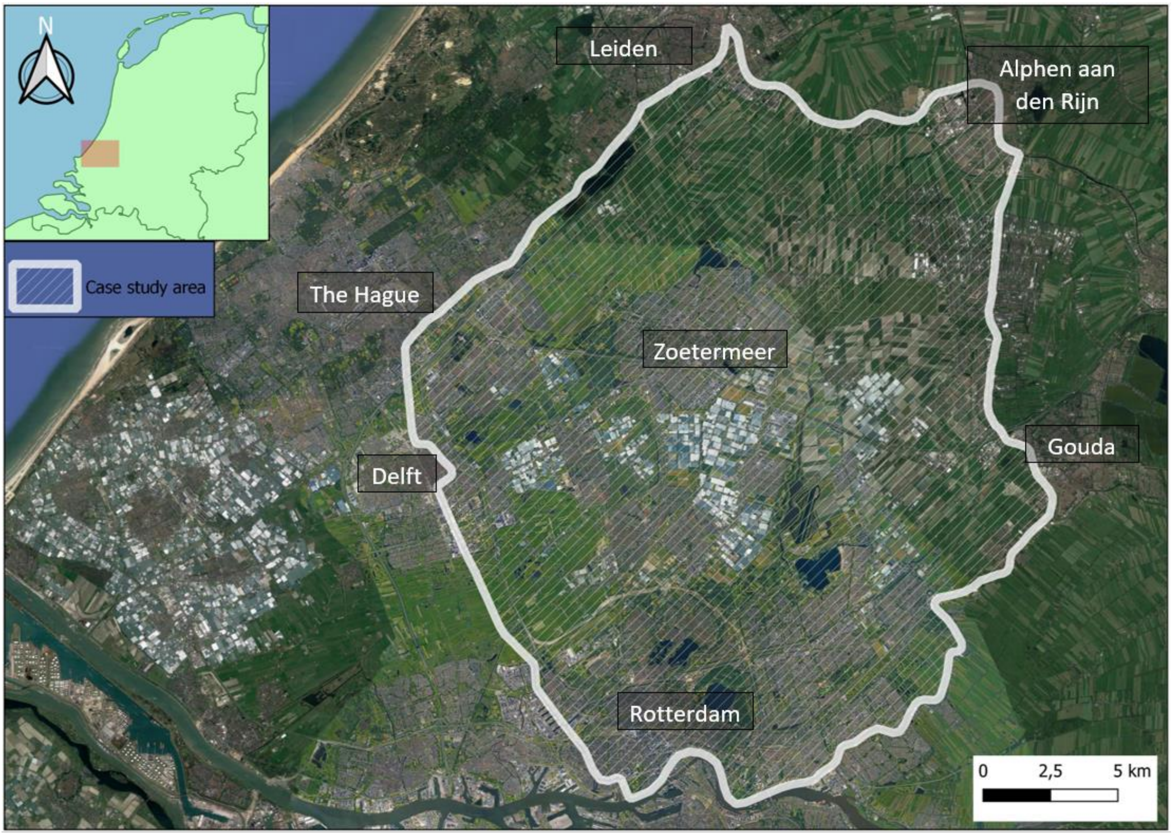


Figure 1- Satellite image of case study area (Google, 2023)

2.1 – Introduction to case study area

The case study area is defined as the region between the cities of Delft, The Hague, Leiden, Alphen aan den Rijn, Gouda and Rotterdam, as can be seen in figure 1. Zoetermeer lies at the heart of the case study area, which in total amounts to 453 km^2. The CSA is confined by channels that connect these cities: the Schie flows through Rotterdam and Delft, the Vliet flows through the Hague and Leiden, the Oude Rijn connects Leiden and Alphen, de Gouwe connects Alphen with Gouda and the Hollandsche IJssel flows from Gouda back to Rotterdam, where it enters the Nieuwe Maas. Figure 2 shows these channels as they have been flowing for the better part of a millennium. The only major recent change in this network is the addition of the Rijn-Schie Kanaal, which connects the Oude Rijn (or Old Rhine) with the Vliet with a bypass south-east of Leiden. The figure shows the old city cores (as they were in 1800) and in the backgrounf the size of the cities as they currently exist in the background. The Hollandsche IJssel is dotted as it is the only water course in the figure that was not used as barge canal.

Figure 2 - Channels that confine case study area (van der Zee, et al., 2021, pp. 11-12)

2.1.1 - Soil types

As visible in figure 3, the case study area is mainly made up of sea and river clay, occasionally with peat on top, and heavy sandy clay. Clay has a low permeability and can take long to settle. Clay and peat can hold water well. Both are susceptible to subsidence upon drainage. The heavy clay has a higher content of microscopic particles than the lighter clay, making it the least permeable natural soil type. (Meulen, Lang, Maljers, Dubelaar, & Westerhoff, 2003) Built-up area is not a soil type, as the figure suggests, but rather a land use. These urban areas usually prevent rainwater from infiltrating into the ground, causing very rapid reactions from water bodies to precipitation.

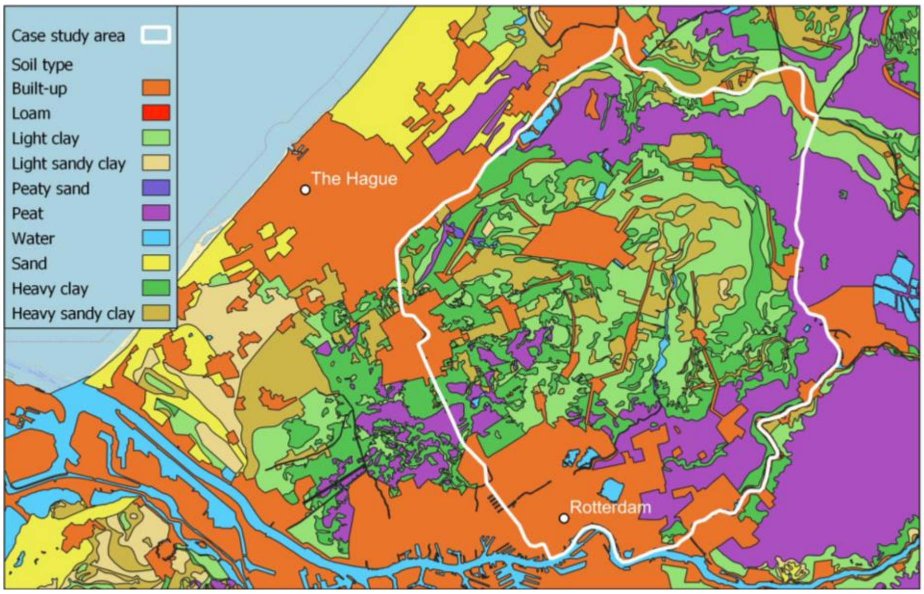


Figure 3 - Soil types in the case study area, data from ***Invalid source specified.***

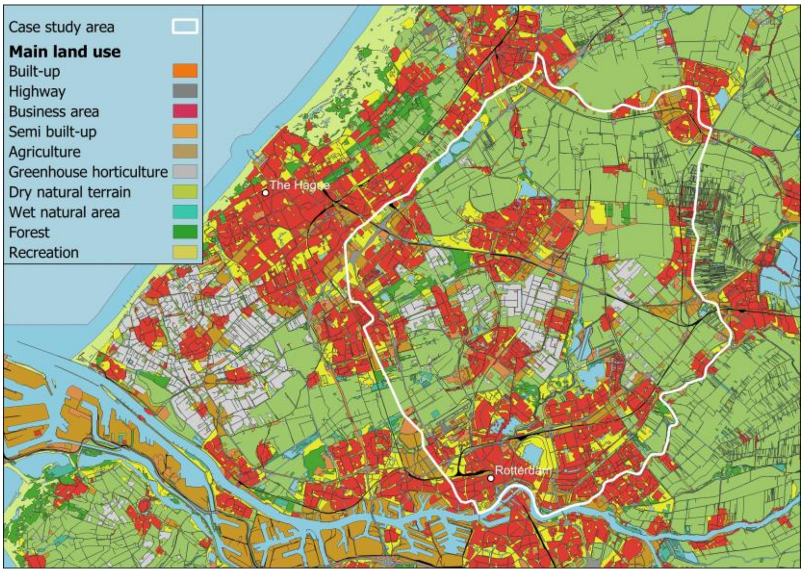


Figure 4 - Land use in the case study area, data from (Centraal Bureau voor de Statistiek, 2015)

2.1.2 – Land use

Different land uses are presented in figure 5. Clay, and especially sandy clay, offers fertile lands to grow crops or hold livestock. Hence, agriculture dominates land use, being 41% of the total case study area surface. It is followed by built-up, which covers 20% of the area. Lying in the densely populated province of South-Holland, more than 1.5 million people live within the borders of the case study area. This was calculated using raster data from (SEDAC, 2020). A total of 29% of the surface is made up of other paved classes and horticulture. The remaining 20% is made up of recreational parks, lakes, streams and forests.

2.2 – Historic background

The characteristic Dutch peatland and sea clay polder landscape has emerged over thousands of years through geological processes and centuries of human intervention. (Abrahams, Zee, & Kosian, 2016, pp. 21-33) The aim of this paragraph is to describe this history to better understand the landscape that constitutes the case study area, focusing on the geological processes (2.2.1)and the more recent anthropogenic influences (2.2.2).

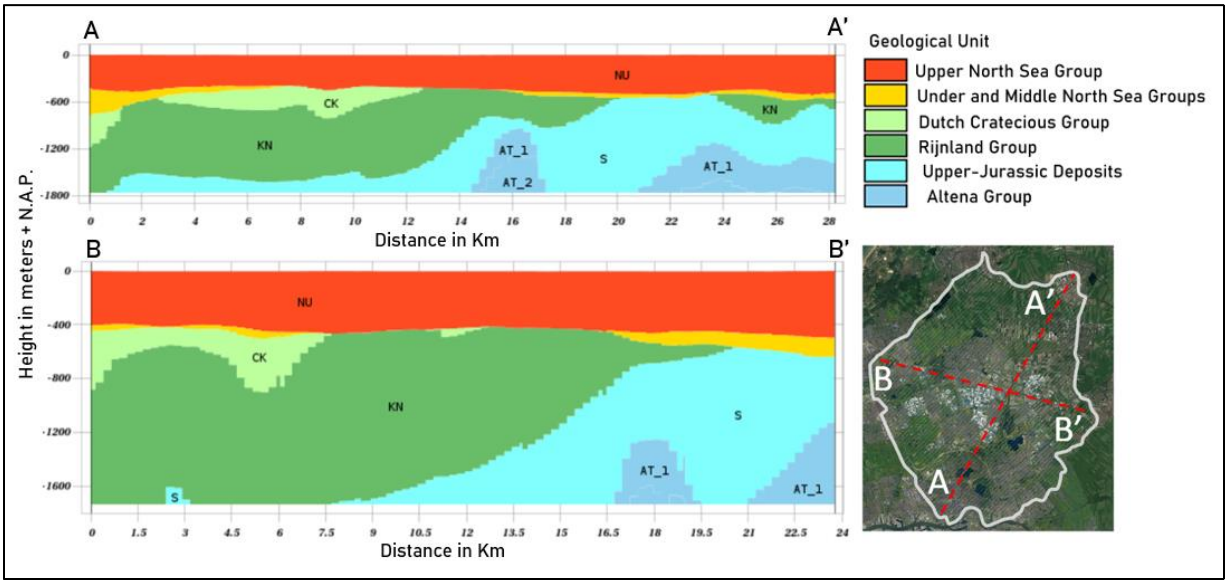


Figure 5 – Deep subsurface intersection of the case study area (DINO loket, 2018)

2.2.1– Geological formation

Two intersections of the case study area have been made to investigate the gross geological layers up to 2 kilometers deep, one from Rotterdam to Alphen (A to A’, respectively) and one from The Hague to Gouda (B to B’, respectively). These intersections can be seen in figure 6 and were generated using an online tool offered by the Data and Infrastructure database of the Dutch Subsurface (DINO loket, 2018). It is clear from the figure that the top layer, the Upper North Sea Group, is at least 400 meters thick at every instance of the intersections. Because the properties of a layer this thick will determine the characteristics of the soil on ground level, only this layer will be considered in this thesis.

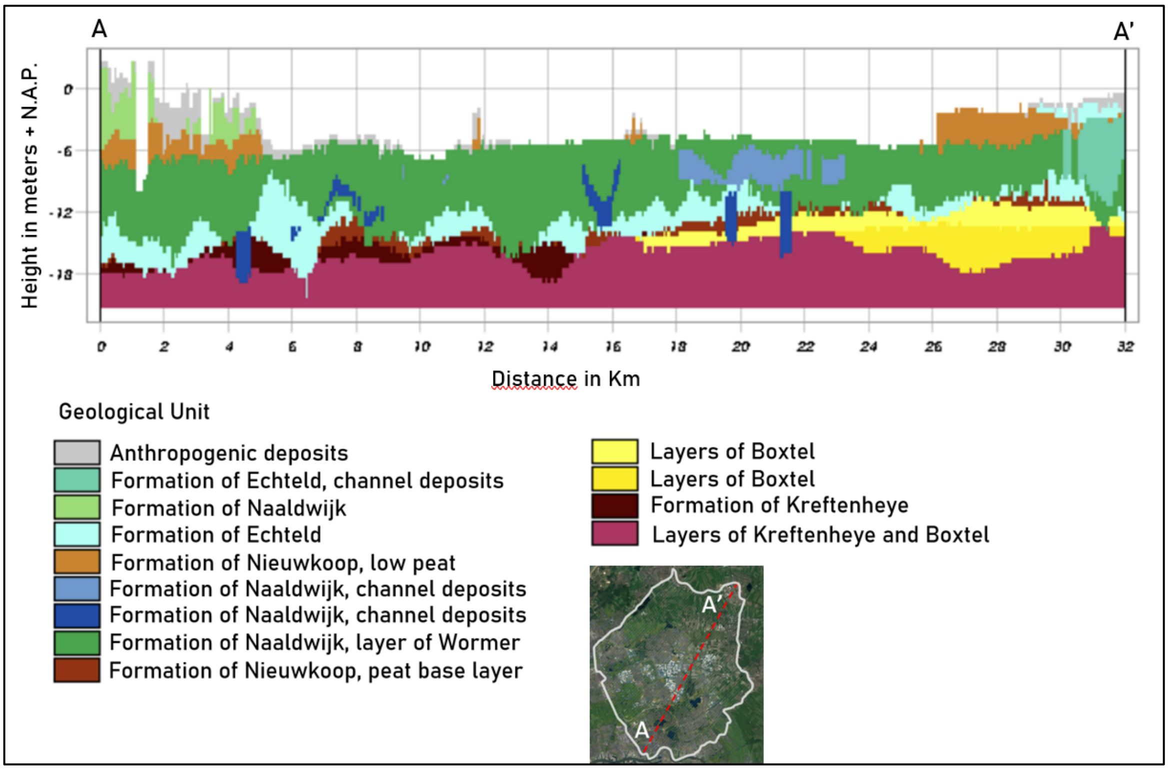


Figure 6 – Shallow subsurface intersection of the case study area (DINO loket, 2018)

According to Data and Information on the Dutch Subsurface (otherwise known as DINOloket), the Upper North Sea Group typically consists of ‘clay and fine-grained to coarse sand, locally gravel or peat and brown-coal seams. There is a general trend from coarse- to fine-grained sediments towards the north and west.’ (TNO-GDN, 2022) The sedimentation began after the last ice age, which ended about 11.700 B.C. The Netherlands was connected by a land bridge to what is now Great Britain. When the global temperature rose and the glaciers that covered the earth melted, the sea level rose as well, finally creating the North Sea around 8.000 B.C. Tides and the shearing of wind created the first row of dunes. The North Sea flowed inland twice a day, carrying clay and fine-grained sand particles. At the peak of flood, flow velocities decreased and allowed these particles to settle, creating layer upon layer of sea clay. (Abrahams, Zee, & Kosian, 2016)

From their end, the rivers Maas and Rhine caused similar deposits, at a more constant rate. These areas around the rivers are marked by river clay and have similar properties to sea clay. The main differences are that sea clay contains less organic material and has more limestone due to shellfish losing their shells onto the seabed. (Meulen, Lang, Maljers, Dubelaar, & Westerhoff, 2003) Upon the clay layers, fen peat could grow. These natural peatlands are a result of a still, wet, shallow landscape and the building up of water plant biomass in them. (Pons, 1992) This process began around 3.000 B.C.

In the hinterland of the dunes, extensive reed fields emerged in shallow, nutrient-rich freshwater areas. When the reeds died, they accumulated in the water, unable to decompose fully due to limited air penetration below the waterline. This process gave rise to a layer of reed peat. Once the foundation of the peat layer was established, it could extend above the waterline. Consequently, the reed peatlands became capable of retaining significant amounts of water, allowing other plant species to thrive on top of the reed peat. Gradually, small trees contributed to the formation of the subsequent layer in a similar manner. As the peat layer grew considerably higher than its surroundings, the plants growing on top were unable to access the nutrient-rich freshwater anymore. Instead, the peat layer functioned as a sponge, retaining rainwater, which is relatively low in nutrients. Notably, peat moss flourished in this challenging environment, becoming the dominant component of the ensuing peat layer. The capacity of peat moss to absorb and retain substantial quantities of water facilitated its continuous growth, eventually resulting in the formation of peat domes. Along greater rivers (like the Maas and the Rijn) so-called low peat can be found. In between those, these peat domes emerged. (Moore, 1987)

2.2.2 – Anthropogenic influence

As of the year 800, small populations began to settle in the vicinity of the Maas River. These people used the area's swamp streams, like the Vlaarding or the Thurlede to drain modest areas of wet peatland to live. 150 years later, these settlers began what is now known as 'the Great Drainage'. The counts of Holland were starting to get more autonomous, enabling them to reclaim more land by draining peatlands. This was done by removing vegetation and digging ditches perpendicular to natural streams. The water that resided in the peat layers then flew through the ditch to the stream and into the Maas, leaving drier land that was suitable for building and farming. (Hoeksema, 2007) (Abrahams, Zee, & Kosian, 2016, pp. 21-33)

The lowering of the groundwater table, while offering fertile dry croplands and grazing planes for livestock, caused dramatic effects in the long run. As peat consists for 70-80% of water, lowering the groundwater table meant land subsidence. When the land finally subsided far enough, in the 14th century, the groundwater table was too high again to live and farm. Only livestock could be kept. Embankments were constructed to keep the drained lands from flooding. (Abrahams, Zee, & Kosian, 2016, pp. 21-33) During that period, local inhabitants discovered that dried peat, known as 'turf,' was highly combustible and could be used as a source of fuel. Considerable amounts of peat were dug out for this precious turf, lowering the land level even further and creating lakes. The lands were now drained with the tidal cycle, using a system of sluices and culverts that opened during ebb with wider canals. (Dam, 2003)

Soon, gravity alone could not drain the peatlands and new techniques were developed. Hand driven mills were used initially. In the 15th century, the windmill was introduced. The wider canals now had to be protected by embankments as well. They were called boezem waters and served as intermediate water carriers. The boezem canals became important for transport as well, an example of which is the tow barge that conveyed persons and goods. The system with windmills was perfected over the centuries until, for a brief time, the steam mill replaced the traditional mills. (Dam, 2003) Eventually, after the 19th century, pumps had to be used to drain the land. This led to the landscape we are familiar with today, where the boezem waters still play a major role. (Hoeksema, 2007) Refer to Appendix A.2 for a digital elevation map of South Holland, which illustrates the relatively low elevation of the polders in the case study area due to the continuous cycle of drainage and land subsidence.

As water levels between lands were not always equal, land separating embankments were created: the *landscheiding* (literally: land division). As the need for collective water management grew, landscheidingen became vital markers for defining the jurisdictions and responsibilities of different communities in managing water resources. They served as the basis for the formation of water boards, which were established to collectively address water-related challenges. In the 13th century, the first water boards emerged. They were responsible for measuring and controlling water levels to prevent floods from happening. The landscheidingen helped delineate the areas where specific water boards had authority and jurisdiction over water management, flood protection, and land drainage. The existence of these physical boundaries facilitated the organization and coordination of water-related efforts within defined regions. Over time, the water boards gained more formalized structures, governing bodies, and powers, becoming specialized institutions responsible for water governance and management. (Mostert, 2020)

2.3 - The polder-boezem system in the heart of South-Holland

As mentioned in 2.2.2, boezem waters were invented to have intermediate water carriers. In general, the first line of pumping stations (polder pumps) elevates water into the boezem canals, and the second line (boezem pumps) drains the boezem canals into a body of water that is in open connection with the North Sea. This section will explain the application of this concept in the case study area. See appendix A.1 for a detailed image of all the subregions, pumps and important water courses in the case study area. It will include the water boards in question (2.3.1), how the concept is applied in their jurisdiction areas and how they deal with relatively dry and wet periods (2.3.2 to 2.3.4). This will be reported in a qualitative way and with focus on the parts of the water boards that affect the case study area.

2.3.1 – The three water boards

The Netherlands counts a total of 21 water boards, of which water board Rijnland was the first to be established in 1255. In 1950, there were 2.650 water boards. (Mostert, Between arguments, interests and expertise: the institutional development of the Dutch water boards, 1953-present, 2017) Numerous fusions made it possible to decrease this number and have regional water board elections, held every four years. (Waterschappen, 2022) The term water board can be translated in Dutch as *Waterschap* or *Heemraadschap*. For the boards with supervision on multiple polders and of higher status, the term *Hoogheemraadschap* (high water board) applies. (Mostert, 2022, p. 36) The Dutch government defines the water board as 'a government organization, like the national government, the provinces and the municipalities. A water board is responsible for the water management in an assigned area. This entails a responsibility for distribution of ample and clean water among residents and protection against flooding.' (Overheid, 2022) Therefore, the water boards are concerned with managing embankments and controlling the water level with pumps, sluices, weirs and other hydraulic works. Water boards usually divide their region into areas with a predetermined level, best described as 'level compartments.' These are presented publicly in a water level ordinance, or *peilbesluit*. The levels of the boezem waters are predetermined as well, some allowing fluctuations between summer and winter levels. The case study area lies in the jurisdiction areas of three water boards, as presented in figure 6. The western part is governed by water board Delfland, the northern part by water board Rijnland and the southeast by water board Schieland and the Krimpenerwaard. (Rijksoverheid, 2022)

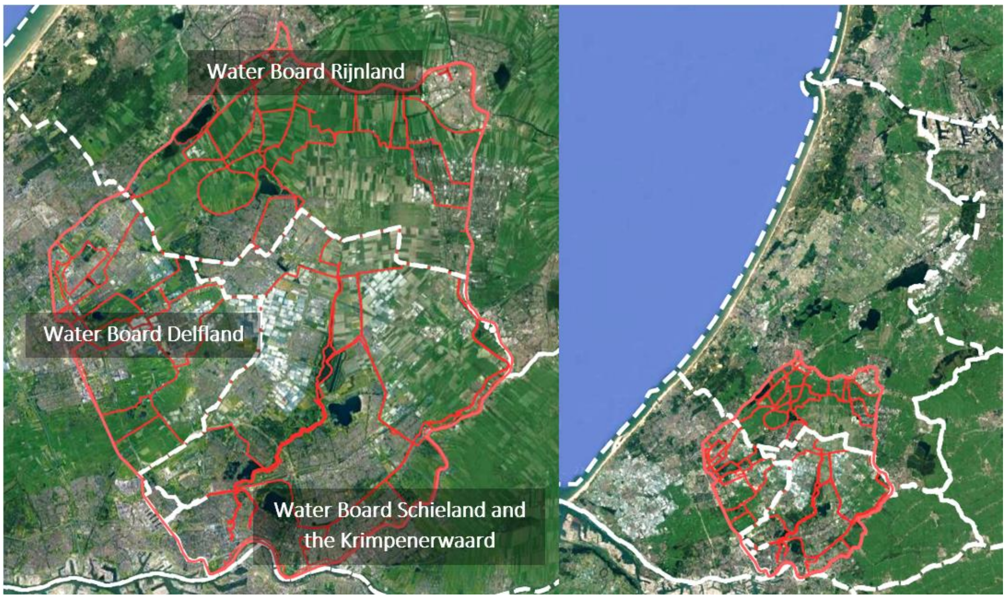


Figure 7 – The case study area and its polders lying in 3 different water board areas

2.3.2 – Water network of Delfland

All three water boards harbor different variations of boezem water networks within the case study area. Within the case study area, 14 polder pumps discharge either directly into the Schie or onto channels that are connected to it. It appears that large polders are situated in the east, relatively far away from the boezem waters. This causes bottlenecks at outlets and subsequently the accumulation of water. To mitigate flood risk, a total of five storage zones are used to hold water to be drained later. Another method by which Delfland manages its water levels is by using flexible levels. Some compartments do not have a single level that the water board has to strive to maintain, but rather a range between a maximum and a minimum level. Action is only undertaken when the actual water level is not in this range or is predicted to be in the short term. As the Schie flows along the city center of Delft and through its internal canal system, this region is built at boezem level. To prevent high boezem water levels from influencing city canal levels, all entrances to the city are equipped with weirs that can be raised automatically. (Hoogheemraadschap Delfland, 2022)

The Schie is drained into the Maas by boezem pump Parksluizen, which has a pumping capacity of 1200 m^3/minute, and the Schiegemaal, with a capacity of 450 m^3/minute. A total of six boezem pumps are utilized to keep the boezem water level at -0.43 m N.A.P., the standard level. On the north side, at the border with water board Rijnland, the sluice of Leidschendam and the pumping station 'mr. dr. Th. F.D.A. Dolk' are situated. (Nederlandse Gemalen Stichting, 2022) The combination of a sluice gate and a pumping station offers the possibility of interchanging water volumes without having an open connection (which would disrupt the boezem level) while still allowing for traffic. The water boards Rijnland and Delfland do interchange water if circumstances necessitate it, which hardly ever happens. In case of a water shortage, water is supplied to Delfland from the Brielse Meer by pumping it underneath the Nieuwe Waterweg with pumping station Winsemius. (Hoogheemraadschap Delfland, 2022)

2.3.3 – Water network of Rijnland

The northern part of the case study area is the domain of Hoogheemraadschap Rijnland. The boezem level is set at 61 cm below N.A.P. in summer and 0.64 cm below N.A.P. in winter. Since Rijnland has a significant surface area and the neighboring water board, Stichtse Rijnlanden, also drains into Rijnland, a sizable discharge must be produced by the 4 boezem pumps, not including the pump at the border with Delfland. They together amount to 194 m^3/s. (Hoogheemraadschap van Rijnland, 2015) When water shortage occurs, the boezem pump at Gouda can take water from de Hollandsche IJssel. In case that source is too brackish, water from Stichtse Rijnlanden (a neighboring water board) is used. This arrangement is called the KWA, or Klimaatbestendige Water Aanvoer. This abbreviation can be translated to: Climate proof Water Supply. (Hoogheemraadschap de Stichtse Rijnlanden, 2014)

In the part of the case study area lying in Rijnland, the east makes use of straight canals leading from boezem water to pumping station, similar to Delfland. In the western part, the boezem water permeates and flows in between the polders, making for quick discharge. Polders in Rijnland usually work with seasonal levels (as the boezem level does) and some zones with flexible levels are found in the larger polders for short term storage. (Hoogheemraadschap van Rijnland, 2022)

2.3.4 – Water network of Schieland and the Krimpenerwaard

The largest contributor to the case study area in terms of surface area is Schieland, the western part of Hoogheemraadschap Schieland and the Krimpenerwaard. The Krimpenerwaard, lying east of the Hollandsche IJssel, is not part of the case study area. The river Rotte is an internal boezem water, springing off in the north and leading southwards to Mr. U.G. Schilthuis, a boezem pumping station that connects the Rotte to the Nieuwe Maas. The station can also function as an inlet. The western part of Schieland also works with an internal boezem level: the Ring Canal, or *Ringvaart*. This canal reaches far inland and connects polders to the Hollandsche IJssel via a sluice (for taking in water) and the Abraham Kroes pumping station (for discharging). The water level in the Rotte may vary between -0.90 and -1.20 m N.A.P. and is usually kept closest to -1.02 m N.A.P. For the largest part of the Ring Canal, -2.15 m N.A.P. is the target level. Smaller segments can have a level down to -2.30 m N.A.P. Water taken in from the Hollandsche IJssel to the Ring Canal can be led to the Rotte via de Eendragtspolder. Schieland has multiple larger open water bodies and the Eendragtspolder available for buffering water. As mentioned, the Rotte can take in water from the Nieuwe Maas (via Mr. U.G. Schilthuis, but from 2021 mostly via the new inlet Leuvenhaven) and the Ring Canal from the Hollandsche IJssel. As these rivers may at times contain too much salt, the Rotte can also take water from the Schie at the Bergsluis. Furthermore, this part of the case study area lies the lowest, with a point in the Zuidplaspolder coming in at -6.76 m N.A.P. (the lowest in the Netherlands), which is why this polder is also called the deep polder. (Hoogheemraadschap Schieland en de Krimpenerwaard, 2005) (Hoogheemraadschap Schieland en de Krimpenerwaard, 2004)

Chapter 3 – Developing a water balance

Key to answering the main research question is a quantitative analysis of the subregions to acquire a water balance. A model will be made to mimic current conditions of the case study area, which can be used later in this investigation to predict future scenarios. The output will tell how much water every subregion pumps out and lets in throughout the year, together with insight into numerous important internal water fluxes. This chapter will describe this process, show the model accuracy by comparing model output to actual measurements and discuss the first model results. First, the concept of a water balance and its main constituents will be addressed in §3.1. Then, the schematization of the case study area in terms of the model is covered in §3.2. The fluxes entering and exiting control areas are described in paragraph §3.3, after which internal fluxes are explained in §3.4. §3.5 will shortly describe the process of building and executing the water balance and §3.6 will validate the model and show results. In §3.7, conclusions will be drawn.

3.1 – Concept of a water balance

A water balance is an account of the storage, inflows and outflows of a certain area. It operates according to the following exemplary formula:

$$\Delta Storage = P + S - R - E = \sum fluxes$$

This equation simply states that the change in any storage is the sum of the fluxes entering and exiting the considered area: P is precipitation, S is seepage, R is runoff and ET is the evapotranspiration. The water balance can be used to compute an unknown, visualize and compare fluxes and to predict water quantities in a specific area. It is important to realize that, though a water balance acquires increased accuracy with more data and area specific information, it is not a precise calculation model. It can give insight into flows and storages over a longer period, which makes it suitable for this investigation.

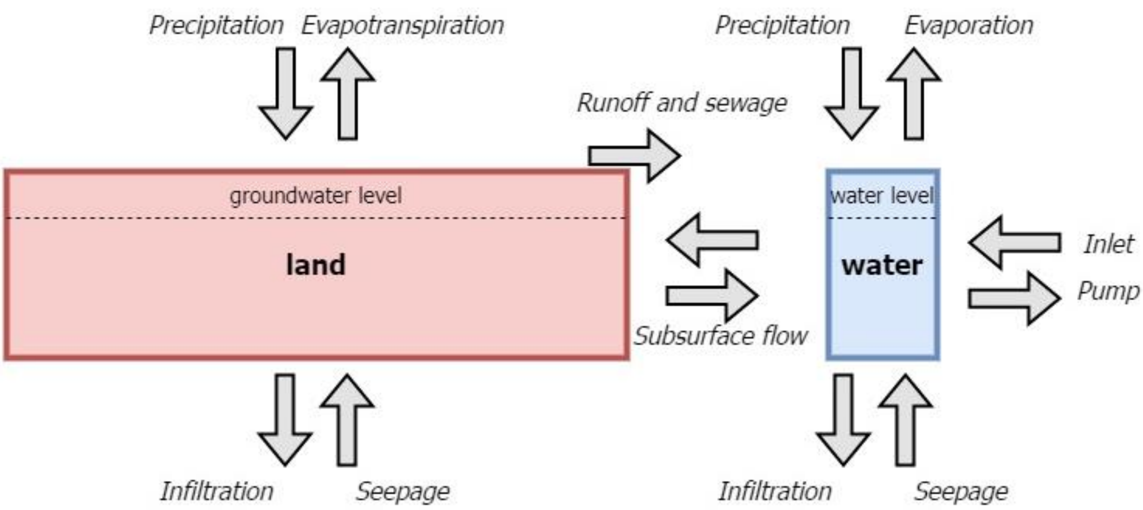


Figure 8 - Schematization of model fluxes

The different kinds of storage can be divided into open water storage (lakes, channels and assigned storage zones) and land storage (ground water and paved surface storage). Figure 8 shows the fluxes that the water balance will account for. In actuality, the water to land ratio in terms of surface area is closer to 1:20. Four horizontal fluxes exist between land and water. Subsurface outflow occurs when groundwater flows towards an open water body, subsurface inflow occurs when surface water enters the groundwater aquifer, runoff is the overland flow towards water bodies and sewage spilling is the overflowing of the sewer system onto surface water. Rain, evapotranspiration, infiltration and seepage influence both water and land storage. Surface runoff is precipitation flowing over the land into water, sewage overflow denotes either the overflowing of a combined sewer system or the discharging of a separate sewer system. At the border of most polders, a pump and an inlet are used to control the water level.

Initially, the water balance aims to mimic the current situation. Thus, pumping data from the actual boezem and polder pumps are compared to the pump values that the water balance calculates. The accuracy can then be increased by changing parameters. Representational historical data of precipitation and evapotranspiration must be present and containing both wet and dry years to give more insight into the water flows. Other relevant information for setting up a water balance of a polder are the total surface areas of open water, paved areas and unpaved areas, the percentage of area connected to combined sewer systems, hydraulic permeability, soil storage coefficient and minimum and maximum allowable water levels. (STOWA, 2018)

3.2 – Conceptualizing the landscape

Before any fluxes are calculated, the polders must be simplified to follow the bucket model from the previous paragraph. Firstly, land use will be categorized into three classes (3.2.1). An explanation will follow of how the water bodies are approached (3.2.2).

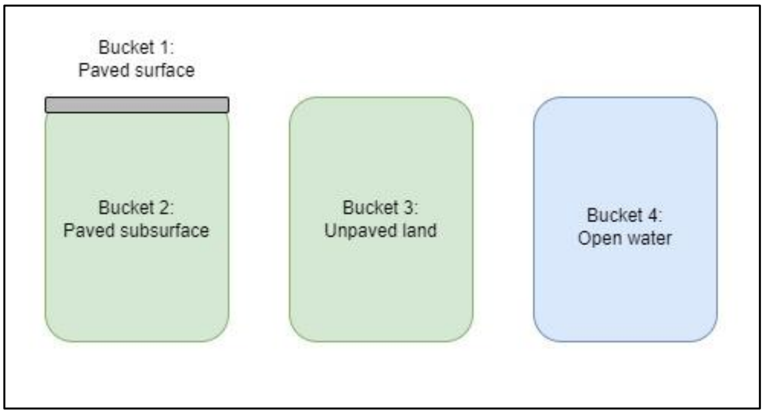


Figure 9 - Land use buckets

3.2.1 – Classifying land use

The schematization of figure 8 suggests a single lumped land bucket while hydrological response depends on difference in land cover. In the model, four 'buckets' are recognized: the paved surface, the paved subsurface, the unpaved land and open water. See figure 9. Paved areas are separated into their upper and lower parts as the paving prevents any flow between them. The land use map from 2.1.2, figure 4, is used to determine different classes of land use. The hydrological class ‘paved’ consists of the categories Built-up, Highway, Business area and Greenhouse horticulture. The Semi Built-up zones are distributed evenly over the paved and unpaved surfaces. Furthermore, agriculture, natural terrains, forests and recreational areas are categorized as unpaved areas, for most polders the largest surface area.

3.2.2 – Water bodies

The surface area in a polder that consists of open water must be determined: a crucial parameter for every polder as it largely determines evapotranspiration and water volume. This requires more precision, as a significant part of the open water surface is made up of hundreds of individual canals and ditches that are not included in the land use map provided by CBS in 2017. Two detailed shapefiles from PDOK, a public Dutch mapping service, are used and laid over the land use map (PDOK, 2017). One contains polygons of open water bodies and broader canals, the other uses lines to mark smaller canals. A table is provided with the average width of the canals, which can be combined with their length to determine their surface area. An algorithm calculates any overlapping between the two maps and generates an extensive dataset stating the surface areas of all categories within their polders.

Within polders, numerous level compartments can exist. As a result of the lumping of land and water bodies, though, all these level compartments must be combined to singular values as well. There are three kinds. The allowable levels can be fixed to one elevation, vary for summer and winter or they can be flexible to be used as a buffer. This means each polder has a minimum and a maximum level for summer and for winter, totaling four values. These have been computed by averaging the effect every level compartment has on the entire polder by size. Here, the absolute striving levels are not important, but the differences between the minimum and maximum levels can represent the amount of flexible storage in a polder.

As an example, a polder with surface area A = 6 km^2 may have three level compartments (A, B and C) with surface areas A_A= 1 km^2, A_B= 2 km^2 and A_C= 3 km^2. Compartment A is fixed to -2 m NAP, compartment B has flexible levels -3 to -2.5 m NAP and compartment C has a summer level of -1.8 m NAP versus a winter level of -2.2 m NAP. The summer minimum level is then equal to:

$$Summer\ min. level = -2 * \frac{1}{6} - 3 * \frac{2}{6} - 1.8 * \frac{3}{6} = -2.23\ m + NAP$$

$$Summer\ max. level = -2 * \frac{1}{6} - 2.5 * \frac{2}{6} - 1.8 * \frac{3}{6} = -2.07\ m + NAP$$

$$Winter\ min. level = -2 * \frac{1}{6} - 3 * \frac{2}{6} - 2.2 * \frac{3}{6} = -2.43\ m + NAP$$

$$Winter\ max. level = -2 * \frac{1}{6} - 2.5 * \frac{2}{6} - 2.2 * \frac{3}{6} = -2.27\ m + NAP$$

3.3 – External fluxes

As explained in paragraph 3.1, a water balance is a control volume with codependent fluxes. Some of those fluxes cross the borders of the control volume: external fluxes. This paragraph describes both the phenomena in question and how the data was acquired and processed. The paragraph is divided into evapotranspiration & precipitation (3.3.1), pumping stations & inlets (3.3.2) and seepage (3.3.3).

3.3.1 – Evapotranspiration and precipitation time series

In the Netherlands, reference evapotranspiration and precipitation are determined at KNMI measuring stations. Large funnel shaped devices indicate precipitation, while crop reference evapotranspiration is registered with a calculation based on temperature, radiation and humidity called the Makkink method. The stations near the case study area were used to acquire data, as visible in figure 10. In the figure, 5 stations are noted, while 4 measurements were used at any given time. This is due to the fact that station 210 Valkenburg was dismantled in 2016. Station 215 Voorschoten, located close to Valkenburg, has been operational since 2014 and was used from that moment on. Furthermore, the datasets have been homogenized by KNMI to account for possible changes in observation location and technique. Furthermore, the series are quite complete and void of gaps, disregarding missing data of two weeks of precipitation at station 215 in Voorschoten in august of 2007.

The datasets were interpolated to acquire specific time series for every subregion in the case study area. Both evapotranspiration and precipitation values were found using Inverse Distance Weighting (IDW) interpolation. This equation was used:

$$Z_p = \frac{\sum_{i=1}^{n}(\frac{z_i}{d_i^P})}{\sum_{i=1}^{n}(\frac{1}{d_i^P})}$$

The variable Z denotes the value of daily evapotranspiration or precipitation of either a point in the case study area (Z_p) or a measurement station (Z_i) and d_i the distance between the point and a measurement station i. In this case, the centroid of the subregion was used for acquiring d. The power value, P, is recommended to be set to 2 on this local scale. When using P = 0, the average of all measurements is taken. When P = 1, measurements are weighted linearly with the distance d. When using P = 2, the measuring stations are quadratically weighted according to their distance, stressing the more nearby stations and revealing more of a local pattern. Using the IDW interpolation technique for both precipitation and evapotranspiration is a reasonable option if no great barriers, such as mountain chains, or other causes of abrupt heterogeneity are apparent in the considered area. In this part of the Netherlands, the heterogeneity of meteorological phenomena is due to atmospheric causes rather than results from interference from obstacles on land, validating this assumption. (Hiemstra & Sluiter, 2011) (KNMI, 2022 (a))

Figure 10 – KNMI measuring stations near the case study area

Evapotranspiration is the total evaporation from soil, plants and other surfaces. Determining this flux begins with acquiring the reference crop evapotranspiration. The reference crop evapotranspiration is determined using the Makkink method, which is a simplification of the widely used Penman method. The equation below is the reference crop evapotranspiration according to Makkink. (KNMI/CHO, 1988)

$$E_r = C \frac{s}{s+\gamma} \frac{K^{\downarrow}}{\lambda} \qquad [kg\, m^{-2}\, s^{-1}]$$

Here, $K^{\downarrow}$ represents the short-wave incoming radiation [W m^{-2}], γ is the psychrometer constant [ca 0.66 mbar/°C at sea level], s is the derivative to temperature of the saturation vapor pressure [mbar/°C] and λ is the heat of evaporation of water [2.45E6 J kg^{-1} at 20 °C]. The constant C equals 0.65. To transform reference crop evapotranspiration to potential crop evapotranspiration, crop factors can be applied. The reference crop is well watered short grass with plenty of nutrients. Plants continuously deliver moisture to the atmosphere as part of the process of photosynthesis, the timing and amount of which is unique for all species. Thus, all have their own empirically determined crop factor that applies during the growing season, which can be assumed to be from April until September. Forests typically have a higher degree of evapotranspiration as trees tend to transpire through droughts more easily than the reference crop, grass. For agricultural areas, it largely depends on the use of the land. (Droogers, 2009) In general, for the climate in the Netherlands, the reference crop evaporation already grants a fairly accurate estimate of actual evaporation. As the reference crop evaporation is largely based on atmospheric demand and not water supply, deviations are found mostly during droughts, when the soil dries and the wilting point in the plant root zone is approached. (STOWA, 2020)

Not much is clear concerning actual evaporation in Dutch cities. In urban landscapes, evapotranspiration will likely be lower than the standard Makkink reference evapotranspiration predicts as the paved area only allows for a thin water layer to be present after precipitation events. Furthermore, reduced actual evapotranspiration can be caused by water infiltrating paved areas or flowing directly into open streams more easily than presumed. (STOWA, 2020) Calculating the actual land evapotranspiration by accounting for all these phenomena is not a realistic task; it would take research far out of the scope of this thesis. To account for both increased and decreased local evapotranspiration, an extra factor is applied per subregion: the EV-Factor. This factor applies to the reference crop evaporation during the growing season, which is the most critical period. As this factor is the only free parameter remaining in the water balance (with all other parameters being based on literature), it is acquired by optimizing it to the lowest possible error. The error is defined as the absolute of the yearly accumulated measured outlet minus the yearly accumulated calculated outlet. The time scale of the year is used as the factor applies over the entire growing season.

3.3.2 – Processing time series of pumping stations

The output of the water balance, the modeled discharges, are eventually compared to pumping station series to determine the accuracy of the model. Data of the pumping stations is acquired from the water boards, the quality of which varies greatly. The water board of Rijnland began keeping a log of certain pumped quantities in 2010, the water board of Delfland in 2013 and the water board of Schieland and the Krimpenerwaard in 2015. In all three cases, certain pumping station series are missing or have been monitored for very short time spans, making it difficult to compare results. While most data sets are complete, some series have (small) time gaps due to maintenance or temporary malfunctions. These gaps are usually small but can lead to the inability to validate model output.

In addition, it is important to consider that daily pumping data may not always be reliable, as accurately measuring discharges can be challenging. When pumps are operating at lower capacities, the measurements tend to be less precise. This is particularly true for centrifugal pumps, which are commonly used in the case study area, and their measurements should be interpreted with some margin of error. Moreover, the age of pumping stations can impact the confidence intervals, with older stations often having overestimated capacities due to deterioration. (Tauw, 2012, p. 26) To get an idea of the scale of the inaccuracy of the reported capacity versus the practical maximum capacity, an estimation is made. The total pumping capacity of the pumps in a polder must be retrieved either way. As will become clear later, the maximum pumping capacity is a limit the model must adhere to if, for example, more water has to be drained than possible. The reported values for the pumping capacity are retrieved from the meta data the water boards have provided, combined with online registers such as the Dutch Pumping Station Foundation (De Nederlandse Gemalen Stichting). The estimate is simply based on the maximum amount of water a pumping station has moved within a calendar day, assuming that this has been the case somewhere in the recorded history of the pumps. Results were wildly different, ranging from exactly right to being a factor two off. Some even showed that the estimated capacity is greater than their documented capacity. The following rules were used to interpret these findings:

1. Estimates are only useful when the time series of the pumping station is sufficiently long, i.e., more than three years.
2. For estimates slightly (10 %) below the documented capacity, the estimate was used, as it is more likely that the actual capacity is a bit lower than registered than that there was no day during which the pumping station did not run on maximum capacity.
3. For estimates significantly lower than documented (more than 10%), the discharges during especially wet periods were looked up and compared. If these were present, the estimate was accepted.
4. For estimates higher than the documented capacity, it was checked if the pumping station had been running on this capacity more often. If it did, the estimate was favored over the documented capacity as it is more likely that one mistake was made in the registration of the capacity than that multiple measuring mistakes were made within the time series.
5. For cases where no capacity is documented anywhere, the estimate was used.

This evaluation lead to the decrease of most pumping capacities by a modest percentage (1-5%). (De Nederlandse Gemalen Stichting, sd)

Furthermore, data of inlets is missing. Water boards do not yet measure the amount of water they admit to their polders. Rather, as a part of the traditional style of level management water boards are accustomed to, field workers will open an inlet throughout the growing season. The model, however, steers solely on the basis of water quantity: opening the inlet when water levels sink below the lower limit and using the pumping station to get rid of excess if the level supersedes the upper limit. An example is the 2018 summer drought in subregion 4 'Hoge Broekpolder' (see appendix A.1 to look up subregion locations). Almost no precipitation fell during this period, causing the model to compute inlet approximately equal to evapotranspiration while keeping the pumping station turned off. In reality, a water board may want to 'flush' the channels in the region to keep the water quality above a certain threshold. Between June 19th and July 26th of 2018, the model computed 0 m^3 of discharge while the data states more than 85.000 m^3 was actually discharged. Upon closer inspection, this region appeared to contain a sizable golf course, which is kept well-watered.

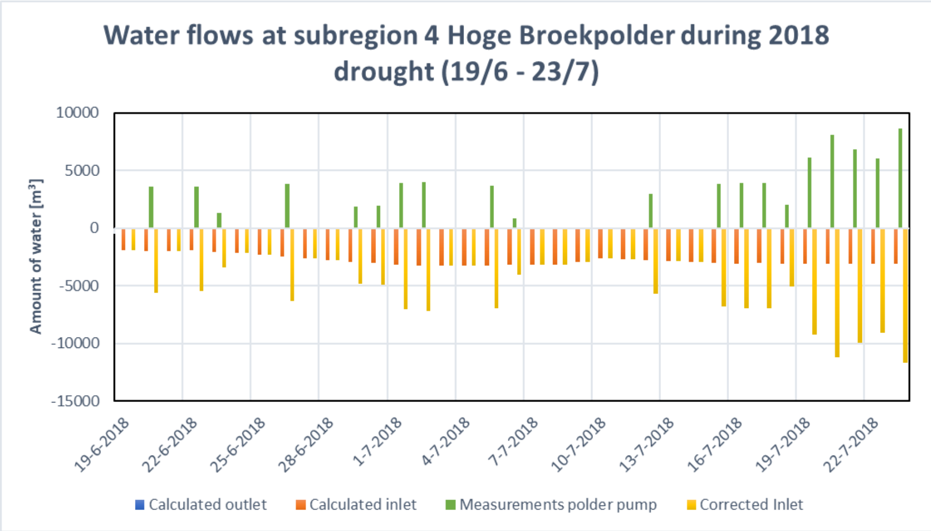


Figure 11 - Water flow at Hoge Broekpolder during 2018 drought, showing that no outlet was calculated

Of course, the significance of this effect differs greatly per polder. Modeling water quality in a way that applies the policy of every water authority per polder in order to account for it falls out of the scope of this thesis. Another way is to compare pumping series between polders in a relative way to find out whether more or less pumping is taking place then would be expected. The following formula was applied to every subregion to acquire a controlling number:

$$C = \frac{Q_{pump}}{A} - S$$

The above equation is a simplification of the water balance where the time scale is a year. Over the course of a year, the pumped quantity has to equal the sum of the fluxes entering and exiting the control volume of the polder, namely precipitation, evapotranspiration, seepage and inlet (see once again figure 7). By dividing the yearly discharge of the polder pump (Q_{year} , [m^3/year]) with the polder area (A, [m^2]) and subtracting the amount of seepage (S, [m/year]), an approximation is made of the quantity of water that is pumped away as a result of precipitation, inlet and evapotranspiration, in this case called C [m/year]. Seepage is explained in 2.4.5. For now, it suffices to view it as a groundwater flux coming from outside the control volume composing a polder, the value of which is best approximated over the time span of a year. As precipitation and evapotranspiration are of comparable quantities across the case study area, the number C can be compared between polders to see if their inlet per unit surface areas is within the expected range. The KNMI states that yearly 850 mm of precipitation falls on the surface of the Netherlands while 600 mm crop reference evapotranspiration is measured (as we have seen in 2.4.2, the actual evapotranspiration deviates substantially). (KNMI, 2022 (c)) This means that C will, for a normal polder, be swaying around 0.5 m/year. Higher values of C indicate that more pumping has taken place than expected, denoting extra inlet (like sprinkling or flushing). Lower values indicate either missing pump data, high evapotranspiration properties or gravitational dewatering into nearby polders. Results are presented in table 1.

Table 1 - C-values of all subregions

ID	Name	WB	C	ID	Name	WB	C
-	-	-	[m/year]	-	-	-	[m/year]
1	Akkerdijksche polder	HHD	0.38	25	Oostvliet- Hof- en Spekpolder	HHR	0.57
2	Berkel	HHD	0.41	26	Polder Alpherhoorn	HHR	0.67
3	Delft-Oost	HHD	0.7	27	Polder de Noordplas en Ambachtspolder	HHR	0.65
4	Hoge Broekpolder	HHD	0.91	28	Polder Groenendijk	HHR	0.73
5	Lage Broekpolder	HHD	0.55	29	Polder Het Zaanse Rietveld	HHR	0.61
6	Nieuwe of Drooggemaakte Polder	HHD	0.44	30	Polder Laag Boskoop en Rietveldse Polder	HHR	1.43
7	Noordpolder van Delfgauw	HHD	0.57	31	Polder Westbroek	HHR	0.61
8	Oude Polder van Pijnacker	HHD	0.36	32	Rhijnenburgerpolder	HHR	0.74
9	Polder van Biesland en Bovenpolder	HHD	0.91	33	Room- of Meerburgerpolder	HHR	0.59
10	Polder van Nootdorp	HHD	0.9	34	Starrevaart- en Damhouderpolder en Vlietland	HHR	0.54
11	Polder Vrijenban	HHD	0.87	35	Zoetermeerse Meerpolder	HHR	0.39
12	Schieveen	HHD	0.25	36	Zwet- en Grote Blankaartpolder	HHR	1.37
13	Tedingerbroekpolder	HHD	0.79	37	Binnenwegse polder	HHSK	0.62
14	Ypenburg	HHD	1.1	38	Boezemland	HHSK	2.35
15	Zuidpolder van Delfgauw en Wippolder	HHD	0.58	39	Oostpolder	HHSK	N/A
16	Geer- en Buurtpolder	HHR	1.41	40	Polder Bleiswijk	HHSK	0.56
17	Geer- en Kleine Blankaardpolder	HHR	0.54	41	Polder Capelle aan den IJssel	HHSK	0.74
18	Grote Polder	HHR	0.57	42	Polder de Wilde Veenen	HHSK	0.39
19	Grote Westeindse Polder	HHR	0.75	43	Polder Esse Gans- en Blaardorp	HHSK	0.7
20	Industrieterrein Grote Polder	HHR	0.77	44	Polder Prins Alexander en Eendragtspolder	HHSK	0.46
21	Kleine Cronesteinse- of Knotterpolder	HHR	0.68	45	Polders van Rotterdam	HHSK	0.06
22	Meeslouwerpolder	HHR	1.16	46	Ringvaart	HHSK	11.34
23	Nieuwe Driemanspolder	HHR	0.48	47	Rotte	HHSK	16.02
24	Oostbroekpolder	HHR	0.74	48	Tweemanspolder	HHSK	0.43
				49	Zuidplaspolder	HHSK	0.45

It appears from the table that numerous subregions have large values for C. Refer to appendix A.1 to locate the subregions. The most extreme are 14 Ypenburg, 16 Geer- en Buurtpolder, 22 Meeslouwerpolder, 30 Polder Laag Boskoop en Rietveldse Polder, 36 Zwet- en Grote Blankaartpolder and 38 Boezemland. It is only logical that 46 Ringvaart and 47 Rotte have enormous C-values as they serve as boezem waters, meaning their inlet equals all the output of the polder pumps connected to them. There are no values for C much below the threshold, except for 39 Oostpolder and 45 Polders van Rotterdam. Of the former, no pumping data series extending to a year are present and of the latter only a fraction of the numerous pumping stations is provided for by the Water Board.

3.3.3 – Seepage and Infiltration

The two down-most fluxes visible in figure 8 denote seepage and infiltration. Seepage encompasses the flows to and from the deeper subsurface and is different for every subregion. It is a result from the difference between the water level in outer waters, such as rivers, and the water level in neighboring polders. Groundwater under rivers with a high water level may seep through the soil layers underneath embankments and well up in the polder landscape. The opposite is true of infiltration, where the polder level has a higher potential. (Waterschap Rivierenland, 2014)

The Dutch hydrological instrumentation (NHI, Nederlands Hydrologisch Instrumentarium) has used ground water data from 2011 to 2018 and the national hydrological model (LHM, Landelijk Hydrologisch Model) to model yearly average seepage values for the Netherlands. In practice, seepage values will vary over the year as the co-dependent water levels change. As no smaller resolution of the model is available and the yearly quantities are leading, this will have to suffice. The result is defined as long term average water exchange between the saturated subsurface and the phreatic surface (the layer between saturated groundwater zones and the surface). The results are compiled in a shapefile and the distribution of seepage can be viewed in QGIS. A clipping algorithm can be used to determine the mean yearly seepage in all subregions, ranging from 0.71 mm/day of downward seepage in subregion 30 Polder Laag Boskoop en Rietveldse Polder to 1.03 mm/day upward seepage in subregion 34 Starrevaart- en Damhouderpolder en Vlietland. (Nederlands Hydrologisch Instrumentarium, 2019)

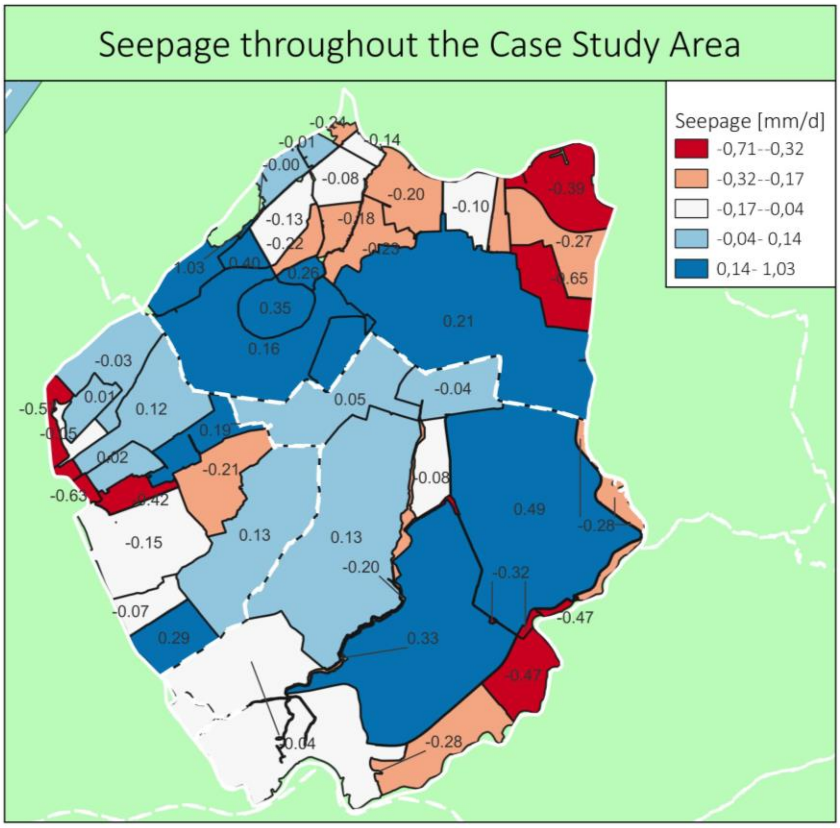


Figure 12 – Seepage in blue and infiltration in red (Nederlands Hydrologisch Instrumentarium, 2019)

3.4 – Internal fluxes

The internal fluxes are simplified to fluxes between land and open water bodies. Firstly, this paragraph addresses subsurface in- and outflow (3.4.1). Secondly, runoff and sewage spills (3.4.2) will be covered.

3.4.1 – Subsurface in- and outflow

The horizontal groundwater flow in and out of open water bodies is called subsurface flow. The direction of flow is always from a high to a low potential. In the model, the potential is defined as the water level. This means that the flow will be directed from the body, either water or ground, with the highest level. The model keeps track of groundwater levels by keeping a separate water balance for every different land type. Two parameters are important to emulate the subsurface flow: porosity and permeability. Porosity is the fraction of space between soil particles that can be filled up by air or water. The permeability is a parameter derived from Darcy's law, which can be expressed generally and in one dimension as:

$$q = -K * \Delta h/\Delta L$$

Where q is the volume flux [m/d], K is hydraulic conductivity [$m*d^{-1}$], ΔL is the length of the medium and Δh is the hydraulic head [m]. The water balance uses a similar function to calculate subsurface flow, with one major difference. As the typical polder has more land surface than open water surface, fluxes towards the water are greater than the other way around. For the well maintained grassy claylike soils of the case study area, the value of K is around 0.3 d^{-1} for flow towards water and 0.15 d^{-1} for flow land inwards. (STOWA, 2018)

3.4.2 – Runoff and sewage spills

Runoff and sewage spills can occur as a result of precipitation over paved areas. As a significant portion of the case study area is built-up (20%), a correct modeling of the hydrological behavior of paved areas, including different sewage systems, is important for an accurate water balance. A standard specific for the amount of water that can be stored on top of the paved surface is 2 mm. Any more, and water will start flowing towards a sewage system or surface water. This flow is called runoff. Consequently, this 2 mm is also the limit for the amount of evapotranspiration that can take place in a day. (Delft University of Technology, 2016)

Paved areas are usually connected to some type of sewer system. There are two major types of sewer systems to account for. Some areas use a separate sewer system, which means precipitation is transported apart from waste water and released upon surrounding surface waters. Others have combined systems, where all received storm water is combined with regular waste water and pumped towards sewage treatment centers. The mixture is only released upon surface water when overflowing using a CSO (Combined Sewer Overflow). While a municipality should try to avoid this, because of the severe consequences it has on water quality, the CSO can be of significance to the water balance. It is approached using the following formula:

$$CSO\ [mm] = \begin{cases} (i - C) * D - S\ ; & if\ D > 0\ and (i - C) * D > S \\ 0\ ; & if\ D > 0\ and\ (i - C) * D < S \\ 0\ ; & if\ D = 0 \end{cases}$$

Which on its turn uses *i* as the intensity of a precipitation event:

$$i = \frac{P}{D}$$

The intensity *i* [mm/h] is an average, acquired by dividing the total amount of precipitation (P, [mm]) by the total duration of precipitation (D, [hours]). The upper equation states that if the intensity of the precipitation exceeds the capacity of the sewage pump (C, [mm/hour]), also known as Pump OverCapacity or POC, for a duration long enough that the total amount of precipitation left is greater than the storage S of the sewer system, overflow will occur. This overflow is equal to the total precipitated amount minus the amount pumped away during the event and the storage of the sewer system. For regular combined sewage systems, the POC amounts to 0.7 mm/hour and the storage in the sewer system equals 7 mm. (Buntsma & Gastkemper, 2015, p. 11)

It is crucial to know of every polder what percentage of the paved area makes use of which sewer system. Horticulture is viewed as using a separate sewer system. Most municipalities present their sewage plans online. These plans, combined with a national sewage map provided by RIONED (figure 13) and, in the case of Rijnland, shapefiles provided by water boards are compared to acquire insight in the distribution of sewage networks. Important municipality plans that were used were published by the counsels of Rotterdam (Gemeente Rotterdam, 2020), Delft (Gemeente Delft, 2011), Pijnacker and Nootdorp (Gemeente Pijnacker-Nootdorp, 2018), Zuidplas (Grontmij Nederland B.V., 2015) and Bleiswijkpolder (Gemeente Lansingerland, 2015).

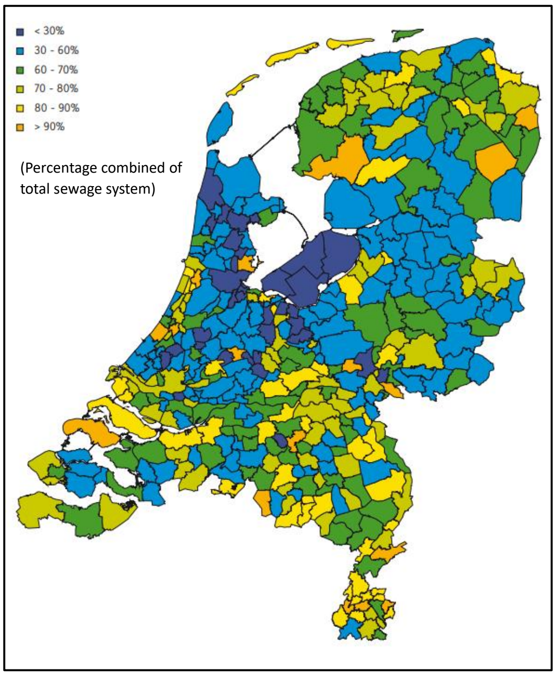


Figure 13 - Percentage combined sewage system of total system per municipality ***Invalid source specified.***

3.5 – Building and running the Water Balance

Now that, in previous paragraphs, the concept of the water balance and its main considerations have been explained in further detail, a description of the water balance execution is in order. 3.5.1 will explain the software of choice, after which 3.5.2 will describe the way the script works.

3.5.1 – Justification for choosing Python

The STOWA provides a water balance in the form of an excel tool, a rather lengthy sheet that can come in handy for the calculation of a small number of regions for which automation is not necessary. For the calculation of 49 different subregions that require automatic central accumulation of results, however, a python script will do better. The main advantages for the application within this thesis are that, in python, large datasets are more easily manipulated, automation of processes is possible, bug fixes are faster, the open source functionality grants more possibilities and, perhaps most important of all, calculations on the scale of this project can be done in seconds.

3.5.2 – Workflow of the Water Balance Function

The script itself follows a simple work flow. Every polder has its own python notebook that imports the water balance function, which is coded in a single central script, making for easy adjusting. The only input required in the notebook is the number of the polder, which is used to load all the necessary data from datasheets. The water balance function takes as inputs the static properties of the polder (areas of described classes), time series of external fluxes and CSO's, allowable water level ranges, the maximum pumping capacity and the EV-factor. All other parameters, such as the 2 millimeter water storage on paved surfaces, were all included within the function for the sake of brevity. The function immediately transforms the evapotranspiration time series to two separate series for water and land, multiplying the latter with the EV-factor. Next, empty lists are generated that are to be filled with either the daily volume of every model bucket or the daily value of every flux that still has to be calculated. The water balance function now calls another function, 'day' that calculates the values of the empty lists for the first day. If the values are such that the resulting water volume, implicating the water level, exceeds the maximum allowable level, the pumping station is turned on to remove excess water. If the surplus is greater than the maximum pumping capacity, the latter will be the pumped away amount of water. In case the water level plummets below the minimum level, the inlet is used (for which an endless supply from a neighboring boezem water is assumed). This 'day' function returns the new values, which are used as input for the next 'day', and so on. Finally, all flows and volumes are returned to the notebook of the polder in question. The notebook of the polder than generates graphs, calculates accuracy indicators and saves the results to a central file. The evaporator, day and water balance function code is added appendix B.2.

3.6 – Model validation and results

After all 49 subregions have been modeled, result compilation and analysis are in order. 3.6.1 will validate the model according to objective measurements. In 3.6.2, the sources of error will be listed with their countermeasures. Finally, 3.6.3 will discuss results from the model over the period 2000-2022. See appendix B.1 and B.3 for an overview of the water balance results.

3.6.1 – Model validation

The polder 2: Berkel is used as an example, as it turns out to be one of the best modeled polders. In the polder's notebook, the generated datasets are plotted with the available pumping data, as in figure 14. It should be noted that a bar diagram would better fit the graph as it does not depict a continuous process but discrete values. Yet, the line graph is very handy for visual inspection: it is easier to see where and when the model succeeds and fails.

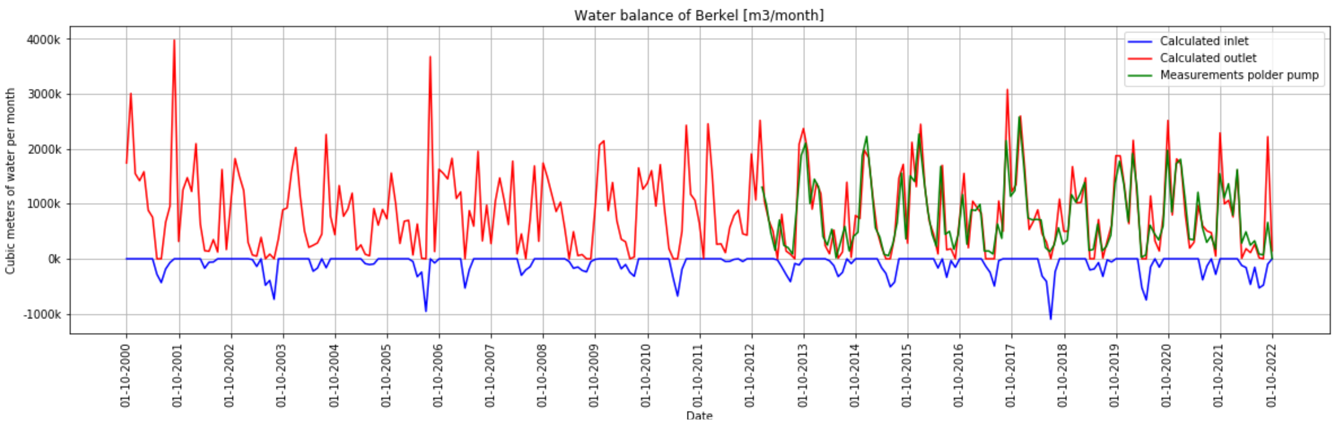


Figure 14 - Water balance result of subregion 2, Berkel

More important than the daily accuracy of the model is the yearly accuracy, as this thesis is centered around the principle of year-round buffering. It is also a better metric because the great end sum over a year will be relatively closer to the real value than the daily sum: where the model will instantaneously react to the water level when it falls outside the allowable interval, a water board's water level manager may wait a day because of various reasons, such as an anticipated precipitation event. An accumulated graph is made, resetting every 1st October. This date is convenient to use as a separator between hydrological years as it marks the transition from the drier, warmer summer to the colder, wetter autumn. See figure 15.

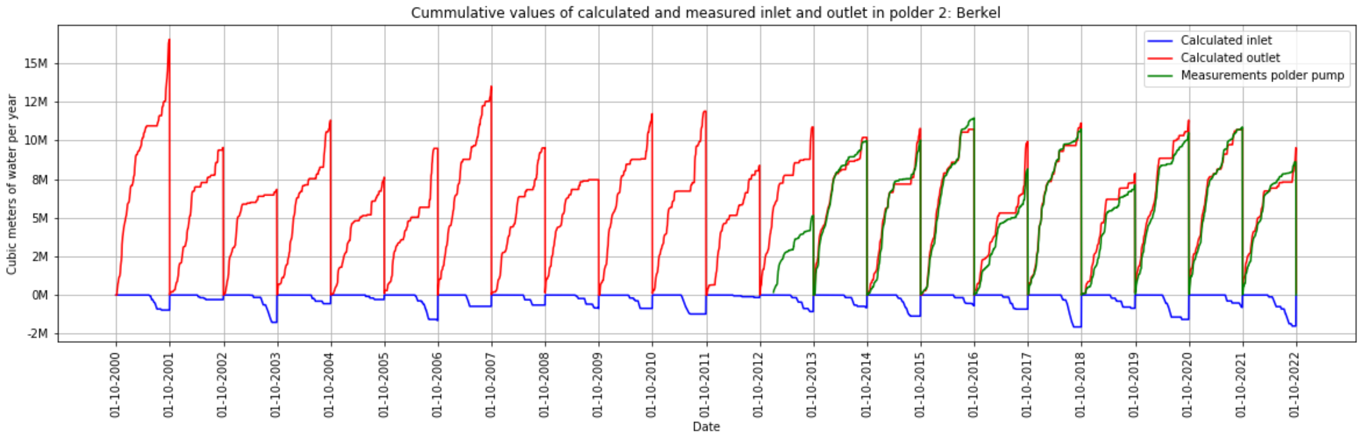


Figure 15 - Cumulative yearly results for subregion 2, Berkel

Another metric is used to denote accuracy: the NSE-value (Nash-Sutcliffe model Efficiency coefficient) is widely used to assess the predictive skill of a hydrological model. It is defined as:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2}$$

In this formula, $\overline{Q_o}$ is the mean of the observed pump discharges, Q_m^t is the modeled discharge at time t and Q_o^t is the observed discharge at time t. The maximum accuracy is achieved if NSE = 1 (as the measured and observed values cancel out in the numerator), meaning the predictive skills are in theory perfect. If NSE = 0, the predictive skill of the model is as good as the mean of the model samples. (McCuen, Knight, & Cutter, 2006) Because of the fact that the pumping stations depend on human behavior, the NSE varies for different time scales. To illustrate this effect, figure 16 is generated. It shows the errors between measurements over different timescales, divided by the number of days in the time scales, for polder 2: Berkel. It clearly shows that the longer time scales are reliable, where shorter time scales are heavily unreliable. Hence, the NSE calculated for years is to be taken more seriously than the NSE that is based on daily comparisons. For subregion 2 Berkel, the daily NSE amounts to 0.036 while the yearly NSE equals 0.73.

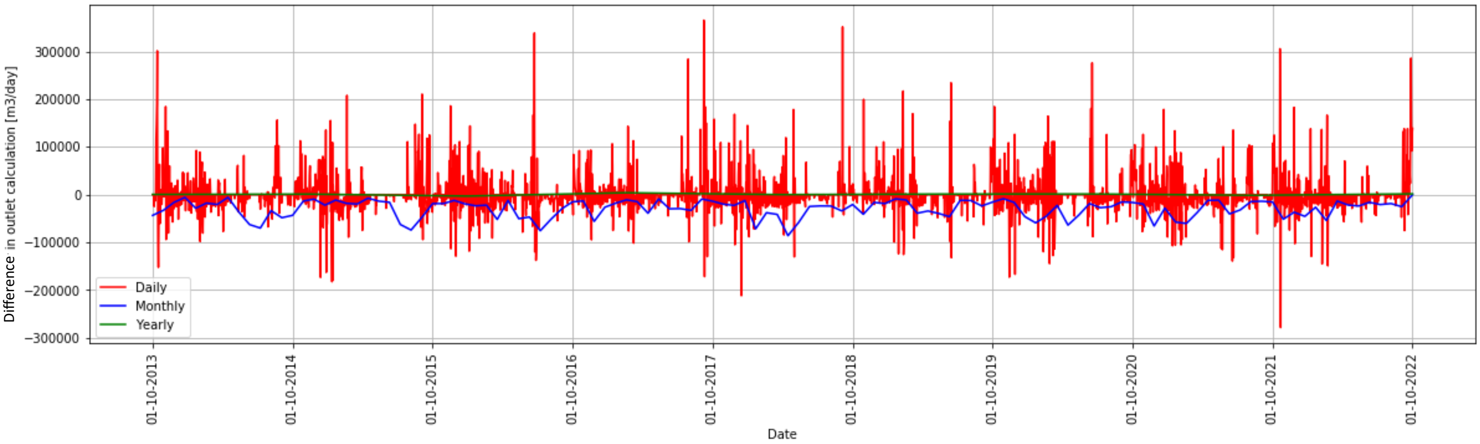


Figure 16 – NSE value over multiple time steps for subregion 2, Berkel

The spatial influence on the accuracy is of comparable importance and follows the same pattern: zooming out and putting together groups of polders will increase the NSE value. This is due to the many water connections between polders, where unregistered flows take place. They exist to diminish water shortages or surpluses by local interchanging of water between polders. The most logical thing to do is to split the case study area into the three water boards, as these areas each have their own water system and exchange of water between water boards is usually done via boezem waters that are not modeled. For determining the accuracy of the model, some subregions are not used, either because of a lack of data or because of a high C-value (3.3.2). Looking at table 2, polders 14 Ypenburg, 16 Geer- en Buurtpolder, 22 Meeslouwerpolder, 30 Polder Laag Boskoop en Rietveldse Polder, 36 Zwet- en Grote Blankaartpolder and 38 Boezemland all have C levels above 1. Subregions 39 Oostpolder, 45 Polders van Rotterdam, 46 Ringvaart and 47 Rotte have too little data to use for the NSE analysis, in the cases of the Rotte and the Ringvaart caused by lack of overlap between pumping series draining the same area. The yearly NSE per water board is presented in table 3. Next to the NSE values, a simple yet important ratio between the observed and modeled pumped discharges is placed. This can be seen as the percentage of water unaccounted for in the model.

Table 2 – Water board NSE values

Water Board	Years of pumping data	NSE	Observed / Modeled
Hoogheemraadschap Delfland	92	0.91	1.004
Hoogheemraadschap Rijnland	158	0.97	1.083
Hoogheemraadschap Schieland en de Krimpenerwaard	57	0.95	1.036

3.6.2 – List of sources of errors

As described, the NSE value, at least on the scale of a polder, is not to be seen as an absolute standard, but rather as an indicator of predictive power. This has to do with the general limitations of the water balance, applied in this way, over multiple 'isolated' polders. The assumptions here are that there are no unregistered exchanges of water crossing the limits of the control volume imposed by the polder, that a lumped bucket model will behave quite like the more complex lay-out of a polder and that a water board manages the water level solely by comparing the water level with its bounds. As described in various paragraphs in this chapter, these general assumptions will not always be safe, as listed in the reasons below:

1. Numerous water connections between polders exist to enable them to diminish water shortages or surpluses. These flows are not registered anywhere. (3.6.1)
2. Water boards have more criteria when managing water levels, like water quality. Hence the phenomenon called flushing. (3.3.2)
3. The difference between a lumped bucket model and the actual polder may be noticeable in the fact that the length of border the land shares with the water can for a great part determine subsurface flow and the different behavior of a set of level compartments versus a single one. (3.2.2 and 3.4.1)
4. The properties of the soil within a polder are not homogeneous in reality. (3.4.1)

There are additional assumptions that are not always safe for various reasons, introducing new sources of errors. These are:

5. The land use classifications can in certain cases be oversimplifications, for example when paved surfaces allow for some infiltration. (3.2.1)
6. Static data sources from 2017 have been used while land use before and after can be different. (3.2.2)
7. Evapotranspiration cannot be modeled with much confidence because of the transformation from potential to actual evapotranspiration carries uncertainties with it. (3.3.1)
8. Pumping data series are not always reliable, complete or sufficiently long. (3.3.2)
9. The percentage of paved area connected to a separate versus a combined sewage system can change significantly over the course of 20 years. (3.4.2)

Out of all of these, statements 1, 2, 5 and 7 seem to have the greatest impact on model performance. As described in previous paragraphs, adjustments were made to avoid great inaccuracy. For statement 1, the polders are lumped together for accuracy assessment (3.6.1). For statement 2, the C-value was calculated for every polder to find any extreme cases (3.3.2). For statements 5 and 7, the EV-factor was applied.

3.6.3 – Model results for 2000-2022

Appendix B.1 and B.3 show water balance results for the current climate. For the goal of this thesis some specific results are of importance. Firstly, an idea of the amount of water discharged over a year versus the amount of water let in over a year on the scales of the case study area, the water boards and the polders. Secondly, bottleneck polders need to be identified. To this end, the results of the model output will be transformed into yearly averages and presented on these three scales via a table and a graph. Next to the 'average' year, a typical dry and wet year will be used as indications of limit cases. Figure 14 shows the total amount of precipitation per year in the Netherlands. Between 2000 and 2022, the wettest year has been 2001: 1015 mm precipitated that year. The driest year has been 2018, with a total precipitation of 679 mm. This corresponds with figure 17 and the yearly cumulative graphs of the other subregions as one would expect the highest total pumping discharge in 2001 and the highest amount of inlet in 2018. These two years will subsequently be chosen as the 'outer bounds' of the hydrological behavior of the case study area.

	All units in [m3]	Dry Year (2018)			Average year (all)			Wet year (2001)			Area
Scale	Area	*Inlet*	*Outlet*	*Difference*	*Inlet*	*Outlet*	*Difference*	*Inlet*	*Outlet*	*Difference*	[million km2]
CSA	CSA	5.32E+07	2.46E+08	1.92E+08	3.47E+07	2.42E+08	2.08E+08	2.57E+07	3.81E+08	3.55E+08	453
Water Board	HHD	1.36E+07	5.41E+07	4.05E+07	8.96E+06	4.90E+07	4.00E+07	7.01E+06	7.67E+07	6.97E+07	95
	HHR	2.28E+07	8.10E+07	5.82E+07	1.60E+07	8.37E+07	6.77E+07	1.13E+07	1.35E+08	1.24E+08	150
	HHSK	1.69E+07	1.11E+08	9.37E+07	9.77E+06	1.10E+08	9.97E+07	7.42E+06	1.69E+08	1.61E+08	208

Table 3 – Main result table

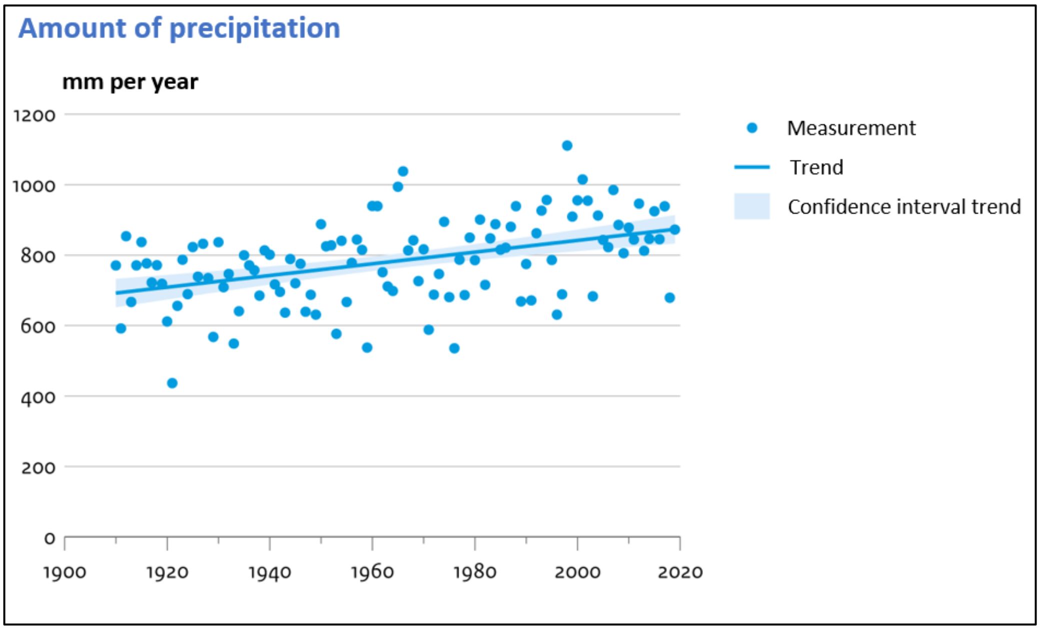


Figure 17 - Precipitation trend for the Netherlands (Rijksoverheid, 2020)

Appendix B.1 shows the end results for the simulation in a table. Table 3 is a shorter version containing only the case study area and the water boards. On average, the total inlet amounts to 14% of the total outlet. The inlet in 2018 was 53% higher than average, while the outlet stayed approximately the same. The outlet in 2001 was 57% higher while the inlet was decreased by 35% with respect to the average year. Figure 18 below shows the results in a map, with the annual inlet and outlet per square meter for every subregion. Subregions 46 and 47 (the Ring Canal and the Rotte) are ignored as they function as boezem waters.

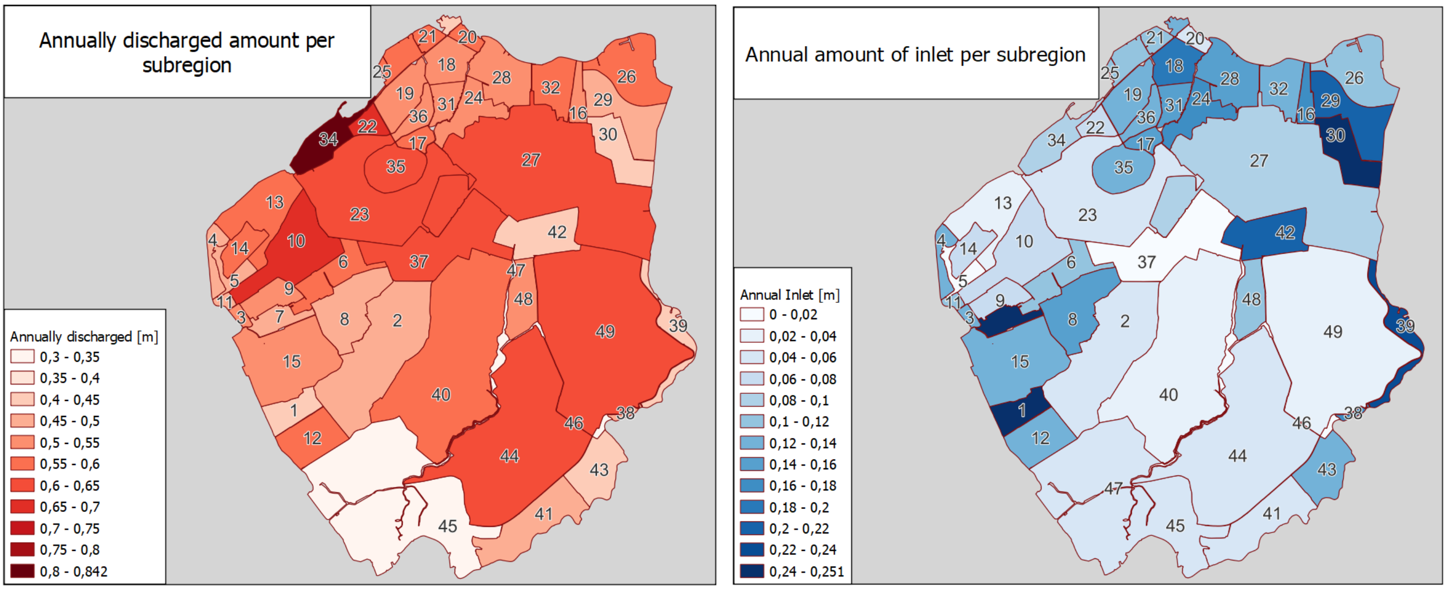
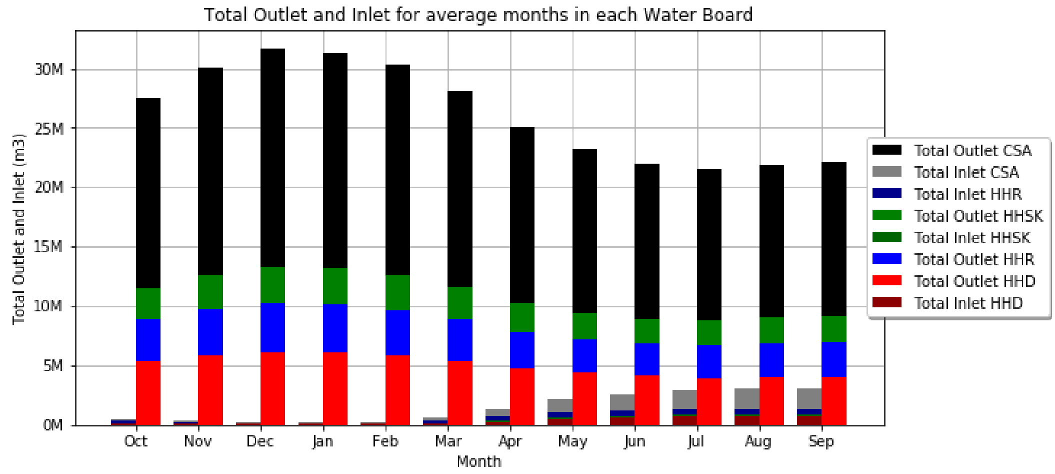


Figure 18 - Annual discharge and inlet per unit surface area per subregion

The bar plots in figure 19 below show the total inlet and outlet for averaged months for every Water Board and the entire case study area. As the inlet is of a considerably smaller scale, it has its own bar graph. The CSA values consist of the sum of the water boards. The bars are absolute, not stacked.



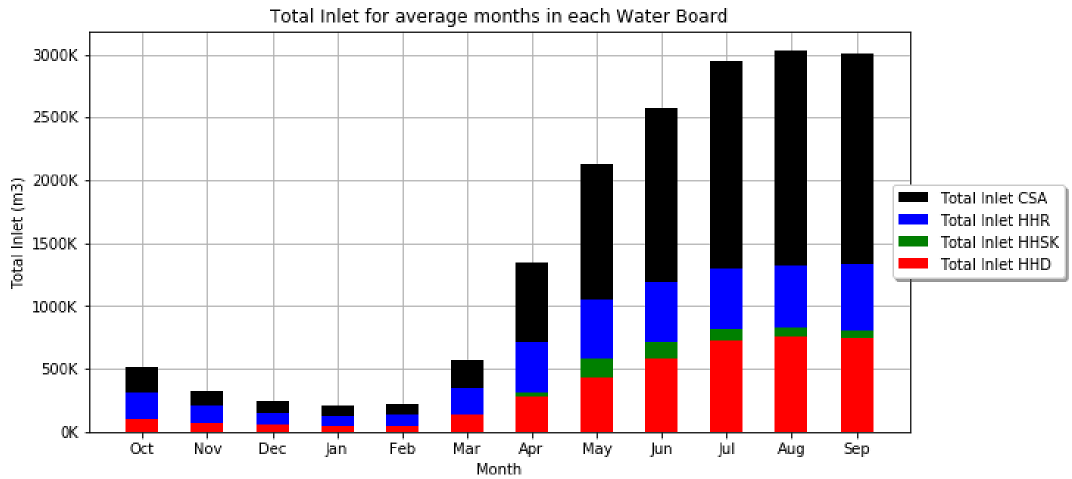


Figure 19 – Total inlet and outlet for average months for each Water Board and the total CSA

3.7 - Conclusion

Some conclusions about the model and the state and workings of the current water systems can be drawn. Firstly, conclusions about the validity of the model will be drawn in 3.7.1. Consequently, conclusions about the model results will be presented in 3.7.2.

3.7.1 – Model validity

The NSE values are indicative for model accuracy, as explained in 3.6.1. As an NSE value above 0.4 is considered acceptable for certain hydrological purposes, the values presented in table 3 indicate a high degree of accuracy. Though the NSE is widely regarded as a useful measure for precision, a visual inspection must be performed as well. Using the example of subregion 02: Berkel once again, figures 10 and 11 can be used. Important aspects are that peaks and baseflow are modeled well, as can be seen in figure 10. Furthermore, figure 11 shows that both wet and dry seasons are modelled well and that the total cumulative flows match the measurements. It is thus concluded that the water balance can be used for the quantitative analysis of the case study area. (Moriasi, et al., 2007)

3.7.2 – Model results

Going on to analyze the model output, three conclusions can be drawn:

1. Table 3 makes clear that the annual outlet follows the size of the area drained while the total inlets of the water board are closer to each other. It also suggests that a dry year does not mean lower outlet but that a wet year does mean less inlet. This can be due to the fact that a dry year is characterized by a lack of precipitation in the summer season while a wet year is characterized by a year-round increase in precipitation.
2. Furthermore, figure 18 shows that, on average, the subregions in the center of the case study area pump out more water while the subregions on the edges let more water in. This follows from the fact that the center subregions tend to experience a high degree of upward seepage, while the outward subregions have low seepage or even infiltration (see figure 12).
3. Throughout the year, the outlet and inlet show the expected counter-phased sinus pattern. The inlet seems to be more sensitive than the outlet, though. This is explained by the evapotranspiration having a relatively more extreme sway throughout the year when compared to precipitation.

Chapter 4 – A hydrological simulation of the center of South-Holland in 2100

To answer the main research question, the hydrological behavior of the polders of the case study area around the year 2100 must be simulated. To this end, the water balance of chapter 3 will be adjusted to represent future conditions. Both the input (like weather time series) and the constant parameters (like the properties of the modeled area) will undergo alterations. The first paragraph will explain what kind of climate scenarios will be modeled and which further adjustments will be made (§4.1). The paragraphs following will describe these: precipitation and evapotranspiration (§4.2), seepage and flushing (§4.3) and the paved surface including sewage (§4.4). All these adaptations and the scenarios will be summarized (§4.5). Then, the water balance will be run and its results presented (§4.6) and compared to the ones in chapter 3 in the conclusion (§4.7).

4.1 – Adaptations to the year 2100

The water balance will be altered to a so-called 0-scenario. This essentially means that the model will predict future conditions in which no extra counter measures are used to combat the growing load on the water system of the heart of South Holland. All other developments will continue. Several variables will have to be changed to mimic these conditions, first and foremost due to climate change, described in 4.1.1. In 4.1.2, changes to the case study area will be identified.

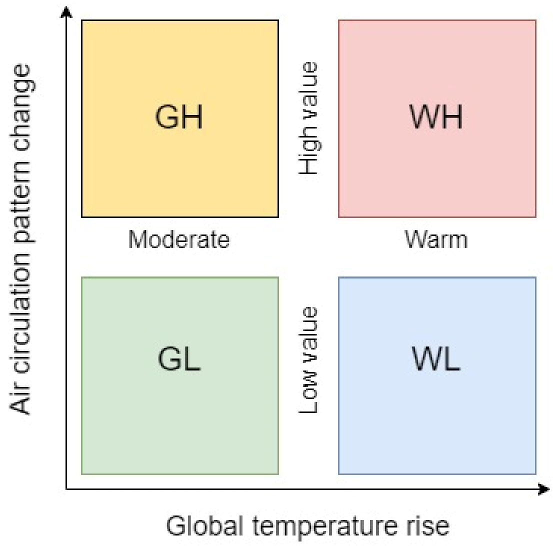


Figure 20 – KNMI climate scenarios (KNMI, 2015 (a))

4.1.1 – KNMI-scenarios

The KNMI climate scenarios will be used to predict the changing weather. (KNMI, 2015 (a)) These scenarios mean to represent the years 2050 and 2085, but the precipitation and evapotranspiration series they model reach to 2105, crossing the desired time horizon of 2100. The KNMI have distinguished four separate scenarios that are combinations of two factors: the effect of global warming (*gematigd* or moderate "G" to warm "W") and the change of air circulation patterns (value of change either low "L" or high "H"). For this thesis, all 4 scenarios will be used, as shown in figure 17: WH, WL, GH and GL. The increases in global temperature are +1.5 °C and +3.5 °C compared to 1990, for G and W respectively. The changing air circulation is hard to represent with such a simple metric but will be implicit in the scenario's outcome. The high value means that, in winter, wind will often blow from the west, which causes soft, wet winters. In summer it means wind direction will increasingly shift to head west, bringing a land climate with, making the weather more dependent upon high pressure zones accompanied by warm and dry air, causing longer rainless periods in summer with occasional heavy precipitation. For the low value these influences are more subtle, yet present. Scenario WH is the most extreme as both global warming and changing air circulation patterns cause extreme precipitation patterns: warm air can hold more water than colder air and high pressure zones can cause spontaneous high intensity precipitation. All scenarios expect, because of the changing precipitation patterns, that river discharges will become higher in winter and lower in summer, possibly affecting the amount of seepage for the subregions that are close to rivers. (KNMI, 2015 (a)) The variables that will possibly change for the water balance because of climate change are thus precipitation, evapotranspiration and seepage.

4.1.2 – Adaptations to the Case Study Area

Next to developments in terms of climate change, the dynamics of changing land use must in some way be represented in the model. There is no way to be sure of how the case study area will look like in 80 years, which is why a number of assumptions are in order. As the model should reflect a 0-scenario, no adaptations to water management are modelled. This means the level decisions, pumps and layout of the polders will remain as they were, to give insight into what would happen if no action were undertaken. The second assumption is that vegetation types will stay approximately the same: these have a substantial influence on evapotranspiration and it is impossible to predict agricultural developments towards 2100. Hence, the evapotranspiration factors will stay constant as well. The last assumption holds that, apart from the paved surface and sewage system use, the land use distribution will stay constant as well. As this last assumption reveals, changes in the paved area and the distribution of sewage systems are supposed to have a significant impact on the future water household, which will be covered in more detail in paragraph 4 of this chapter.

4.2 – Transforming precipitation and evapotranspiration

In a sizable collaboration, KNMI, HKV, STOWA, Het Waterschapshuis and Hydroconsult Siebe Bosch have created time series for numerous climate scenarios and time horizons. Different sources and techniques were used for the statistically derived series, hence the division in 4.2.1 (precipitation) and 4.2.2 (evapotranspiration) in this paragraph.

4.2.1 – Precipitation in 2100

Future precipitation time series are made available on meteobase.nl, a repository for meteorological data. As certain statistical parameters are location sensitive, the Netherlands has been divided into regions with different statistical properties, as in figure 18. The letters stand for a range of factors that is multiplied with the 'base statistic,' a bench mark time series. The H stands for a high value, the L for a low value and the R for a multiplication factor of about 1. The case study area thus falls under the regional class H-R. This means that, throughout the year, the area receives a relatively large amount of precipitation while the winter regime is more moderate, compared to the rest of the country. (STOWA, 2019 (b))

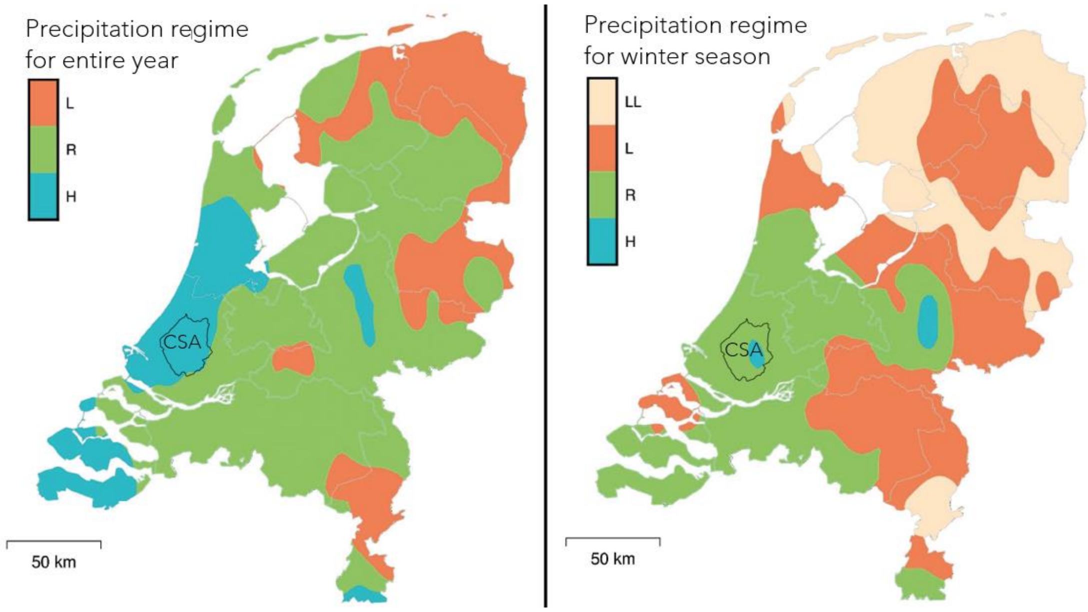


Figure 21 – Statistically different precipitation regions (STOWA, 2019 (b))

Table 4 – Comparing scenarios and present conditions, data from (KNMI, 2015 (c))

Scenario	Driest year	Prec. amount	Wettest year	Prec. amount	Average yearly prec.	Average yearly evap.	Summer days P = 0 mm	Summer days P < 1 mm
Present	2018	679	2001	1015	858	627	98.5	98.5
WH	2087	638	2089	1521	996	661	73	110
WL	2089	628	2091	1511	993	636	69	106
GH	2089	629	2091	1430	963	614	69	104
GL	2089	622	2092	1451	956	615	46	93
All amounts in millimeters								

The acquired data sets are analyzed for the relatively dry and wet years. See table 5. Compared to the dry and wet years of the past twenty years, 2018 (679 mm) and 2001 (1015 mm), it can be noticed that the gap between these extremes has grown. Especially the wettest year is wetter, being increased by around 50%. Upon analysis of the precipitation time series, it was discovered that the quality of the statistical transformation lacked in an important aspect. Editing rain intensity is done quite straightforward, by applying a statistical variable to existing series. Creating periods of drought, though, appears to be difficult to model. (Bakker & Bessembinder, 2012) Lack of this quality is fatal for modeling inlet during summers, rendering reduced change or even reduction of total inlet where it is expected to increase. The last two columns of table 4 show this effect. The summer days are counted from May up to and including August. The current summer climate shows almost no small precipitation events, solely drought or more sizable precipitation events. The future scenarios show the reverse: fewer dry days and a lot of days with small precipitation events, while the drought effect should actually be increased.

In table 5, the percentage of total precipitation per season for every scenario is shown. Scenario GL stands out as it shows a sizable decline in winter and autumn precipitation and a rise in summer and spring precipitation compared to the present climate, which is not the case for the other scenarios. It goes to show that if both global warming and air circulation pattern change are small, the precipitation distribution will levitate towards the warmer seasons. The opposing scenario, WH, shows that an increased effect of these phenomena will emphasize the current distribution. Another remarkable observation can be made of scenarios WL and GH, the more moderate scenarios, as they show nearly equal distributions in both table 4 and table 5. Apparently, the effects of global temperature rise and air circulation pattern change are quite comparable in these respects. What is very important to keep in mind while observing the average yearly numbers is that the future scenarios all have more variability between the hydrological years. For instance, variance in the yearly precipitation sum for the present measurements is around 11.000 mm for all weather stations (using data from 2000-2022 on the 5 KNMI stations depicted in figure 10), while for scenarios it ranges from 29.000 (GL) to 41.000 mm (WH). This means that, for all future scenarios, yearly accumulated precipitation will be much less consistent.

Table 5 – Percentages of seasonal precipitation and evapotranspiration, data from (KNMI, 2015 (c))

Scenario	Winter		Spring		Summer		Autumn	
	%P	*%EV*	*%P*	*%EV*	*%P*	*%EV*	*%P*	*%EV*
Present	26	5	18	32	27	47	29	16
WH	30	5	19	30	22	50	29	15
WL	25	5	20	30	26	49	29	16
GH	26	5	19	32	26	48	30	15
GL	18	5	27	32	30	48	25	15

All numbers are percentages of the total yearly precipitation or reference evapotranspiration for a scenario

4.2.2 – Evapotranspiration in 2100

KNMI have developed a transformation program for the adaptation of existing time series to future scenarios. The Makkink reference evapotranspiration (from 3.3.1) cannot be transformed directly, though. Rather, global radiation and temperature are projected and the Makkink reference evapotranspiration is calculated as a function of those through the following equation.

$$LE_{pot} = \alpha \frac{s}{s+\gamma} K \downarrow$$

Here, LE_{pot} is the Makkink reference evapotranspiration, α represents an empirical coefficient, s denotes the slope of the saturation function at the modelled air temperature T, γ is the psychrometric constant and K is the modelled incoming global radiation. In short, for modeling temperature, regional parameters and a gradation in percentiles was used. An extensive energy balance for the atmosphere generated the numbers for the global incoming radiation. (KNMI, 2015(b))

As can be seen in table 5, crop reference evapotranspiration predictions exceed current standards for the W-scenarios while the G-scenarios fall slightly below todays' average. This is remarkable because even the G-scenarios to some extent count on global warming and thus an increase of global radiation. The explanation lies in the transformation: the stations available at the transformation program (KNMI-stations 210 Valkenburg and 344 Rotterdam) measure a slightly lower average evapotranspiration than the additional stations that were used to compute the current evapotranspiration. Furthermore, table 5 presents the seasonal percentage of the yearly evapotranspiration, indicating that the evapotranspiration distribution hardly changes for all scenarios.

4.3 – Seepage and flushing in 2100

This paragraph considers both seepage and flushing as these phenomena are intertwined: the majority of the water volume used to flush a polder is due to seepage, as it is the major contributor to desalination. Thus, seepage will be quantified first (4.3.1) and consequential flushing second (4.3.2).

4.3.1 - Seepage

Not many model runs have been devoted to modeling the magnitude of seepage in the future. The *Klimaateffectatlas* (Climate effect atlas), however, gathers such information to visualize climate change effects. Figure 20 shows the amount of change of seepage expected in 2050 for scenario WH, modeled with the *Nationaal Water Model* (National Water Model) in 2016. (Klimaateffectatalas, 2016) It shows that by far the greatest portion of the area will not or barely be dealing with changes in seepage within the next 30 years, which is logical as the boezem water levels are fixed. The only significant changes appear to be in regions that have an aggravated amount of seepage in the present as well, being located alongside the Gouwe and the Hollandsche IJssel on the eastern side. Extrapolating to the year 2100, this development is expected to continue linearly. Hence, the amount of seepage will be slightly different for some polders compared to the validation data using the same procedure as in 3.3.3. There are good reasons to believe that the upwelling of brackish water will be limited by human interference in case these predictions are too conservative: the cost of brackish upwelling is immense since it interferes with agriculture and biodiversity. There are possibilities to limit seepage in the target area, for example by closing the Nieuwe Maas with a sluice that blocks the intruding saline water. It is thus assumed that, either naturally or artificially, seepage increase is limited and can be extrapolated from the National Water Model.

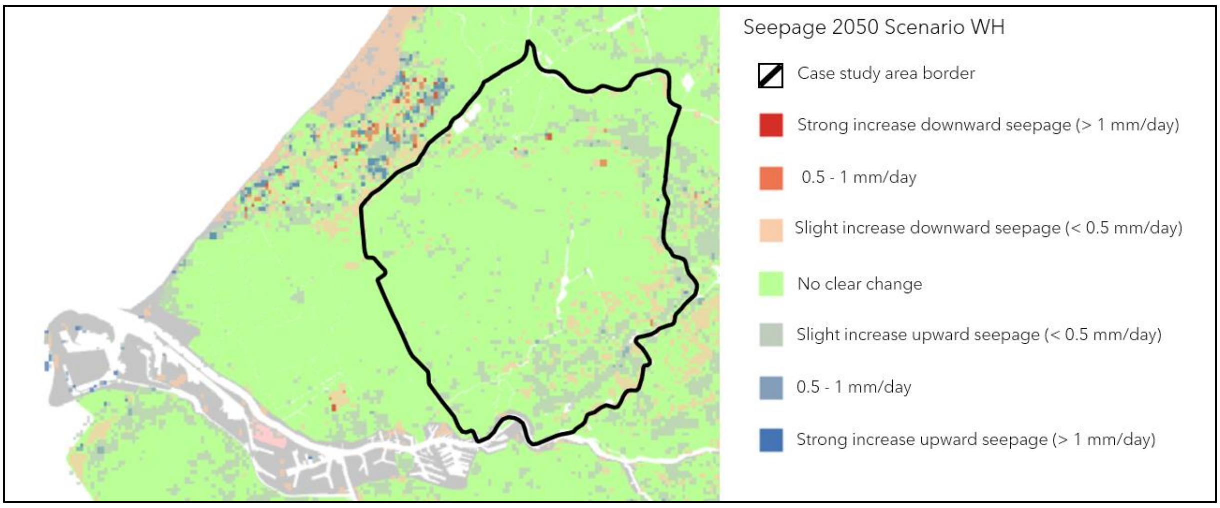


Figure 22 – Seepage in 2050 according to NWM (Klimaateffectatalas, 2016)

4.3.2 – Flushing

As the introduction of this paragraph stresses, flushing is immediately linked to (upward) seepage due to the solvents in the upwelling water. Since the amount of seepage is said to barely change in comparison to the other input variables, flushing will similarly remain constant. That is to say, as flushing is implicit in the outcome of the validated model, it will be implicit in future scenarios as well.

4.4 – The paved surface and sewage systems in 2100

The hydrological behavior of the case study area will change due to the expansion of cities such as Rotterdam, the Hague, Zoetermeer and Leiden but also by the emergence of new urban cores. The increased paved area will have its effect (4.4.1) and consequently the changing trend in sewer system use (4.4.2).

4.4.1 – Distribution of paved surface area in 2100

Specific data on the spatial development of paved areas towards the year 2100 is not yet available. In South-Holland, however, the portion of paved area is dominated by the residential category. To estimate the increase in paved area, it is assumed that the building of new residences will follow the provincial population growth. Between 2019 and 2050, the province of South-Holland expects their population to increase from 3.71 million to 4.2 million persons, an increase of 13.2%. (Province of South-Holland, 2020) The national population is expected to grow in the same period from 17.3 million to 19.6 million persons, an increase of 13.2 % as well, calculated by the CBS (Central Bureau for Statistics). (CBS, 2022) Apparently, according to the province, the population of South-Holland will grow as fast as the national population. The national population growth projections can thus be used to estimate the provincial growth. Towards 2100, a total of 22.8 million citizens are expected to be living in the Netherlands, an increase of 31.8%. South-Holland will then host about 4.89 million people, using the same percentage. A second assumption is that the total paved area will grow with this percentage as well, as all these new residents will need an equal increase in utilities, work space and infrastructure. Underlying this assumption is the question of efficient land use. It is hard to say if the efficiency concerning residential space, residents per surface area unit, will change. This area already contains some of the most densely populated zones in the Netherlands: of the 10 most densely inhabited cities, 8 are located within or near the border of the case study area. (Top10Tiers, 2019) Additionally, the number of persons per residence is expected to drop in the future as a result of a longer life expectancy and an increase in divorces. (PBL/CBS, 2022) On the other hand, the pressure on land use will increase, making it more likely that the new residences will for a great part be relatively space efficient. Also, water boards are determined to make paved areas more permeable, granting more infiltration and making for less paved surface area within the urban zone. (Province of South-Holland, 2021) For this thesis, it is assumed that these phenomena will balance each other out, so that we can conclude to a total increase of 32% of paved surface area in the province of South-Holland.

The portion of new housing projects that the central part of South Holland, the case study area, will take upon itself is difficult to quantify, though some ball park figures can be derived from the current building plans. The province of South-Holland plans to build circa 250.000 new houses before 2030, indicating that the region between Leiden and Dordrecht will foremostly be deployed to this purpose. (Province of South-Holland, 2023 (b)) About half of that zone lies within the case study area, the half with the most unpaved space left. The case study area clearly seems appealing to the province. Conversely, as mentioned earlier in this section, the central part of South-Holland already is one of the most densely populated zones and these large projects on the short term do not guarantee a trend of cramming up this area in the long run, especially since the province announced the emergence of new urban cores throughout the province. It is, in conclusion, likely that the case study area will follow a comparable increase of housing towards 2100 with respect to the entire province.

Within central South-Holland, existing cores will expand and new cores will emerge, especially along the section between Leiden and Dordrecht. A set of possible buildup zones is shown in figure 20. In the datasheet holding the static spatial data, existing cores were expanded by 20-30% depending on available space and the new zones were used to fit the eventual amount of additional paving. By 2100, the paved surface area will by this estimation cover 43% of the case study area, about 10% more than it does currently. A balance between giving up agriculture and nature was strived for. Especially subregion 27: Noordplaspolder will be used for living space, about a quarter of the total added surface area. In this scenario, Rotterdam will expand to the Northeast. Delft, Leiden and Alphen aan den Rijn grow Southwards and Zoetermeer Northwards. In total, 12 subregions have been appointed to contain building sites. As unsure as this impression may be, it is used for the sake of this thesis' thought experiment to get across a possible scenario. Even if the distribution of the added paved area comes out differently, the water balance results will still be relevant as this research is focused on coarse numbers.

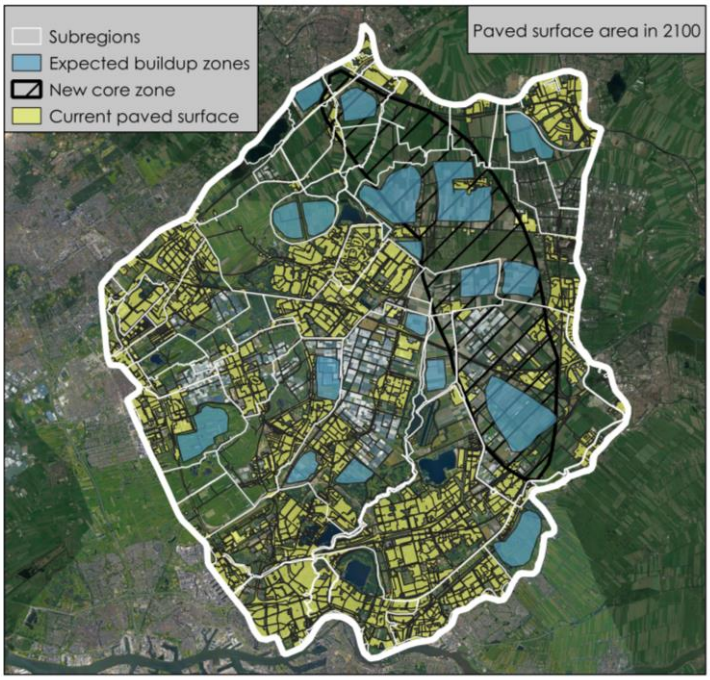


Figure 23 - Possible build up scenario for 2100

4.4.2 – Sewer systems in 2100

The expected increase in paved surface area is accompanied by a proliferation of separate sewer system deployment, as all municipal sewer plans (see 3.4.2) seem to point to this system as the preferred method, foremostly because of the water quality issues combined sewer systems create and the unnecessary large influent they cause for sewage treatment plants. This means that most newly built residential areas will make use of a separate sewer system and that, where possible, they might replace combined sewer systems when their service lifetime has ended. As the average sewer system has a service lifetime of 60 years, replacements will be in order long before 2100. Yet, it is unlikely that all combined sewage systems will disappear. As the paradigm shift towards separate sewer systems demands large scale excavations and additional subsurface infrastructure, historic city centers often do not permit sewage transformations. Besides, municipalities usually begin with transforming the 'low hanging fruit,' i.e., the cheapest and easiest regions to reconnect, which can result in hybrid systems where only part of a system is decoupled. . (STOWA, 2019 (a)) Thus, since the time horizon of 2100 is distant, it can be expected that great parts of the urban region have been decoupled but that certain parts of historic city centers will be part of hybrid systems. In the data sheet holding static spatial data, all paving is drained by means of separate systems except for a portion of historic city centers, of which about 40% may remain combined (stichting RIONED, 2013)

4.4.3 – Hydrology of future build-up

While the average required living space per person is assumed to remain somewhat constant over the course of the next century, the permeability of the paved surface area is likely to increase. As hydrologically advantagous technologies, like green roofs, wadi's, infiltration crates and permeable pavement tiles are acquiring more and more popularity among hydrologists and urban planners, a significant segment of the paved area will allow for infiltration and the retainment of precipiation. (Hattum, Blauw, Jensen, & Bruin, 2016) As these methods will not be deployed right away but gain momentum within the next couple of decades, not all newly build areas will contain them. By 2100, it is estimated that 30% of the additional paved zones (blue in figure 23) will allow for infiltration and water retention. Any degree of overestimation in this percentage might be compensated by posing that, if a transition towards 30% greener paving is too costly or in any other way challenging, there is the option of building more vertically. Deploying more high-rise could very well reach a hydrological equivalent in terms of paving compared to water smart techniques. On top of that, these techniques will have an influence on the existing paving as well. Wadi's, permeable tiling and subsurface water storages are relatively easy to install in gardens, especially since multiple provinces, water boards and municipalities are starting projects to subsidize the 'climate friendly garden'. (Province of South-Holland, 2023 (a)) (Waterschap Hollandse Delta, 2022) As a result, it is estimated that 20% of the existing paved area will be transformed to allow for infiltration and water retention, marked yellow in figure 23.

4.5 – Model scenario summary

Four climate scenarios are modeled in the water balance. Table 6 states the properties of the scenarios, summarizing what has been stated in paragraphs 4.1-4.4.

Table 6 – Summary of the four future scenarios

	GL	GH	WL	WH
Global temperature rise	+ 1.5 °C	+ 1.5 °C	+ 3.5 °C	+ 3.5 °C
Wind pattern change	Low value	High value	Low value	High value
Effect	Summers are slightly drier, winters will be somewhat warmer and wetter.	Soft and wet winters, dry summers.	More extreme weather pattern with storms and softer winters.	Most extreme scenario, summer droughts with storms and warmer, wetter winters.
Seepage	All scenarios deal with slightly increased seepage, especially for the polders positioned near the Hollandsche IJssel.			
Flushing	As seepage increases only slightly for all scenarios, so does flushing.			
Paced surface area	For the entire area, 32% paving is added with respect to the current amount. Of new paving, 30% will allow for infiltration while 20% of existing paving will do so.			
Sewer system	Newly built areas will be using separate sewer systems, while 40% of the existing paving will remain connected to combined sewer systems.			

4.6 – Model results

Below, in figure 24, the main output graph of the simulation is shown. Output for the jurisdiction areas of all three water boards for all scenarios can be found in appendix C. Some observations can be made immediately. Firstly, scenario GL seems to be tamer, in all respects, than the current climate. Secondly, seasonal differences in outlet and average monthly outlet will increase for

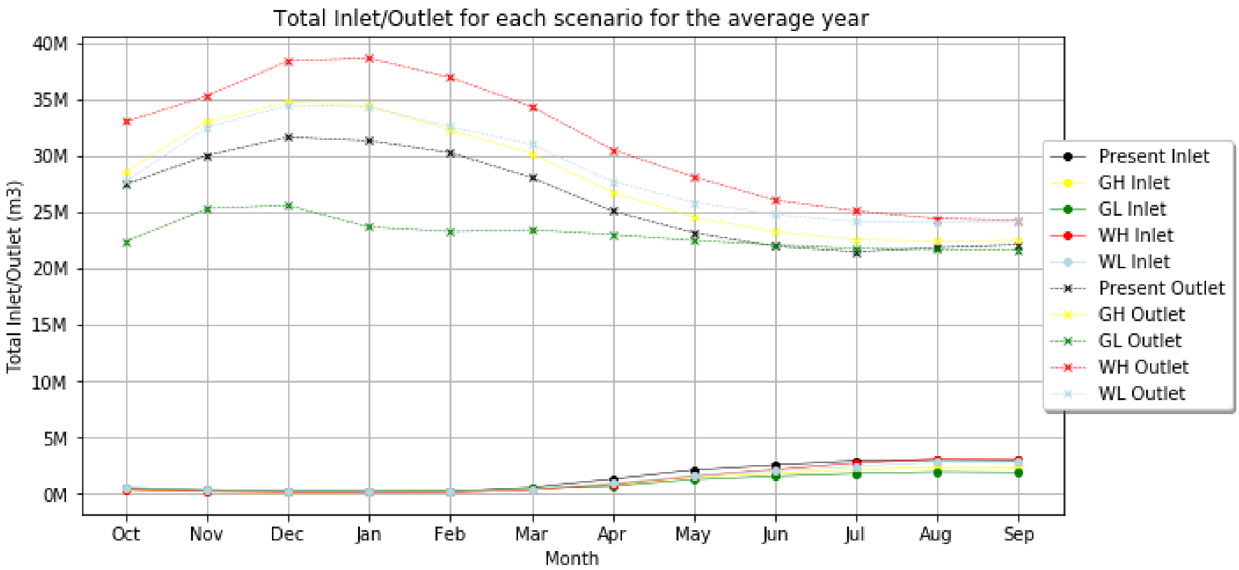


Figure 24 – Main output graph of simulation, values are discrete

all scenarios except GL. Thirdly, monthly inlet for the average year hardly changes for each scenario. The figures in appendix C show similar results. All water boards respond comparably to the scenarios (almost identical when accounting for differences in surface area). Figure 25 presents the mean of the scenarios with and without scenario GL versus present conditions. Furthermore, appendix C.2 shows the average annual inlet and outlet in meters, as it is made up of cubic meters of moved water volume over square meters of surface area.

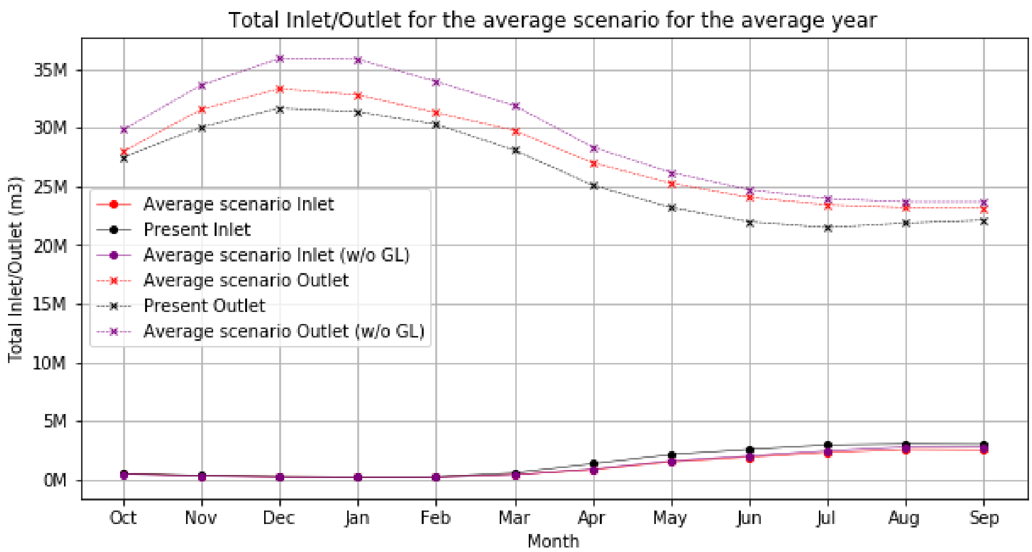


Figure 25 – Mean climate scenario outcomes, values are discrete

4.7 – Conclusion

Several important conclusions can be drawn from this chapter to be taken into consideration in the next chapter.

1. The model outcome shows a likely increase of year-round discharge while inlet remains constant. As discussed in 4.2.1, the constant inlet was to be expected as the precipitation time series did not contain sufficient drought periods to mimic expected future weather conditions. It is important to keep in mind that actual inlet will be greater while designing the water buffer.
2. All scenarios predict a more extreme variant of the yearly precipitation distribution, except for GL. For GL, total outlet will decrease despite its higher mean annual precipitation sum because of the rather uniform distribution of its precipitation.
3. Variability of yearly precipitation sums will greatly increase for all scenarios. This matters for the size and purpose of the water buffer.
4. Looking at appendix C.2, the distribution of bottlenecks will stay as is, dominated by the amount of seepage. One major change can be noticed, though: the increased paving on larger center polders will make these more sensitive to precipitation and thus make them stand out even more in terms of discharge.
5. Inlet and outlet are scalable for every water board according to their surface area.

Chapter 5 – Water buffering capacity

In the previous chapter, the water balance was run for future scenarios and insight into the in- and outflows of the case study area was created. To be able to establish the required buffer volume, it must be clear for what purpose the buffer will be used. The first paragraph will explain the general hydrological purpose and separate it into three criteria (§5.1). Consequently, these criteria are analyzed individually. Firstly, the buffering of increased inequality of water inflow distribution throughout the expected average hydrological year (§5.2), secondly the contribution during droughts (§5.3) and thirdly the ability to hold storm water (§5.4). The net buffer capacity is determined lastly (§5.5). The physical means by which the buffering of the entire case study area will take effect is now simply called 'the buffer', but there is no definitive form to it yet. As considered in the next chapter, it is possible to have multiple buffering zones with different qualities. Central to the design of the buffer is that it should mitigate the expected *increase* in flood and drought severity.

5.2 – General hydrological purpose

This paragraph will start the design process. Section 5.1.1 will introduce the ultimate goal of the buffer and the design climate scenario. Section 5.1.2 will then produce three design criteria from the general goal.

5.1.1 – Formulating the hydrological goal and design scenario

The ultimate goal of the supposed buffering is to provide robustness to compensate for the influences the changing climate will pose on the water system of the case study area in the year 2100. The scenario that will be used to design the buffer capacity is the average of the output of scenarios WH, GH and WL. Scenario GL is excluded because of two reasons. First and foremost, picking a scenario to act as the design load on the system requires choosing a relatively unfavorable possibility. An extremely unfavorable scenario might lead to unrealistic outcomes and a moderate scenario might lead to underestimation of the optimal design. The second reason is that, as described in 4.2.1, the time series for GL might unintentionally be more timid.

5.1.2 – Introducing three criteria

From a water management point of view, three main uses are envisaged for the buffer to realize this ultimate goal. The first purpose is to buffer the increased inequality of water income for the expected average hydrological year. As the KNMI scenarios predict, water distribution throughout the year is expected to become more asymmetrical in the future, creating more periods of drought and extreme precipitation events. That leads to the second purpose: the buffer should be able to contribute in times of serious droughts, i.e., droughts that are expected less frequently than once per year. The third purpose is to serve as a fast solution for preventing flooding calamities. As discussed in the previous chapter, KNMI reports covering the changing weather patterns denote that extreme precipitation events will occur more often throughout the year and that they will be of considerably higher intensity compared to todays' climate. The possibility of quickly discharging a portion of the surplus might be provided by a buffer. (KNMI, 2015 (a))

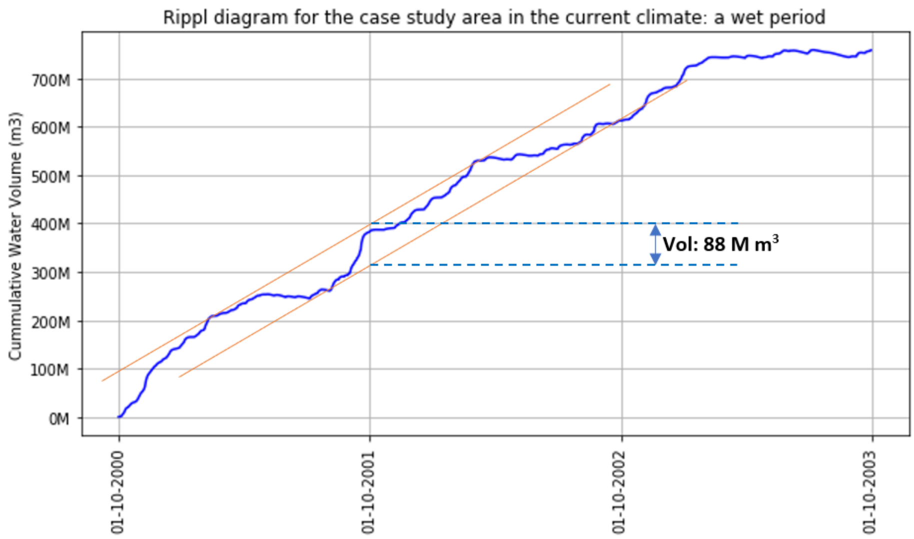


Figure 26 – Rippl diagram for case study area in current climate using model output

5.2 – Criterion 1: Buffering throughout the expected average year

For determination of the buffer size needed to mitigate the increased inequality in water inflow distribution, the expected future cumulative inflow can be compared to the current cumulative inflow. A proven way to do this is to make use of the Rippl diagram, which is introduced in 5.2.1 and deployed to solve for the first criterion in 5.2.2.

5.2.1 – Introducing the Rippl method

This method uses the accumulated water flow of the water system to estimate the size of a reservoir depending on the water demand, see figure 26 as an example. The figure shows the cumulative water volume flowing through the water system between 01-10-2000 and 01-10-2003, which consists of the sum of precipitation, surface runoff, combined sewer overflow, subsurface flow, seepage and evapotranspiration. The entire water system of the case study area acts as the control volume in determining these fluxes. The two parallel tangent lines are drawn from winter peak to winter peak (upper orange line) and from summer trough to summer trough (lower orange line), which can be seen as demand lines. When the cumulative volume is approaching the upper line, the reservoir is filling up. When it steers away towards the lower orange line, it is spilling water. The steepness of the tangent lines determines the demand, and by that the degree to which the reservoir is filling or spilling. (Santos, Filho, Vasconcellos, Júnior, & Santos, 2022) The distance between these tangent lines along the vertical axis determines the magnitude of the reservoir needed to fully buffer the water system for the period 2001-2002, in this case 88 million m^3.

5.2.2 – Capacity determination for criterion 1

Having a buffer capacity of 88 million m^3 would be excessive. With such a buffer, there would be almost 200 mm of buffer water across the entire case study area (452 million m^2), and all the necessary water inflow could be obtained from the precipitation falling within the area. The use of rivers for inlet, as is currently done, eliminates the need for such a large buffer. The main objective is to address the increase in water inflow distribution inequality, so the crucial factor is the difference in size between a buffer that can handle an average hydrological year in the current climate and one that can do so in the chosen climate scenario. For every climate scenario and for the current climate, four separate Rippl diagrams were created. Every set of diagrams contains a wet period, a dry period and two average periods. All these diagrams are included in appendix D. Table 7 below summarizes their results. The dry, wet and average periods were chosen by comparing the output of yearly sums of the water balances, which are included in appendix C.2. It appears that, except for the GL scenario, all mean buffer sizes exceed the buffer for today's climate. Keeping with the chosen scenario, which is the average of scenarios GH, WL and WH, the future total buffer size would amount to 86 million m^3, which is 18 million m^3 more than the buffer would have to be for the current climate. This 18 million m^3 represents the minimal required buffering capacity to mitigate the increased inequality of water inflow distribution across the case study area between today and 2100. To account for inaccuracies in the drawing of tangents and the choosing of representative time periods, 10% is added to arrive at 20 million m^3. Finally, as the timescale of the buffering is in the order of months, evapotranspiration is of importance. As presented in figure 27, the median precipitation deficit amounts to a maximum of about 115 mm, which will be the minimum thickness of the protection layer when designing for an average hydrological year.

Table 7 – Results of Rippl diagrams

All volumes in million m^3	**Wet Period**		**Dry Period**		**1st Average Period**		**2nd Average Period**		**Average volume**
Scenario	*Year*	*Volume*	*Year*	*Volume*	*Year*	*Volume*	*Year*	*Volume*	
Current	2001	88	2018	65	2008	55	2012	65	**68**
GL	2092	70	2085	60	2098	63	2104	61	**64**
GH	2092	100	2084	65	2098	70	2104	80	**79**
WL	2091	80	2096	110	2098	75	2104	100	**91**
WH	2091	60	2096	110	2098	75	2104	100	**89**

5.3 – Criterion 2: Buffering capacity for droughts

A drought is a prolonged period of abnormally low rainfall, leading to a shortage of water. The term 'shortage of water' can itself be interpreted within its context, depending on what exactly is going wrong because of it. In the Netherlands, droughts are commonly associated with low crop yield as agriculture demands most fresh water. Section 5.3.1 will show the current and future drought statistics, which are used in section 5.3.2 to acquire insight into the expected aggravation of droughts. Section 5.3.3 then determines the capacity required to meet this criterion.

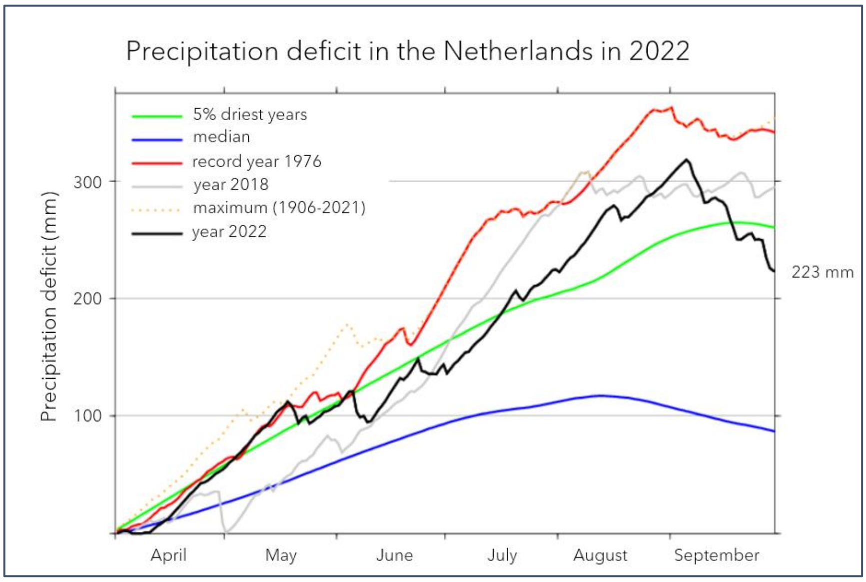


Figure 27 – Cumulative precipitation deficit of mile stone droughts in the Netherlands (KNMI, 2022 (b))

5.3.1 – Transformation of national historic drought data to future values

Droughts are measured in precipitation deficit, which equals the precipitation minus potential evapotranspiration over a certain period of time. Figure 24 shows the accumulated precipitation deficit for some of the greatest droughts in recorded national history. The 2018 drought had a precipitation deficit of 309 mm, ranking fifth of the top droughts in the Netherlands with an expected return time of 30 years. The worst drought was in 1976, showing 361 mm of deficit with a return period of 90 years. KNMI have analyzed these droughts and updated their return period according to the KNMI scenarios, the results are summarized in table 8. The longest return period corresponds with the least extreme scenario, the shortest with the most extreme scenario. Observe that return periods will decrease with a factor of 1.2 to 5, quite a substantial range. For scenario WH, an average increase of 50% is expected for the precipitation deficit in summer months. (Sluijter, Plieger, Oldenborgh, Beersma, & Vries, 2018)

Table 8 – Drought information table (Sluijter, Plieger, Oldenborgh, Beersma, & Vries, 2018)

Ranking	Year	Prec. deficit [mm]	Return period [years]		
			2018	*2050*	*2085*
1	1976	361	90	30 – 60	20 – 60
5	2018	309	30	15 – 25	10 – 25
10	2003	234	10	3 – 8	2 – 8

5.3.2 – Comparison of current and future drought statistics

Precipitation deficit is defined as total precipitation minus potential evapotranspiration. Potential evapotranspiration is the amount of evapotranspiration that would occur if a sufficient source of water is available. As water storages are not infinite, e.g., the soil is barren at some point, less water actually evaporates than denoted in the table. It is thus more useful, for approaching the effectiveness of the buffer in terms of combatting droughts, to compare the shortages of current and expected droughts than to look at the absolute precipitation deficit compensation provided by a buffer capacity. A drought with a precipitation deficit of 234 mm currently has a return period of 10 years (the 2003 drought). In the year 2085, using the conservative scenario, a drought with the same return period will resemble the severity of the 2018 drought (309 mm). Thus, an increase of around 75 mm can be expected for a return period of 10 years. For a return period of 30 years (currently the 2018 drought), a precipitation deficit of the scale of the 1976 drought can be expected, an increase of 51 mm. From these predictions, it appears that, in compensating for the increase of drought severity, a larger reservoir capacity is required for a drought with a return period of 10 years than for 30 years. The same is true when looking at even smaller return periods. For a return period of 2 years, a drought in the current climate is expected to cause a precipitation deficit of 150 mm (Klijn, Velzen, Maat, & Hunink, 2012, p. 32). Table 8 states, for an extreme scenario in 2085, a deficit of 234 mm (the 2003 drought) for the same return period, the difference coming down to 84 mm.

5.3.3 – Capacity determination for criterion 2

The case study area has a surface area of 453 million m^3. Keeping an increase of precipitation deficit of 75 mm as a standard for the case study area, a reservoir of 34 million m^3 would compensate for the increase of the severity of droughts with a return period of 10 years and above and would cover about 90% of the increase of droughts with lower return periods. Designing a reservoir for an increase of 84 mm would require a capacity of 38 million m^3 and would account for the aggravation of 2 year return period droughts as well. It must be clear that, in establishing the appropriate buffer size, the difference in precipitation deficit between current and future droughts will still have a tendency towards an overestimation, for the same reason that the absolute precipitation deficit leads to an overestimation: it is defined in terms of *potential* evapotranspiration. Differences between potential evapotranspiration will be smaller in reality, but it is difficult to prove by what margin. Elaborate studies concerning the actual evapotranspiration over potential evapotranspiration ratio suggest that it is almost never greater than 0.8 for dominantly agricultural areas (Peng, et al., 2019). The paved areas, of course, will have a substantially lower ratio. To be on the safe side, a factor of 0.9 is applied, leading to a required buffer capacity of 34 million m^3.

5.4 – Criterion 3: Buffer capacity for flood prevention

The last general hydrological purpose of the water reservoir is to mitigate imminent flood risk due to the expected increase of extreme precipitation intensity. Section 5.4.1 narrows down the volume required for this criterion. As the resulting required reservoir capacity is relatively small, it is interesting to see if the buffer can go beyond its original goal by capturing (portions of) storm water of entire storm events. This is done in section 5.4.2.

5.4.1 – Capacity determination for criterion 3

The STOWA have released a report containing future return period values for precipitation events lasting a maximum of 24 hours. (Beersma, Bessembinder, Brandsma, Versteeg, & Hakvoort, 2015) The precipitation intensities with corresponding return periods were combined, once again for scenarios GH, WH and WL, by averaging their daily precipitation amounts. These values are presented in table 9. As, once again, the focus lies on compensating for the increase of weather extremes towards 2100, the difference between current and future values is listed there as well. It is apparent that covering for the increase of precipitation extremes, less space is required than for drought aggravation. The most severe increase is that of a precipitation event with a return period of 1000 years (16.7 mm), for which a reservoir of a mere 7.5 million m^3 is needed with a case study area of 453 million m^2.

Table 9 – Storm event precipitation (Beersma, Bessembinder, Brandsma, Versteeg, & Hakvoort, 2015, pp. 58-59)

Return period [y]	Precipitation current climate [mm/d]	Averaged precipitation scenarios GH, WH and WL [mm/d]	Difference [mm/d]
	2014	*2085*	
0.5	30	32.9	2.9
1	36	39.9	3.9
2	42.4	47.3	4.9
5	51.4	57.7	6.3
10	58.5	66.0	7.5
20	66.1	74.7	8.6
25	68.6	77.7	9.1
50	76.7	87.0	10.3
100	85.1	96.8	11.7
200	94.1	107.2	13.1
500	106.6	121.7	15.1
1000	116.6	133.3	16.7

5.4.2 – Holding increased amounts of storm water in the buffer

Figure 28 is added to see what portion of a certain 24 hour precipitation event from the design scenario can be stored by several reservoir capacities. Deltares has made risk analyses of numerous precipitation events using a region in the case study area as target area (the municipality of Bodegraven). According to them, a precipitation event of 35 mm can already cause damages to buildings. (Deltares, 2018) As the figure shows, most precipitation events can be mitigated quite sufficiently with decent buffer sizes. Of course, it will not be necessary to store all precipitation of a storm. Parts will infiltrate into the soil, flow into sewage systems or be pumped towards boezem pumps, which is why this figure merely serves as an indication of how much a reservoir of a certain size can contribute to absorbing storm events. It shows that, from a capacity of 30 million m^3 onwards, total storm water volume of even the most severe storms can be stored for a great portion in the reservoir, assuming that it is sufficiently emptied in advance. However, despite the possibility of storage in a buffer, the water system has to be capable of delivering storm water to the buffer in time. In chapter 6, the capacity of canals between boezem and buffer is determined to timely drain the boezem water system, but bottlenecks may appear before the water is drained from the polders into the boezem water. This topic requires a thorough water system analysis, which is not included in this thesis, but which is of interest for follow up studies.

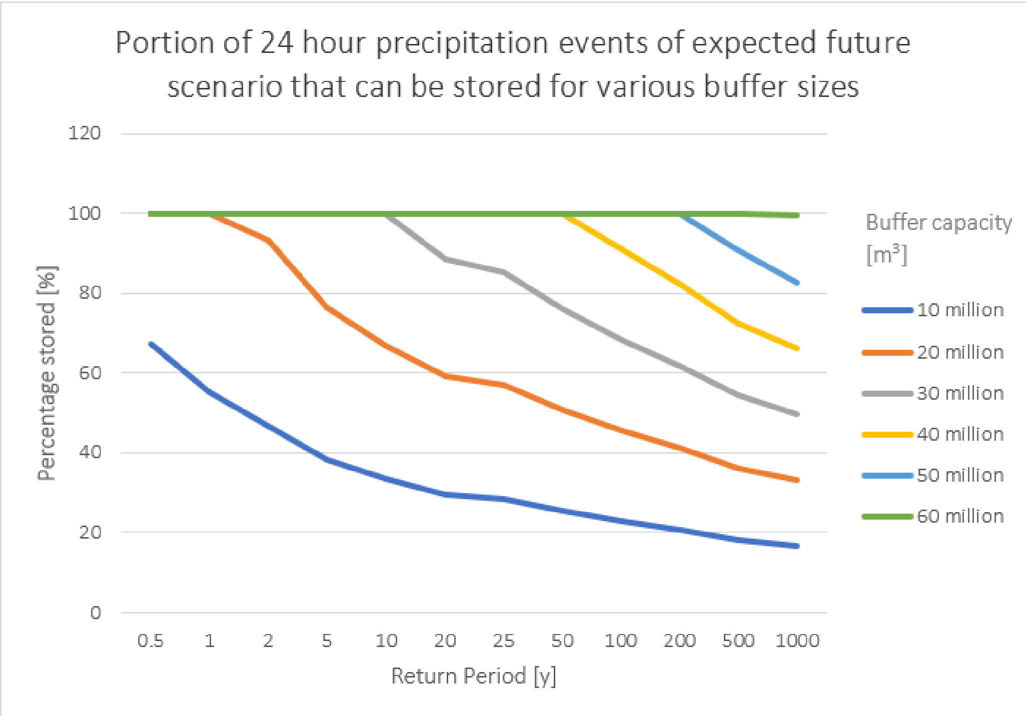


Figure 28 – Graphs depicting the portions of precipitation events that can be held inside numerous buffers

5.5 – Final net buffer capacity and buffer use

The net buffer capacity is defined as the space in the buffer that is flexible, i.e., reserved for buffering. It must be clear whether the final net buffer capacity is the sum of the required volumes of the individual hydrological purposes or not, as section 5.5.1 will describe. Section 5.5.2 will consequently prescribe broadly how the buffer could be used, after which section 5.5.3 will determine the final net buffer capacity.

5.5.1 – Criteria integration

The 3 criteria are now called Y (year-round buffering), D (drought mitigation) and F (flood mitigation). Three duos can be made to test compatibility. First off, Y and D. With good buffer management these criteria do not seem to collide, as the difference in buffer deployment is one of degree, not kind. To mitigate drought, more capacity is required, but the goal remains to buffer the area throughout the year. Secondly, Y and F. These purposes can coexist as well as long as the buffer is sufficiently emptied in anticipation of extreme precipitation events. Today, forecasting extreme precipitation is difficult due to the random and local nature of these phenomena. (Edelenbosch, 2022) Towards 2100, it is expected that these techniques will have advanced to a level where it is safe to assume that adequate anticipation is possible. Advances are already made rapidly in this field with new technologies like HHHR-forecasting, used for hurricanes in North America. (Yue & Gebremichael, 2020) Then, the only remaining problem is the pumping capacity to prepare the buffer for heavy rainfall. Suppose that the buffer is filled up and the 7.5 million m^3 storm storage room is needed. If anticipatory draining begins 48 hours in advance of the event, a minimum capacity of 2,600 m^3/minute is necessary to empty. Currently, boezem pump Mr. P.A. Pijnacker Hordijkgemaal has the largest capacity in the case study area with 2.400 m^3/minute. It is conceivable that, only for emergencies, comparable pump capacities would be deployed for draining the buffer in expectation of heavy storms. Lastly, the combination F and D. It is evident that these purposes would rather complement than hinder each other, with the notation that it is extra important that the predicted heavy rainfall will actually occur, risking the loss of precious buffer water. It is thus concluded that these three potentials do not necessarily demand a superposition of their individual required volumes. Rather, the most critical can be chosen as net buffer capacity if proper buffer management is applied.

5.5.2 – Buffer fill and spill cycle

As can be derived from section 5.5.1, it is important for the design of the buffer that it is managed well. Primarily draining and filling the buffer timely and adequately are of importance. One could imagine that a kind of schedule can be applied to managing the mean buffer level throughout a hydrological year. Starting in October, the buffer is filling up with autumn precipitation. During the fall season, it is important to drain the buffer as intense precipitation events occur frequently. The same goes for the winter months. The buffer can be allowed to fill up towards spring when evapotranspiration intensifies and dry periods are ahead. As discussed in the previous chapter, the summer months will be characterized by periods of drought with occasional excessive rainfall. The buffer could be drained in anticipation of these extreme events and make use of the surplus it receives.

5.5.3 – Buffer capacity determination

As §5.2 shows, 20 million m^3 plus a layer of at least 115 mm should guarantee that the increased inequality of water inflow distribution can be buffered for standard expected hydrological years. §5.3 describes that 34 million m^3 is needed to compensate for drought aggravation and §5.4 reports that only 7.5 million m^3 is needed to deal with the increased precipitation events. As §5.5 concludes that the criteria are mutually compatible with each other, the largest criterion capacity is critical: 34 million m^3. The additional 115 mm needed for criterion 1 is no longer necessary as its required capacity is almost doubled.

Chapter 6 – Qualitative assessment of buffering strategies

Now that the minimal required buffering capacity to mitigate drought and storm aggravation as a result of climate change are known, the concept of the buffer has to be applied. Several strategies can be adopted to realize the buffer. This chapter suggests three strategies and discusses, in a broad and qualitative manner, their (dis)advantages according to a set of important aspects. These three strategies will be introduced in §6.1, where the best application of the strategies are discussed. Yet, the eventual optimal choice might very well be a combination, depending on the qualitative assessment. The aspects that will be considered are hydrology (§6.2), ecology (§6.3), recreation and nautical navigability (§6.4), historical values (§6.5), relinquishments and investments (§6.6). Finally, the recommended strategy is described in §6.7.

6.1 – Introduction of buffering strategies

Firstly, the strategies are described generally in 6.1.1. Consequently, the strategies are discussed in more detail in 6.1.2 (strategy I), 6.1.3 (strategy II) and 6.1.4 (strategy III).

6.1.1 – General description of the strategies

The strategies are initially characterized by buffer distribution only. Strategy I entails the realization of one grand buffer reservoir to serve the entire center of South Holland (the CSA), strategy II holds that each water board will have their own reservoir and strategy III suggests buffers will be realized on the scale of the individual polder. Concepts of strategies I and II are presented in figure 29 with a digital elevation map. The selection of the water board as the strategic scale for Strategy II is primarily based on the fact that water systems in the area are predominantly divided according to the jurisdiction areas of water boards. As described in section 2.2.2, the presence of landscheidingen has historically demarcated the boundaries of water boards and resulted in the separation of water systems. Considering this, it is advantageous for the hydraulic functionality of the buffer within the water system to focus on buffering the water exclusively within its own water board. Strategy III is not presented in this image, for every polder an ideal buffer location will have to be

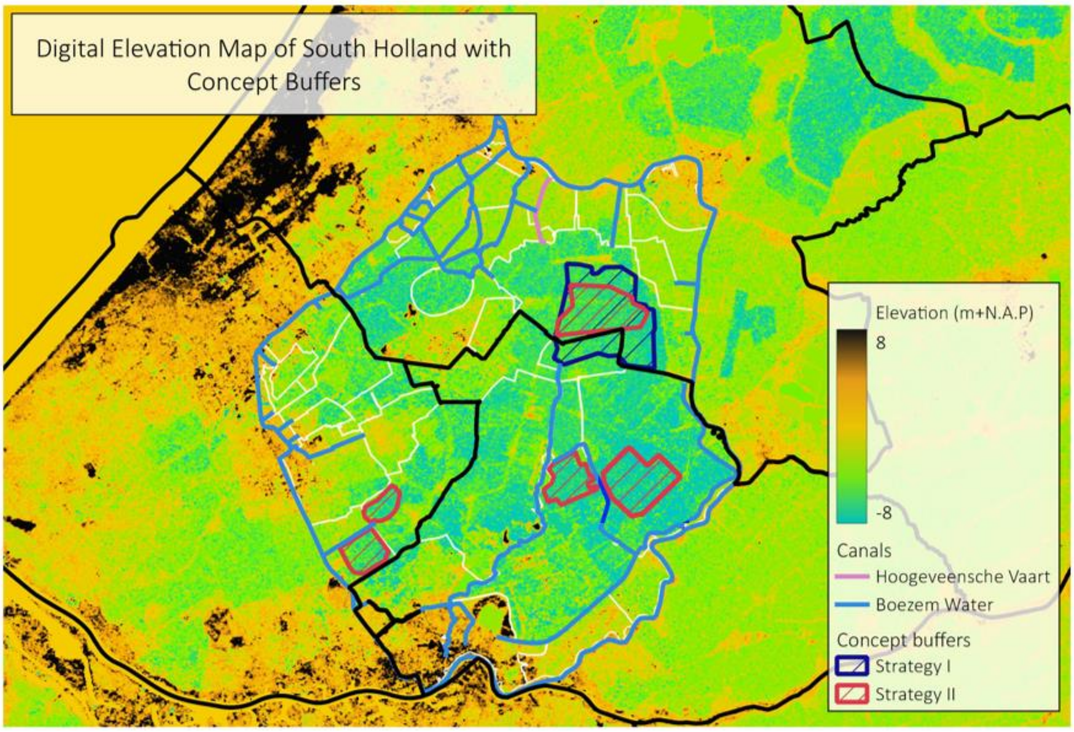


Figure 29 – DEM with conceptual buffers, data from (PDOK, 2019)

narrowed down in further research. The locations of the concept reservoirs are based on the favorability of low elevation (for easy inflow and less excavation), little build up (minimizing relocation), least possible disturbance of existing infrastructure (mainly highways and railways) and the presence of boezem waters. Central zones with relatively large annual discharge per unit surface area were favored as these run higher risks of inundation anyway. Additionally, large existing flexible level zones were expanded to avoid redevelopment issues as much as possible.

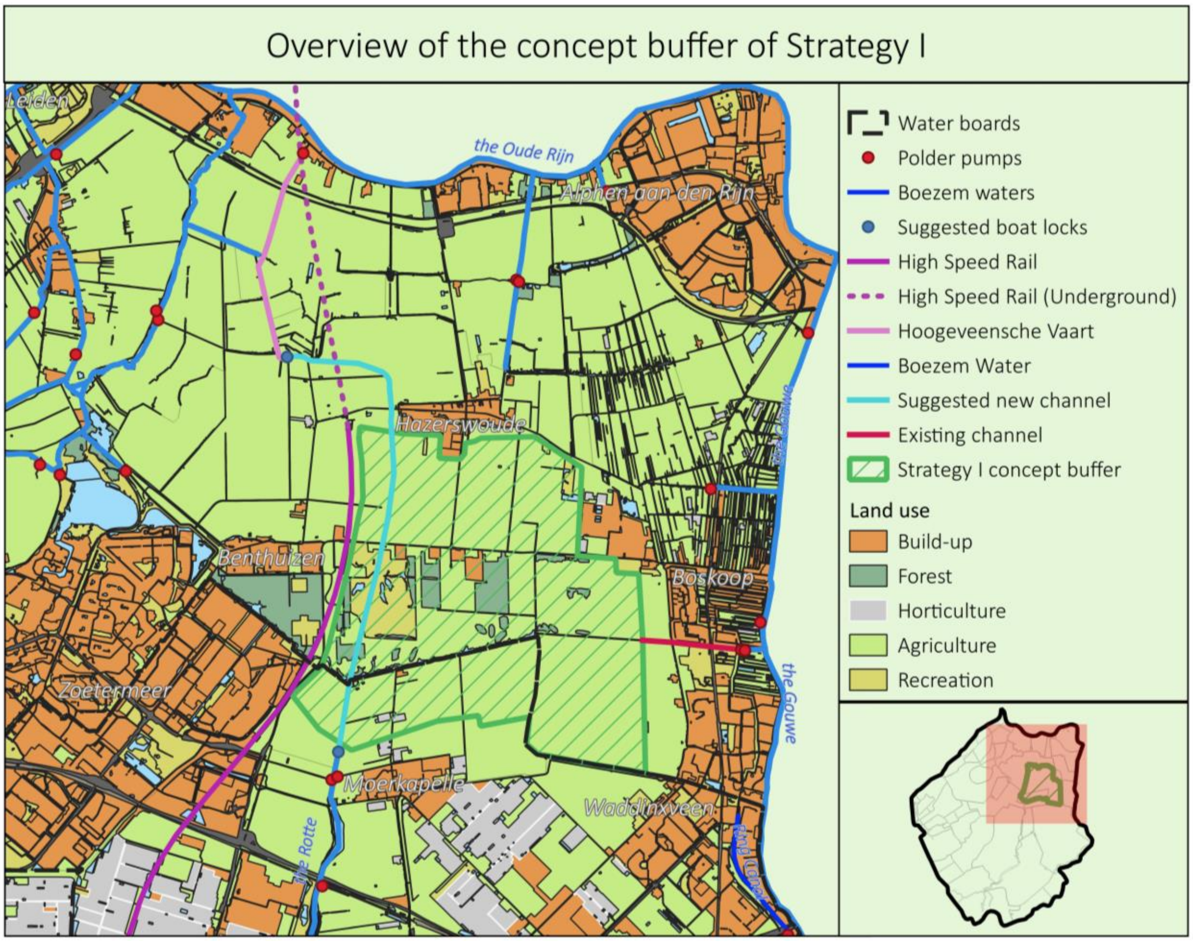


Figure 31 – Depiction of strategy I concept

6.1.2 – Specifying strategy I

As can be seen in figure 31, the target area of strategy I lies in the deep Noordplaspolder (subregion 27), consists partly of recreational and natural space and exists between the boezem water systems of Rijnland and Schieland, making it the most suitable area. Most other larger deeper areas are already deployed as residential areas. The concept buffer stretches over the Bentwoud, a golf course and for the bigger part agricultural planes, being restricted in the West by the High Speed Rail. Since this rail continues its path Northward via a long tunnel that reaches 30 meters in depth (the *Groene Harttunnel*), there will not be any problems connecting the buffer to canals in its North-West direction. The suggested new connection can be made via the Hoogeveensche Vaart, which was once connected to the Rotte (see 6.5.2). As the Hoogeveensche Vaart is only 0.9 meters in depth, the connecting part will have to be dredged to at least 2 meters. (Hoogheemraadschap van Rijnland, 2022) Two boat locks are suggested at both ends of the new canal, both of which will have to be able to reach 4 to 5 meters of elevation. It is recommended that pumps are located at the positions of the boat locks.

The existing channel connecting the buffer to the Gouwe is interesting as it could enhance the connectedness of the buffer, ensuring the channel capacity is great enough. As will be clarified in 5.2.4, Delfland's boezem system cannot be connected to this concept buffer. The boezem water, especially the Schie and the Vliet, can thus be used to have flow between the central buffer and Delfland. This is schematized in figure 32.

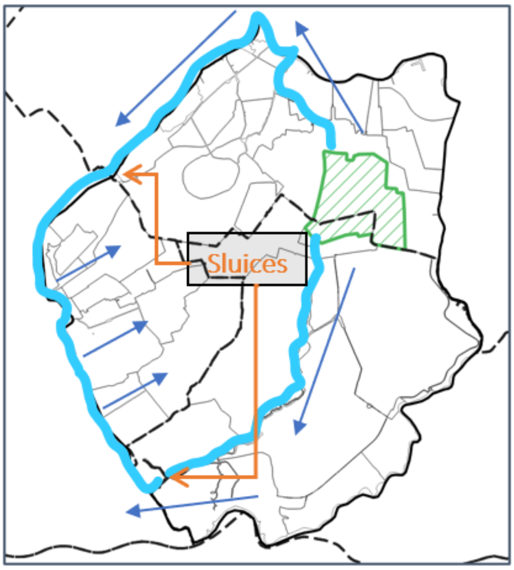


Figure 32 - Water distribution among water boards according to strategy I

The single buffer amounts to a volume of 34 million m^3, as determined in 5.5.3. The surface area of the concept buffer is 20.1 km^2, which means an average water depth of 1.7 meters is required. The suggested channel should be dug lower to keep it accessible throughout the year, having a permanent level. At least 2 meters depth should suffice for most conventional recreational watercraft, with a minimal width of 10 meters to permit traffic in both directions. (Rijkswaterstaat, 2017, pp. 33-34) See figure 33 for a schematization. This setup does require excavating a canal of considerable depth, with a maximum depth of 3.7 meter. When viewing the figure, do realize that the flexible buffer level covers an area of 20.1 km^2 and that the new channel below it is just a fairway through it.

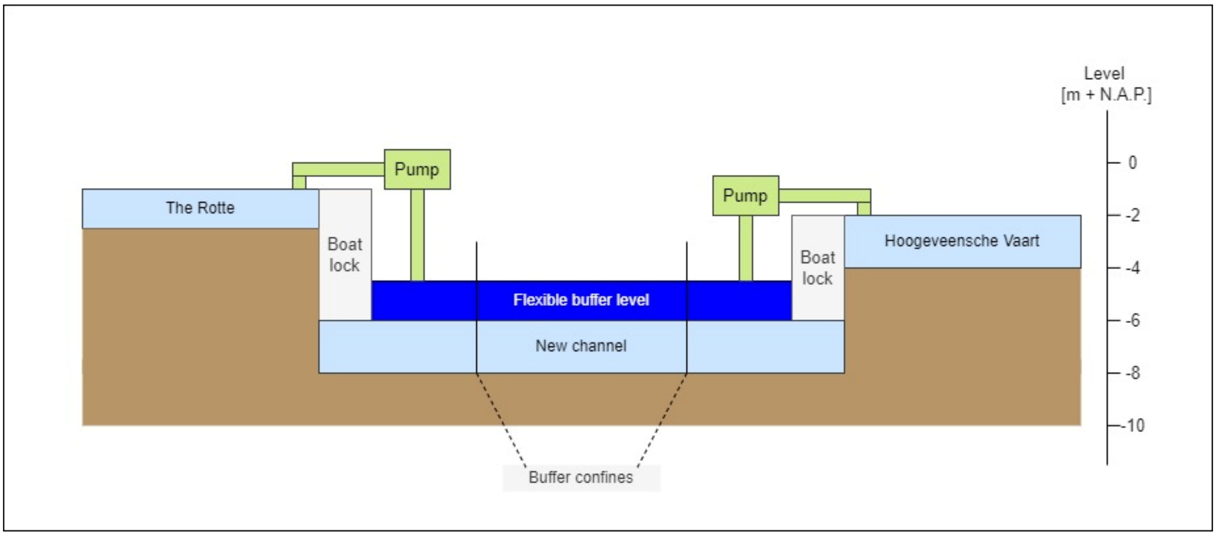


Figure 33 - Schematization of new channel connection

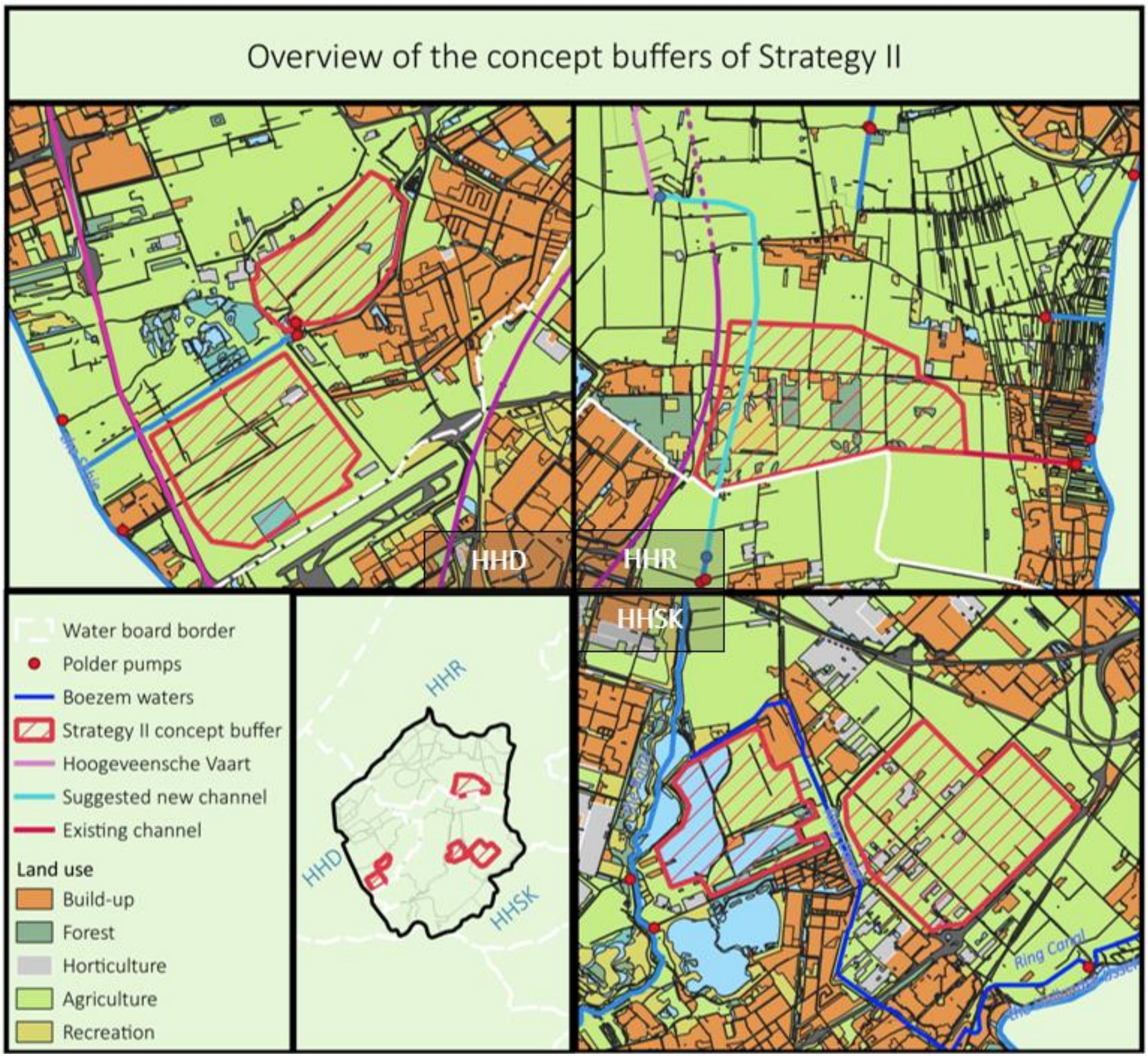


Figure 34 – Overview of concept buffers according to strategy II

6.1.3 – Specifying strategy II

Figure 34 shows an overview of the buffer distribution concept of strategy II. See appendix E.1 for enhanced, more detailed images per water board. For strategy II, the buffer sizes are approached by scaling according to water board surface area, as is deemed possible by conclusion 5 of chapter 4. Of the minimal 34 million m^3 buffer capacity in total, Delfland would need 21% (7.14 million m^3), Schieland and the Krimpenerwaard 46% (15.64 million m^3) and Rijnland 33% (11.22 million m^3). The polygons in the figure are drawn to this scale, assuming maximum depths between 1.5 and 2 meters. Rijnland's buffer is located in the Bentwoud, the same region as for strategy I. It is essentially a smaller version of the great reservoir of strategy I, using the same connections. The surface area amounts to 6.8 km^2, the average depth is 1.7 m. The same new canal is suggested as for strategy I as well, including its minimal depth of 2 meters and width of 10 meters.

For Schieland and the Krimpenerwaard, two reservoirs are conceptualized to get the desired 15.64 million m^3 capacity. The Eendragtspolder (subregion 44), which is already a reservoir, can be expanded. It can be both deepened and broadened. This location is convenient as it is situated between the Rotte and the Ring Canal and minimizes redevelopment issues. It might only be too small to serve Schieland on its own. Currently, the Eendragtspolder has two reservoirs (see figure 35): the Northern reservoir having a capacity of 3 million m^3, a surface area of 1.5 million m^2 and an average depth of 1.5 m, the Southern reservoir having a capacity of 1 million m^3, a surface area of 1 million m^2 and an average depth of 1 m. If the entire polder is used (4 km^2), an additional 4 million m^3 can be achieved with a maximal average water depth of 2 meters. It is desirable to enlarge the Eendragtspolder capacity as much as possible as it would reduce the sacrifices that need to be made to realize the second buffer. The lion's share of 11.64 million m^3 is stored in the Zuidplaspolder (subregion 49). It is about the only region left in the water board's jurisdiction area within the confines of the case study area without a dominant residential function. It lies directly next to the Ring Canal and is positioned close to the Rotte and the Eendragtspolder, which is important for its connectivity. The Zuidplaspolder concept buffer stretches over what is now agricultural soil and has a surface area of 6.9 km^2. With an average water depth of 1.7 meters, the additional 11.64 million m^3 is accounted for.

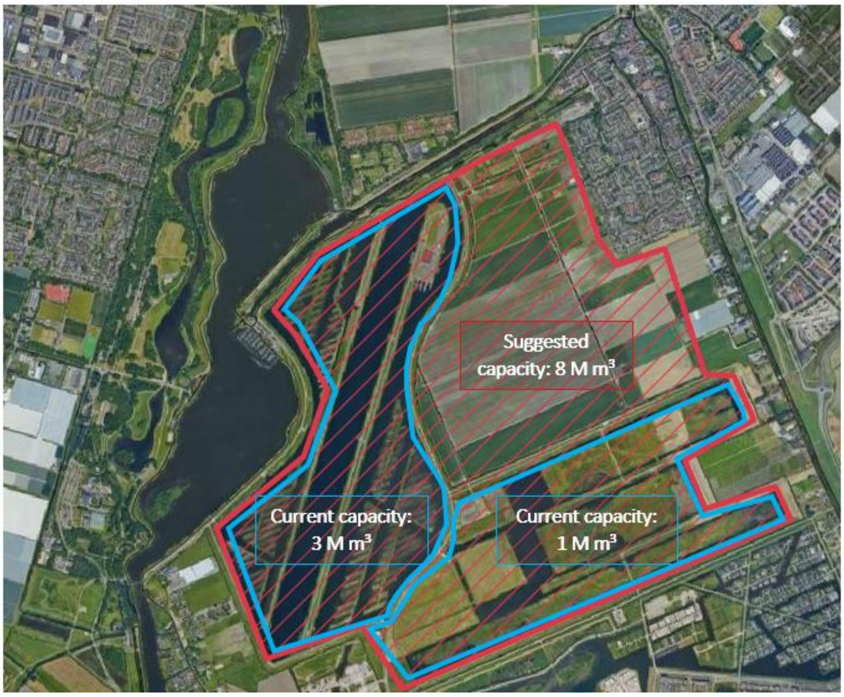


Figure 35 - Eendragtspolder reservoir

For Delfland, two locations are interesting, which combined are to achieve 7.14 million m^3 of volume. Berkel (subregion 2) has a reservoir that can be expanded (again, vertically and horizontally) and the nearby Schieveen polder (subregion 12), which is being turned into a natural wetland already by order of the municipality of Rotterdam. Schieveen is routinely closed off during the breeding season to protect meadow birds like the godwit and most agricultural activities have already been moved. (De Havenloods, 2023) The municipality of Rotterdam plans to transform the area into a permanent nature reserve which, as will be discussed in paragraph 6.3, is perfectly compatible with the envisaged floodable landscape. (Wesseling, 2016) The area in the Schieveen polder marked for buffering amounts to a surface area of 3.26 km^2. With a maximal average water depth of 1.7 m, 5.54 million m^3 can be stored. The remainder is captured by the expansion of the Berkel reservoir, see figure 36. It currently holds 1.2 million m^3 with a flexible level of 1.25 m and a surface area of almost 1 km^2. Expanding this to a zone of 1.85 km^2 with a flexible water depth of 1.51 meter would suffice to gain 1.6 million m^3 in capacity. Together with the Schieveen reservoir, 7.14 million m^3 of volume is reached.

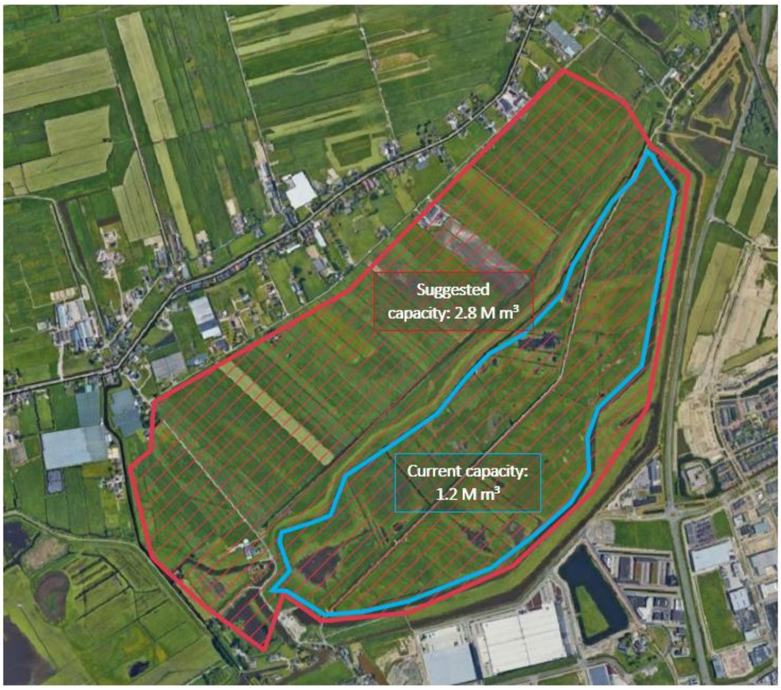


Figure 36 - The Berkel reservoir

6.1.4 – Specifying strategy III

Strategy III has not been conceptualized graphically. However, the idea is to harbor water as much as possible within each polder, supposing dozens of smaller buffers that are connected as much as possible to the existing water infrastructure. Available flexible zones will most likely be expanded. In strategies I and II, 4-6% of the total surface area is devoted to buffering, which means about a twentieth of a common polder will have to be sacrificed in case of strategy III. Determining each buffer size and location exactly is tedious and difficult as the existing model is less accurate on the scale of the individual polder and because buffer designs depend on numerous local factors. Rather, strategy III is used as the decentralized counterpart to compare to the other, more centralized strategies.

6.2 – General hydrological aspects

The 3 buffering criteria Y (year-round buffering), D (drought mitigation) and F (flood mitigation), described in 5.1, set some demands for buffer distribution and design. First off, the hydraulic demands required for drought and year-round buffering are discussed in section 6.2.1. Then, the hydraulic demands for dealing with storm events are treated per strategy. In 6.2.2, describes this for strategy I, 6.2.3 for strategy II and 6.2.4 for strategy III. Then, as a separate hydrological demand, section 6.2.5 describes the relation of the strategies to the limitation of open water evaporation.

6.2.1 - Hydraulic aspects for drought and year-round buffering

For Y and D, it would be convenient if inlet water could be transferred quickly. If water were to be transferred via boezem waters from A to B, the time it takes for water to start rising at B is determined by the speed of the wave front instead of the actual water flow in the channel, which generally is a lot faster:

$$c = \sqrt{g * d}$$

With *c* being the wave front speed (ms^{-1}), *g* the gravitational constant (ms^{-2}) and *d* the channel depth (m). In a boezem water with a typical depth of 3 meters, wave speeds would reach 5.5 m/s, traveling from Rotterdam to Leiden (i.e., across the case study area) in 90 minutes. This evidently is fast enough for the distribution of inlet water, for which a long time scale applies.

6.2.2 – Hydraulic aspects for flood mitigation for strategy I

For F, the immediate storage of storm water, hydraulic demands may be more critical. In the Netherlands, the acceptable inundation risk is largely determined by the amount of casualties at stake, which is difficult to predict. (Rijkswaterstaat, 2011) To portray the demands on the canals feeding the buffers, it is demanded that a precipitation event with a return time of 25 years should not cause any more inundation than it does currently. Once again, the buffer should compensate for the increased intensity. Following table 9, the increased precipitation is 9.1 mm in 24 hours, which would cause a mean flow of 47.7 m^3/s towards the buffer(s). It is further assumed that flow velocities of around 1 m/s may occur when digesting a precipitation event with a return period of 25 years.

First looking at strategy I, the buffer is connected from three directions (see figure 31): the Rotte (transporting HHSK's share of the storm water), the Hoogeveensche Vaart and the Machinetocht Omringdijk (denoted as the existing channel in figure 31). The latter two transport HHD's and HHR's part of the storm water. As the boezem water level of HHD is higher (-0.41 m N.A.P.) than that of HHR (-0.62 m N.A.P.), it is easy for Delfland to drain towards Rijnland at the sluice at the water board border. Furthermore, the Rotte is well connected to 60% of the polders of HHSK. The remaining 40% is connected to the Ring Canal, which lies 1 meter lower. This means that a pumping station will have to be realized there of a substantial capacity: 526.6 m^3/minute at the minimum. Alternatively, the Ring Canal level may be raised by a meter. For the Hoogeveensche Vaart, dimensions are the suggested 10 meter top width, 6.5 meter bottom width and a depth of 2 meters. The Machinetocht Omringdijk has 13.17 meter top width, 8.92 meter bottom width and 1.4 meter depth. (Hoogheemraadschap van Rijnland, 2022) The wet surface areas are 16.5 m^2 and 15.46 m^2, respectively. To get the design flow, the portion of the surface area drained is multiplied by the total design flow (47.7 m^3/s). The surface area of HHR and HHD combined is 54% of the case study area, meaning that the total mean flow becomes 25.8 m^3/s for these channels. Adding their wet surface areas (31.96 m^2) this gives a mean flow velocity in the channels of 0.81 m/s. The Rotte has a varying width, with a bottle neck of 5.49 m and a longer bottle neck of 6.41 m in width towards the buffer zone. See figure 37. These both are to be broadened to the width of the middle section. The critical wet surface area of the Rotte then would have a width of 18.93 meter and a depth of 1.2 m. (Hoogheemraadschap van Schieland en de Krimpenerwaard, 2022) Its wet surface area would amount to 22.7 m^2 and, as HHSK covers 44% of the total surface area, the mean flow would become 21.94 m^3/s. The average flow velocity is 0.96 m/s. If the suggested modifications to the Rotte River are implemented, the mean flow velocities for all three channels would remain below 1 m/s when considering the difference in precipitation amount between the present and 2100. This applies to a 24-hour precipitation event with a return period of 25 years. Hydraulically, strategy I is attainable as long as storm water can be directed towards the boezem waters in time.

Lastly, the hydraulic capacity to drain the buffer in anticipation of extreme precipitation is checked. According to section 5.5.1, a joined capacity of 2,600 m^3/minute is necessary to timely empty the buffer for a 1000 year return period event. The pumping station at the east end of the existing canal has a capacity of 260 m^3/minute, leaving 1,170 m^3/minute per pump for the remaining stations, which amounts to 19.5 m^3/s for the suggested new channel, resulting in flow velocities of 1.18 m/s for the Hoogeveensche Vaart and 0.87 m/s for the Rotte. Considering the rareness of the event, these velocities are certainly acceptable.

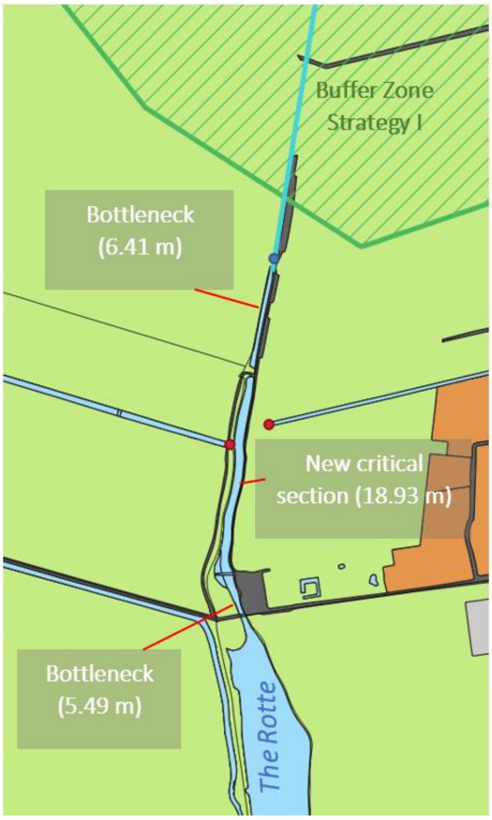


Figure 37 - The Rotte bottlenecks (left) and the Schieveen and Berkel reservoirs (right)

6.2.3 – Hydraulic aspects for flood mitigation for strategy II

The total mean flow of 47.7 m^3/s, determined for strategy I, is used here as well. In the case of strategy II, the channel dimensions seem less critical in general as the storm water is divided over the water boards to 5 buffers and do not have to accumulate towards one buffer. For Delfland, the Schieveen Polder and Berkel are connected to the Schie via de Zweth, if a short new channel between the Zweth and the Schieveen buffer zone is realized. See figure 37. At its critical width, between the Schie and this new connection to the Schieveen polder, the Zweth has dimensions of 10 meter top width, 8 meter bottom width and 1.95 meter water depth. (Hoogheemraadschap Delfland, 2022) This amounts to 17.55 m^2 of wet surface area. The average design flow for Delfland (which covers 21% of the CSA) is 10 m^3/s, amounting to an average flow velocity of 0.57 m/s. The existing flow towards the reservoir in Berkel during heavy precipitation events should be added to the total flow, but this information is unknown, and it is safe to assume that it would not increase the flow velocity to over 1 m/s, as the current reservoir in Berkel is less than half the size of the suggested capacity. Thus, for strategy II, flood mitigation seems to be hydraulically attainable.

For Schieland, the Ring Canal and the Rotte deliver water to the buffers in case of strategy II. As was used for the water balance model, subregions 38, 39, 41, 43, 46, 49 and 50% of 44 all discharge into the Ring Canal. The other subregions in HHSK discharge into the Rotte, namely subregions 37, 40, 42, 45, 47, 48 and 50% of 44. See the schematization in appendix A.1 to see the subregions lying around the Ring Canal and the Rotte. The surface area draining into the Ring Canal amounts to 40% of HHSK's surface area, meaning the Rotte takes on 60% of that. Now, the buffer in the Zuidplaspolder is located along the Ring Canal and can hold 11.64 million m^3 while the Eendragtspolder, located alongside both the Rotte and the Ring Canal, can only hold 4 million m^3 more than it does now. This means that water must be transferred from the Rotte to the Eendragtspolder and to the Ring Canal to reach the

Zuidplaspolder. As the level of the Ring Canal is 1 meter lower than the Rotte (-1 vs -2 m N.A.P., see section 2.3.4), this transfer is easily done. The resulting design flow velocities are based on the proportions of the buffer sizes, being critical at the section between the Rotte and the reservoir in the Zuidplaspolder. The total flow for Schieland (which covers 46% of the CSA) amounts to 21.9 m^3/s. The Zuidplaspolder has 74% of the buffer volume, which means the critical waterway has an average discharge of 16.3 m^3/s. There is one bottleneck in the critical waterway of 6.64 meter in width, which will have to be widened to the next smallest canal width of 11.64 m. See figure 38. Then, with a depth of 1.30 meter, the wet surface area is 15.13 m^2 and the average flow velocity would be 1.08 m/s. However, the calculated flow velocity is based solely on the difference in precipitation amount between a 24-hour precipitation event with a return period of 25 years now and in 2100. It does not consider the total precipitation amount for the entire event, which is 77.7 mm, according to table 9. The Zuidplaspolder buffer is placed upstream of the Ring Canal, meaning that not much extra stress is put on the critical section by the draining of the rest of the storm water. Regardless, it is still highly likely that, upon closer inspection, it is found that even with the widening of the bottleneck, the capacity of the canal is found to be too small and flooding will occur. The further expansion of the Ring Canal will in that case be necessary. The hydraulic attainability thus seems low.

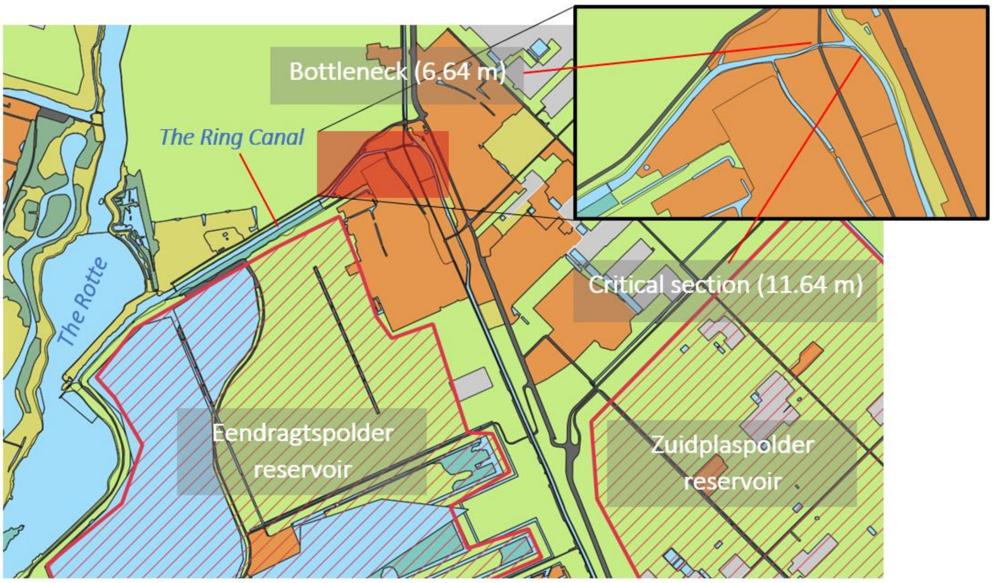


Figure 38 - Ring Canal bottle necks

For Rijnland, the same calculation would go as for the large buffer of strategy I, but with two differences: it would only take on the precipitation fallen in HHR and only two connections can be used for water transferring: the Hoogeveensche Vaart and the Machinetocht Omringdijk, having wet surface areas of 16.5 m^2 and 15.46 m^2, respectively, as calculated for strategy I. As Rijnland constitutes 33% of the CSA, 15.9 m^3/s would be the average flow towards the buffer. The average flow velocity than becomes about 0.5 m/s.

6.2.4 – Hydraulic aspects for flood mitigation for strategy III

In the case of strategy III, buffers are present immediately on-site, saving precious time and unburdening the rest of the water system directly. Hydraulic demands are minimal, and strategy III is thus evidently more robust when it comes to the swift draining of storm water.

6.2.5 – Limiting evaporation

Another important hydrological demand is the limitation of evaporation during the growing season. For the buffer to hold on to water (for purposes Y and D), evaporation should be constrained to a minimum. Two factors are leading: open water surface area and water temperature distribution. The deeper and larger the body of water, the more water will be saved in this period. By increasing depth, one can limit the open surface area for the same volume. By having a larger water mass, the lower winter temperatures are maintained longer and the sensitivity to short warm periods is decreased. This does mean that winter evaporation increases, as the summer warmth is maintained longer as well. Increased winter evaporation improves the buffer's effectiveness, as winter contains more wet days. (Morton, 1986) Here, strategies I and II have an advantage because of their depth and large volumes. The smaller buffers of strategy III will be prone to more summer evaporation.

6.3 – Ecology

The continuous draining and filling of the buffer will undeniably change the landscape, making way for new ecosystems, depending on how the buffer is distributed, designed and managed. 6.3.1 will introduce the floodable landscape. 6.3.2 will discuss how the biodiversity within this landscape could cope with seepage.

6.3.1 – Introduction of the floodable landscape

One way to realize the buffer is to have a permanent minimal water depth, much like a regular lake, with a flexible layer of water on top. The advantages of a lake are that the increase in depth minimizes evaporation (see section 6.2.2), that it can harbor aquatic life and that recreational activities like boat driving can be done throughout the year. The obvious disadvantage is a sizable increase in the required buffer size, further increasing the project's scale. To harbor sizable aquatic life, like carp, the buffer has to have a minimal permanent depth of 1.2 m. (BTL Liners, 2020)

Another option, to avoid having to cope with a permanent minimal depth, is to have a buffer that harbors an ecosystem that can withstand being drained and flooded periodically. Studies covering this topic suggest that a high degree of biodiversity can be achieved, featuring unique species that fill a very particular niche in biology. The dry and wet phases may complement each other in doing so. The terrestrial community can leave biomass to be used by the aquatic community and vice versa. Three situations are distinguished: flooded, pooled and dried. The rest speaking for themselves, the pooled phase means that a certain deeper part (i.e., a ditch) is inundated while the surrounding plane lies dry. Situated in a sea climate, such seasonal lakes can harbor a variety of plants. Reed, cattail, yellow flag iris, water lily, water horsetail and marsh marigold, to name a few. The executive flooding and drying creates peatland gullies, much like the natural landscape that once covered a large part of the Netherlands. Some examples of animals that would be expected to inhabit such a habitat are waterfowls, different wetland birds (like the heron, egrets and ibises), fish (like the carp, pike and perch), amphibians (like frogs, toads and smooth newts), insects (like dragonflies, damselflies, and water beetles), aquatic invertebrates (like water bugs, snails, and various insect larvae) and mammals (like water voles and common shrews). Most of these species can be expected to proliferate by strategy III as well, though it is unclear what the effect of the scattering of the buffers will be on the degree to which they will do so. It is probable that fish will have a hard time reaching basins that are closed off of the water network. It furthermore seems likely that the water level of the smaller buffers strategy III suggests will sway more drastically and less predictable throughout the year than the larger water buffers, making a less stable environment for developing this biodiversity. (Williams D. D., 2012) (Stubbington, England, Wood, & Sefton, 2017)

6.3.2 – The floodable landscape and seepage

If a buffer were realized in a region coping with severe seepage, it might render the buffer water brackish to a degree and have its influence on local ecology. As will be recommended, more study should be done on keeping proper water quality in the water buffer, involving limiting seepage. This thesis consequently does not assume a brackish water buffer. Nonetheless, a brackish environment can still host quite unique and valuable biodiversity. Some plants that have adapted to a more saline environment that could show up are glasswort, sea aster, common reed, sea rush and sea purslane. These species are more common in estuarine environments, and the salinity does not seem to prevent (low) peatlands from being created out of them. Examples of animals include water fowls, shorebirds (like redshanks, dunlins and avocets), fish (like eels, mullets and gobies), crustaceans (like brackish water shrimp and fiddler crabs), marine invertebrates (like brackish water snails, bivalves and worms) and reptiles and amphibians (like pond turtles, marsh frogs and green toads). As the water might not be dominantly brackish, coexistence of these species with the ones abundant in fresh water flood plains is possible, being especially benevolent towards species like crustaceans, algae and cephalopods but harsher on salinity-sensitive species like fish and frogs. (Brouns, Hefting, & Verhoeven, 2018) (Williams W. D., 1985)

6.4 – Recreation & nautical navigability

These aspects will have more to do with economic opportunities and public support. If strategies permit the public to enjoy natural feats, either by unique biodiversity, water sport facilities or the possibility of crossing by boat, the project would be more appealing to realize. Section 6.4.1 deals with the aspect of recreation and section 6.4.2 discusses possibilities of water craft passage.

6.4.1 - Recreation

In the case of Strategy I, hardly anything must be done to ensure proper recreational possibilities. The existence of a large water mass is an excellent medium for various recreational activities. The same goes for strategy II, as the average buffer size per water board will be on the scale of about twice the Kralingse Plas. For both strategies I and II, the resulting buffers will probably be appealing to the public on their own and will not depend on the connection with other recreational facilities, while that could of course still be beneficial. For strategy III there will not be one or a couple of new central recreational areas, but rather a change of landscape across the case study area. It is harder to predict the exact contribution in terms of increased recreational or touristic advantages, but it seems likely that a portion of these buffers will be solely devoted to hydrological purposes and too small for recreational activities like sailing.

6.4.2 – Nautical navigation

The significant addition of canals navigable by (recreational) watercraft will not likely fit into strategy III at all, except when only a very minimal water depth is required (e.g., canoes and pedal boats). Strategies I and II do offer some possibilities in this regard on account of their buffers being connected to boezem waters, though a struggle lies in the water level difference. Boezem water levels are maintained between -0.4 and -1 m N.A.P. for the three water boards, while the buffers will have highly flexible levels and are on both strategies I and II most likely situated in deeper parts of the case study area, currently lying as deep as -5 m N.A.P. This means boat locks will have to be built. Furthermore, Delfland's water system cannot be easily connected to the Rotte or de Noordplaspolder by means of a navigable canal due to the presence of the High Speed Rail and the fact that the waters near the water board borders generally consist of ditches and small level compartments. The passage of boats would be an enormous and unlikely project due to the highways, railways, level difference and sheer distance. Thus, this connection is not considered feasible in this thesis, hence the workaround by assigning the Schie and the Vliet as water carriers for Delfland.

6.5 – Historical values

As a part of the heritage project of the province of South Holland, which is about the rich national tradition of water works and delta geography, historical values are important for this project. Bringing back past events, connections, sights or traditions are all goals set by the province, and the topic of this thesis brings opportunities to realize that. Three aspects of the project can be put forward in this regard. Firstly, the Schie and the Vliet as water carriers (6.5.1), secondly, reconnecting the Oude Rijn and the Rotte (6.5.2) and thirdly, the possibility of regrowing peatlands (6.5.3).

6.5.1 – The Schie and the Vliet as water carriers

Firstly, the expanding role of the boezem waters, especially the Schie and the Vliet, as water carriers. The old barge canals have grown to become vital hydraulic connections among the water boards and between the land and the outer waters, embodying a critical role in the water management of the center of South Holland. Buffering will lead to an increased emphasis on the role of the boezem waters as water carriers. This expansion of function is greatest for strategy I, as all the buffering water on Delfland's part will have to travel through the Schie and the Vliet, but also substantial for strategy II and perhaps even III, as it is logical to have more water traffic in between the buffered water boards in the future as local weather extremes enforce collaboration.

6.5.2 – Reconnecting the Rotte and the Oude Rijn via the Hoogeveensche Vaart

Secondly, the connection between the Rotte and the Oude Rijn (Old Rhine) can be brought back via the Hoogeveensche Vaart and the suggested new canal (see section 6.1.2). Before 1492, a boat lock connected these waters at Hildam, which was located at the North end of the Rotte. Traders traveling between Rotterdam and Amsterdam would use this route to avoid the city of Gouda and its toll. The boat lock was quickly destroyed by order of the city of Gouda, as the toll was important for its proceeds. (De Rotte, 2018) (Vlasveld, 2019) The entire connection has stayed disrupted ever since. The Hoogeveensche Vaart was eventually closed off in 1759 when the Noordplaspolder was reclaimed. (Smit, 1994) Figure 39 presents the old connection, though this is a map from the year 1300. The Oude Wilcke was the connection between the Rotte and the Oude Rijn back then. Later, this connection was moved eastwards, to where the Hoogeveensche Vaart is nowadays. For additional information concerning the reconnection plan, a reference to another thesis within the heritage project of the Province of South-Holland is in place. 'Water as a carrier for Future Values', by E. Kuit, presents a design for the long term transition of the Noordplaspolder, the location of the suggested new channel. (Kuit, 2022)

Bringing back this old connection would greatly benefit flow exchange and the ability to drive boats across these water board jurisdiction areas, like in the days before. For strategy III, this connection would be less of a necessity as no great reservoir would be connected, but still beneficial to the development of the region and water network expansion.

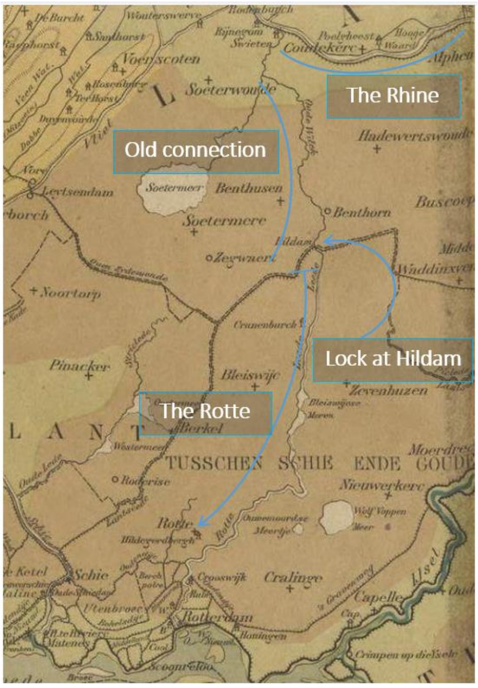


Figure 39 - Configuration of connection between the Rotte and the Oude Rijn in 1300

6.5.3 – Regrowing peatlands

The third theme that brings attention to historic values is the growth of low peatlands in the temporary water landscape as described in 5.2.3. As the introduction into the case study area reports, peat wetlands used to be leading in the composition of the regional landscape after centuries of tidal flooding. Peat bogs grow in acidic, poorly drained, oxygen-poor environments, which is not offered by the envisaged buffer zones. This emphasizes the rareness and value of the peat bogs that are still left. (International Peatland Society, sd)

6.6 – Relinquishments and investments

The realization of the buffering strategies will come at a cost: certain areas will have to give up their function. The plans also require investments for their realization. Section 6.6.1 will discuss these aspects for strategy I, section 6.6.2 for strategy II and section 6.6.3 for strategy III.

6.6.1 – Strategy I

As described in 6.1.2, the concept buffer area of strategy I stretches primarily over agricultural land, about 17 km^2. It also covers a forest and a golf course. Except for the forest, which might be left to change to the new landscape, these land uses will have to be removed. Among some other infrastructure of less importance, one N-way lies in the target area of the concept buffer. Perhaps the greatest relinquishment is that this region has been assigned to host residential areas in the future, as described in 4.4.1.

The investments that strategy I demands initially come down to the dredging of the canal, the building of embankments to enclose the reservoir, the placing of pumps (the joined capacity of which will be somewhere around 3000 m^3/minute, according to 5.5.1) and 2 boat locks, the construction of a bridge over the new suggested canal (to replace the removed N-way) and ecological maintenance and supervision. Also, two parts of the Rotte will have to be widened (see section 6.2.1). Lastly, a pumping station of about 530 m^3/s has to be built for pumping water from the Ring Canal into the Rotte during storms, or the Ring Canal's level will have to be raised by a minimum of 1 meter.

6.6.2 – Strategy II

For the buffer of the water board of Rijnland, the relinquishments are exactly the same as for the variant of strategy I, except for the amount of agricultural land that needs to be reclaimed: about 4 km^2. The investments are similar as well, only the area enclosed by the embankment will be smaller and, consequently, there would be more space left for residential planning. Also, the widening of the Rotte will not be necessary.

Now for the concept buffers that lies in the water board of Schieland and the Krimpenerwaard. As the Eendragtspolder is a water buffer already, relinquishments are kept to a minimum: only 0.5 km^2 of agriculture has to be repurposed for buffering. The Zuidplaspolder reservoir, though, does demand repurposing. Currently, the target area primarily hosts agricultural functions and, secondly, horticulture. No important connections are disrupted by the reservoir. Again, a relinquishment is the giving up of potential living space as this region too is marked as potential residential area (see section 4.4.1). The investments initially come down to building and enlarging embankments, constructing a short connection to the Ring Canal and, in the case of an open connection, the construction of a bridge for the N-way that is situated between the Ring Canal and the reservoir. It will also need its own pump, or the enlargement of the (boezem) pumps that are already draining the Ring Canal. Finally, the Ring Canal itself will probably have to be expanded significantly in order to feed the Zuidplaspolder reservoir during intense precipitation (see 6.2.1).

The Berkel reservoir in Delfland is similar to Eendragspolder, as it too is a water reservoir. The additional agricultural land relinquishment amounts to 0.9 km^2. For the Schieveen reservoir, relinquishments are minimal as well since the polder is already being repurposed to become a natural reserve (see section 6.1.3), which is conceivably well compatible with the floodable landscape (described in section 6.3.1) that the buffer will introduce. Investments thus mostly consist of the new embankments, the expansion of Berkel's embankments, the enlarging or adding of polder pumps, the addition of a short channel between de Zweth and the Schieveen reservoir and ecological maintenance and supervision.

6.6.3 - Strategy III

In the case of strategy III, relinquishments are spread over the entire case study area. Approximately 5% of every polder will have to be repurposed for buffering (the ratio of the strategy I buffer). This means different sacrifices per polder, but it is conceivable that urbanized polders make use of neighboring, more open polders to buffer water for them. Then, primarily agricultural functions will be relinquished.

A great part of further forfeitures and investments will be determined by either excavating or embanking the buffer. In polders without evident suitable deeper areas, buffers that are built using embankments will elevate the ground water table and cause an upwelling effect in the area around them. To limit unwanted buffer drainage and additional land relinquishments due to upwelling, costly maintenance would be required. Embankments would also require every buffer to have its own pump, equipped with a capacity to drain the polder in case of heavy rainfall. Alternatively, the buffers could be excavated, which would heavily increase initial investments (as, evidently, more ground will have to be moved) but which would make them more durable and easier to fill during precipitation events. A thorough cost-benefit analysis is recommended to be done in further research. Whatever the method of construction, investments will also take the form of a great coordination and collaboration plan, possibly using subsidies to stimulate agrarians to realize reservoirs.

6.7 – Recommended strategy

The most relevant aspects have been discussed in a broad and contemplative sense and all require more thorough investigation. However, on the basis of that broad consideration, a recommended strategy can be devised. First, a brief summary of the considerations made in this chapter about the buffering strategies is presented in section 6.7.1. Then, the recommended strategy is described in section 6.7.2.

6.7.1 – Strategy considerations summarized

From the standpoint of hydraulics, strategy III is desirable as each polder has immediate access to its buffer during heavy precipitation, which unburdens the water system and makes for the fastest digestion. For strategies I and II, capacities of the channels and pumps will become critical, especially for HHSK in the case of strategy II, though still attainable. Immediate access to the large water buffers does, however, substantially alleviate the water system. When minimizing evaporation, strategies I and II are desirable because of their large water masses. Ecologically, strategies I and II are preferable since the smaller water buffers of strategy III would not allow for a stable flooding pattern and because the scale hinders the development of certain species. As for recreational possibilities, strategies I and II are preferable as well, once again due to the larger scale of the water bodies and their increased connectivity to the water system, facilitating the passage of boats. Lastly, historical values can be brought back best in the contexts of strategies I and II. These strategies require the deployment of the Schie and the Vliet as water carriers and reconnection between the Rotte and the Oude Rijn. Strategy III will require use of the Schie and the Vliet as water carriers to a lesser degree and will not demand the old connection to be remade. Peat growth is unlikely for all strategies. Lastly, the relinquishments and investments, which are sizable for all strategies. All demand large amounts of space, dredging, and the building or enlarging of embankments and all require maintenance. The addition of pumping stations, the canal with its boat locks and probably a bridge is a significant extra investment for strategies I and II. The collaboration and coordination necessary to realize strategy III, on the other hand, will be costly as well. It is difficult to distinguish a favored strategy in this respect, among other factors due to uncertainty in economic profits of most of the investments.

6.7.2 – Detailed description of resulting recommended buffering strategy

Minimizing evaporation during the growing season, supporting great biodiversity in the buffer zone(s), creating recreational space and revaluing historical themes are all the aspects in which both strategies I and II are favorable. Strategy III only seems to perform best during intense precipitation events. These aspects considered, strategies I and II are preferred to characterize the recommended strategy. There still is potential for application of strategy III. It is recommended that a thorough water system analysis is done in combination with a cost-benefit analysis concerning flooding in the case study area and that subregions with a high risk of inundation and vulnerable, important assets should have their own storage zones in case of emergencies. However, as such an analysis is yet to be done, strategies I and II will in this thesis be applied.

A combination of strategies I and II seems optimal. Due to the lack of connectivity between Delfland's boezem water system and the Rotte or the planned buffer area in the Noordplaspolder, and considering Delfland's flexibility in implementing buffers, it is necessary for Delfland's portion of the case study area to have its own dedicated buffer according to strategy II, including the addition of a short channel between de Zweth and Schieveen reservoir. Realization of the Zuidplaspolder buffer (in Schieland) seems to be more difficult and expensive to realize than the buffer in the Noordplaspolder (in Rijnland). Thus, the buffering of Schieland and Rijnland will happen at the strategy I buffer location, with the addition of the expansion of the Eendragtspolder, the suggested connection to the Hoogeveensche Vaart through the buffer zone (with its boat locks, bridge and pumping stations) and the connection to the existing channel east of the buffer, the Machinetocht Omringdijk. The channel widenings on the north end of the Rotte also still apply.

The resulting modifications are presented in figure 40. The buffer zone in Rijnland (number 1 in the image) now has a design capacity of 23 million m^3. With an average flexible level of 1.7 m, its surface area is 13.5 km^2, which is in between the concept designs of strategies I and II. The channel connection is the same as schematized in figure 33. The pump capacity, assuming drainage for heavy precipitation events is done 48 hours in advance (see section 5.5.1), should combined be 1.800 m^3/minute. This was calculated by multiplying the capacity obtained in 5.5.1 by the ratio of the capacities of the recommended buffer and the strategy I buffer. Since the pumping station at the existing canal already has a capacity of 260 m^3/minute, the two new pumps at the boat locks should together amount to approximately 1540 m^3/minute. As this is lower than in strategy I, hydraulic capacity of the canals is great enough to timely drain the buffer in case of severe precipitation (see 6.2.2).

The Eendragtspolder (number 2) is expanded from 4 million m^3 to 8 million m^3, resulting in an area of 4 km^2 with a maximum average water level of 2 meters. This reservoir will be used for buffering water from the Ring Canal. The surplus can be pumped to the Rotte via a new pumping station, requiring a capacity of about 400 m^3/minute (see section 6.2.3).

For Delfland, the Berkel reservoir (number 3) is expanded from a capacity of 1.2 million m^3 to 2.8 million m^3, rendering a surface area of 1.85 km^2 with a flexible water level of 1.51 meter. Lastly, the Schieveen reservoir (number 4) is suggested to be designed at a capacity of 5.5 million m^3, with a surface are of 3.26 km^2 and a flexible water level of 1.7 meter. This reservoir does need a new connection and pumping station. Draining the reservoir for intense precipitation events 48 hours in advance as well, the pumping capacity for the strategy I buffer of section 5.5.1 (2600 m^3/minute) is scaled to about 425 m^3/minute. Similarly, Berkel's current pumping capacity should be increased by 125 m^3/minute.

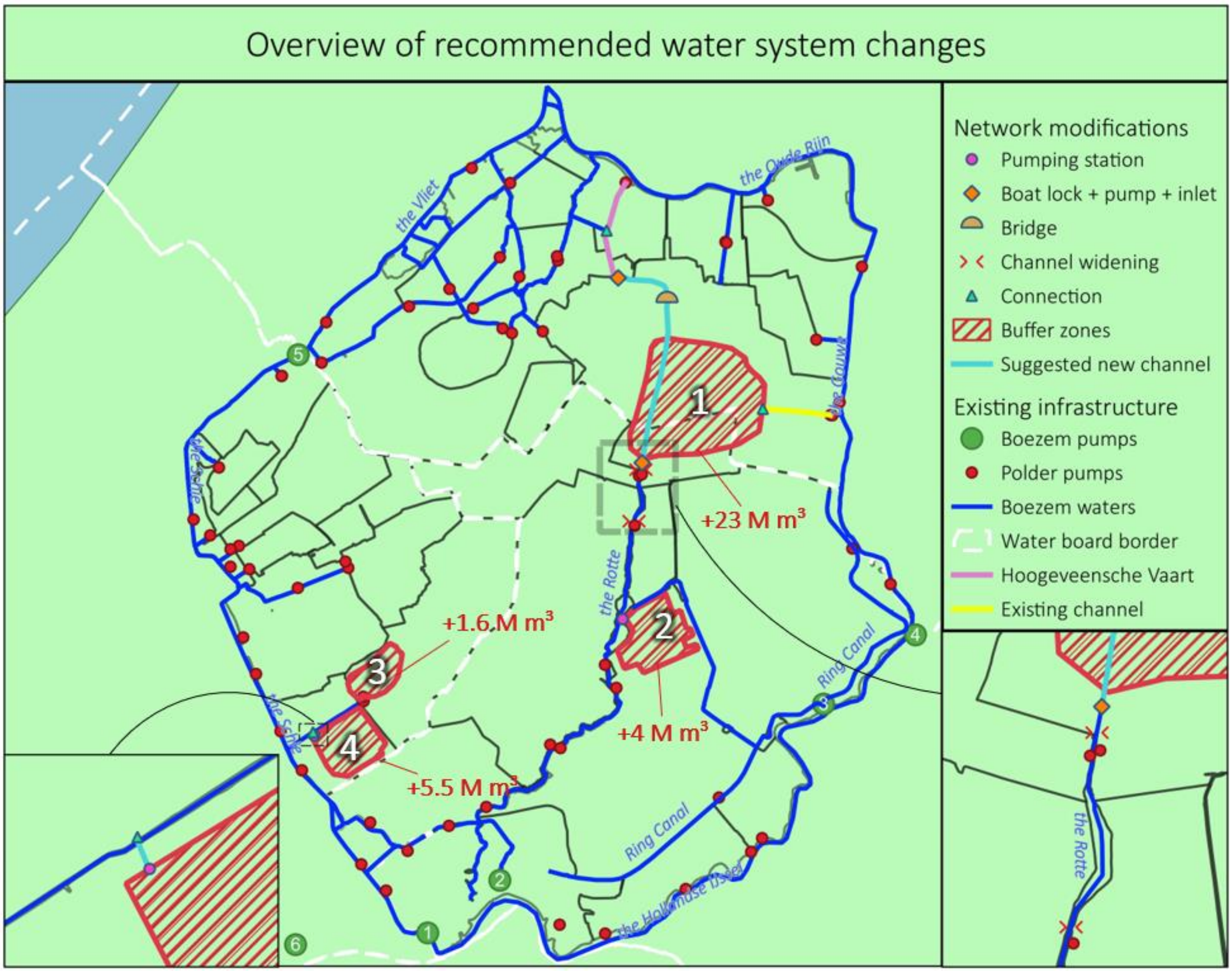


Figure 40 – Recommended strategy overview with suggested modifications

Chapter 7 –Discussion, Conclusion and Recommendations

This chapter concludes the thesis. First, a discussion about limitations and results is in place (§7.1). Final conclusions are then drawn (§7.2) and, lastly, recommendations are listed (§7.3).

7.1 – Discussion

Four themes are dealt with in this discussion. Firstly, the determination of the buffer size is discussed in 7.1.1. Then, in 7.1.2, the method of strategy evaluation is treated. The recommended strategy is discussed in 7.1.3 and the appropriate buffer operability in 7.1.4.

7.1.1 – Buffer size determination

When considering the accuracy of the water balance, it is important to acknowledge several limitations. The model's validation relies on various measurement time series, such as pump measurements, which may contain inconsistencies and errors that are challenging to compensate for. Additionally, some crucial time series data, including inlet and flow between polders, are missing. Despite high NSE-values for spatial scales of the water boards and larger, indicating suitability for this thesis' application, the model's outcomes should not be treated as absolute truth.

Furthermore, the model's projections for future conditions have additional limitations. The KNMI time series fail to fully capture expected weather patterns like increased droughts, which can impact result accuracy. Assumptions regarding water quality issues are also made, assuming that water quality will influence water flow proportionally to its current impact, which may not necessarily be true. Similarly, assumptions regarding the development of paved areas, sewage systems, and the distribution of new housing projects are based on available data but ultimately rely on reasonable estimates. Eventually, final minimal buffer capacity was determined through the more critical analysis of future drought scenarios. Uncertainty in this regard is that the droughts are measured in terms of precipitation deficit, which is based on potential evapotranspiration. Translation to actual evapotranspiration has proven to be difficult, especially during droughts. Thus, despite a correcting factor, an overestimation of the actual required capacity is likely.

It is important to note that the scale of the minimal required buffer size (34 million m^3) is considered reliable based on the current analysis. However, to enhance the accuracy in further research, the model may be further refined. More site specific parameters may be incorporated, like apparent vegetation types and soil moisture content modeling, to have more insight into actual evapotranspiration. The addition of water quality parameters would help in making better inlet predictions. Additionally, more validation data would benefit the model. This would not only involve the addition of pump time series, but also data of inlets, flow exchange between control volumes (polders) and subtraction of ground water. By incorporating these improvements and addressing the identified limitations, future research can strive for a more accurate and comprehensive understanding of the water balance dynamics in the study area. These advancements would contribute to better-informed decision-making regarding buffer sizing and management strategies in the face of changing environmental conditions.

7.1.2 – Buffer strategy evaluation

Further limitations lie in the buffer strategy evaluation, as all aspects used to consider the buffer strategies deserve their own thorough and site-specific investigation. In this thesis, these subjects are briefly addressed to strengthen the conclusion, establish a connection with the case study area, and identify key factors for future research. The aim is to provide a foundation for further investigation and exploration of these aspects. To make more informed decisions regarding the robustness of the water system, several aspects are paramount.

Firstly, it is essential to gain a comprehensive understanding of the bottlenecks within the water system that hinder efficient discharge during storm events. This knowledge will help identify polders that require their own buffering, as outlined in strategy III, or necessitate improvements in existing infrastructure. By pinpointing these bottlenecks, targeted measures can be implemented to enhance the system's overall performance. Secondly, it is vital to investigate the ecological implications of large-scale water buffering in the study region. Understanding the potential effects on the local ecosystem will enable the development of sustainable and ecologically sound buffer design strategies. This includes assessing the impacts on flora, fauna, and the overall ecological balance. Furthermore, optimizing the dimensions of the buffers warrants dedicated modeling efforts. By employing separate models, the dimensions can be fine-tuned to achieve maximum efficiency and effectiveness in water buffering, taking into account factors such as hydrological dynamics, storage capacity, and hydraulic performance. Lastly, a comprehensive cost-benefit analysis should be conducted, incorporating all the mentioned aspects. This analysis will provide valuable insights into the economic feasibility and overall advantages of implementing the proposed water buffering strategies. It will serve as a valuable tool for informed decision-making, considering both the short-term and long-term implications.

7.1.3 – Recommended buffering strategy

This thesis will have a preliminary recommended strategy in advance of the recommended activities. In considering the various aspects, such as minimizing evaporation, supporting biodiversity, creating recreational space, and revaluing historical themes, both strategies I and II demonstrate favorable attributes. However, strategy III appears to excel primarily during intense precipitation events. Based on these considerations, strategies I and II are preferred in characterizing the recommended strategy. Optimally, a combination of strategies I and II is deemed suitable. Given the lack of connectivity between Delfland's boezem water system and the Rotte or the planned buffer area in the Noordplaspolder, it becomes necessary for Delfland's portion of the case study area to possess its own dedicated buffer following strategy II. Implementing the Zuidplaspolder buffer (in Schieland) is expected to be more challenging and costly compared to the Noordplaspolder buffer (in Rijnland). Therefore, buffering for Schieland and Rijnland will occur at the strategy I buffer location.

7.1.4 – Buffer operability and use of Schie and Vliet

The buffer is operated throughout the year in these three phases:

1. October to Winter: The buffer begins filling up with autumn precipitation. It is important to drain the buffer during the fall and winter seasons as intense precipitation events are frequent.
2. Spring: As evapotranspiration intensifies and dry periods approach, the buffer can be allowed to fill up gradually.

3. Summer: The summer months bring periods of drought with occasional heavy rainfall. Anticipation of these extreme events is essential to drain the buffer accordingly. The surplus water received during these periods can be valuable afterwards.

It is apparent that this cycle depends on the accurate forecasting of water availability. It is assumed in this thesis that weather forecasts, especially the short-term forecasts of intense precipitation events, will significantly improve towards 2100. However, due to the localized nature of extreme precipitation events, there is a risk of water loss or excessive boezem levels. To address this challenge, the plan incorporates an enhanced role for the Schie and the Vliet as water carriers, facilitating the transfer of water between Schieland and Rijnland during such situations.

7.2 – Conclusion

The main research question being:

'How can water buffering compensate for the effects of climate change on water quantity management in central South Holland in 2100?'

Required buffer capacities for three criteria were obtained. For a moderately extreme climate scenario, the model showed that a net buffer capacity of 20 million m^3 plus 115 mm of evapotranspiration reserve would be needed to buffer the increase in net water inflow distribution inequality for the expected average year. A capacity of 7.5 million m^3 would cover for the aggravation of precipitation intensity of a storm with a return period of 1000 years and below. To harbor water compensating for the aggravation of droughts with return periods of 2 years and above, a capacity of 34 million m^3 is required. The capacities resulting from these criteria are complementary to each other as long as action is timely undertaken in anticipation of extreme storm events. Thus, a capacity of 34 million m^3 would suffice.

Three strategies are under discussion in deciding a buffer distribution, with strategy I supposing one great buffer, strategy II suggesting a separate buffer per water board and strategy III entailing each polder to have its own water buffer. Concept buffer locations were made based on elevation, build up, existing infrastructure, annual discharge and existing reservoirs. Each strategy was broadly and qualitatively examined using the following aspects: achieving primary hydrological purposes, ecology, recreational possibilities, nautical navigability, historical values, relinquishments and investments. Strategy III brings the greatest robustness in responding to extreme precipitation events, but strategies I and II excel in all other aspects and are thus the best to characterize the recommended strategy. The impossibility to connect Delfland's' boezem waters towards the Rotte or the Noordplaspolder and the fact that the Eendragtspolder is too small to buffer the entire jurisdiction area of Schieland suggest a combination of strategies I and II would be optimal. A buffer should be placed in the Noordplaspolder that would at least be 23 million m^3 in capacity and one in Schieveen that amounts to 5.5 million m^3. The Eendragtspolder should be expanded from 4 to 8 million m^3 and the Berkel reservoir from 1.2 to 2.8 million m^3. Delfland then contains its own buffering capacity and is able to connect to Schieland and the Krimpenerwaard via the Schie and to Rijnland via the Vliet, acting as water carriers to share (excess) water with other water boards.

To fully employ these buffers, several additional modifications are recommended. A canal must be excavated through the Noordplaspolder reservoir from the Rotte to the Hoogeveensche Vaart. The connecting ends of this canal must be equipped with boat locks, pumping stations and inlets. Also, the reservoir must be connected to the Gouwe with the Machinetocht Omringdijk. The Eendragtspolder will buffer water from the Ring Canal. In case of extreme precipitation, a new pumping station must be in place to drain the Ring Canal into the Rotte, towards the large Noordplaspolder reservoir. The Schieveen reservoir requires its own pumping station and the addition of a canal to the Zweth. The Berkel reservoir will need an enlargement of its pumping station.

Overall, the recommended combination of strategies I and II provides a promising framework for enhancing the water management capabilities in the case study area. The proposed modifications outlined in this discussion offer a starting point for future research and decision-making processes, paving the way for sustainable and resilient water systems that can better withstand various challenges and contribute to the overall well-being of the region.

7.3 – Recommendations

As mentioned already in 7.1.2, numerous research topics could come forth from this work. Future research should include a more detailed risk assessment of floods and droughts for the case study area to have more knowledge on the degree to which these need to be solved. Local flooding bottlenecks should be investigated as well, after which either the capacity of drainage or local storage could be enhanced. To be able better predict water flows in the future, better statistical transformations of the KNMI scenario time series should be produced. Also, research should be done to harbor water quality in buffer areas with temporary waters and to combat brackish seepage water. Investigations should be done on the ecological implications of large-scale water buffering in the study region to develop sustainable and ecologically sound buffer design strategies, considering the impacts on flora, fauna, and the overall ecological balance. It is recommended to perform optimizations of the dimensions of the buffers through dedicated modeling efforts, considering factors such as hydrological dynamics, storage capacity, and hydraulic performance, to achieve maximum efficiency and effectiveness in water buffering. This analysis should include variants of the suggested plans, like excavated versus embanked buffers, and site specific investigations. Notably, it is advisable to have a holistic economic and organizational analysis of this project to establish whether it is feasible and profitable.

As the thesis has made clear, the spatial development of the center of South Holland is under pressure. Parts are targeted to house many more civilians in the future while the area needs space increasing the robustness of its water system. The Province of South Holland should thus reconsider targeting areas in the center of South Holland, like the Noordplaspolder, as potential hosts of a residential function. The space for water should be an essential part of the Province's spatial planning.

Finally, the realization of the recommended strategy requires the water boards of Delfland, Rijnland and Schieland and the Krimpenerwaard to cooperate with each other. They should plan to jointly confront the imminent challenges that regional water management faces due to the changing environment. Also, it is recommended that these authorities start measuring all water flows in their system. Inlet data would especially benefit modeling of their water flows.

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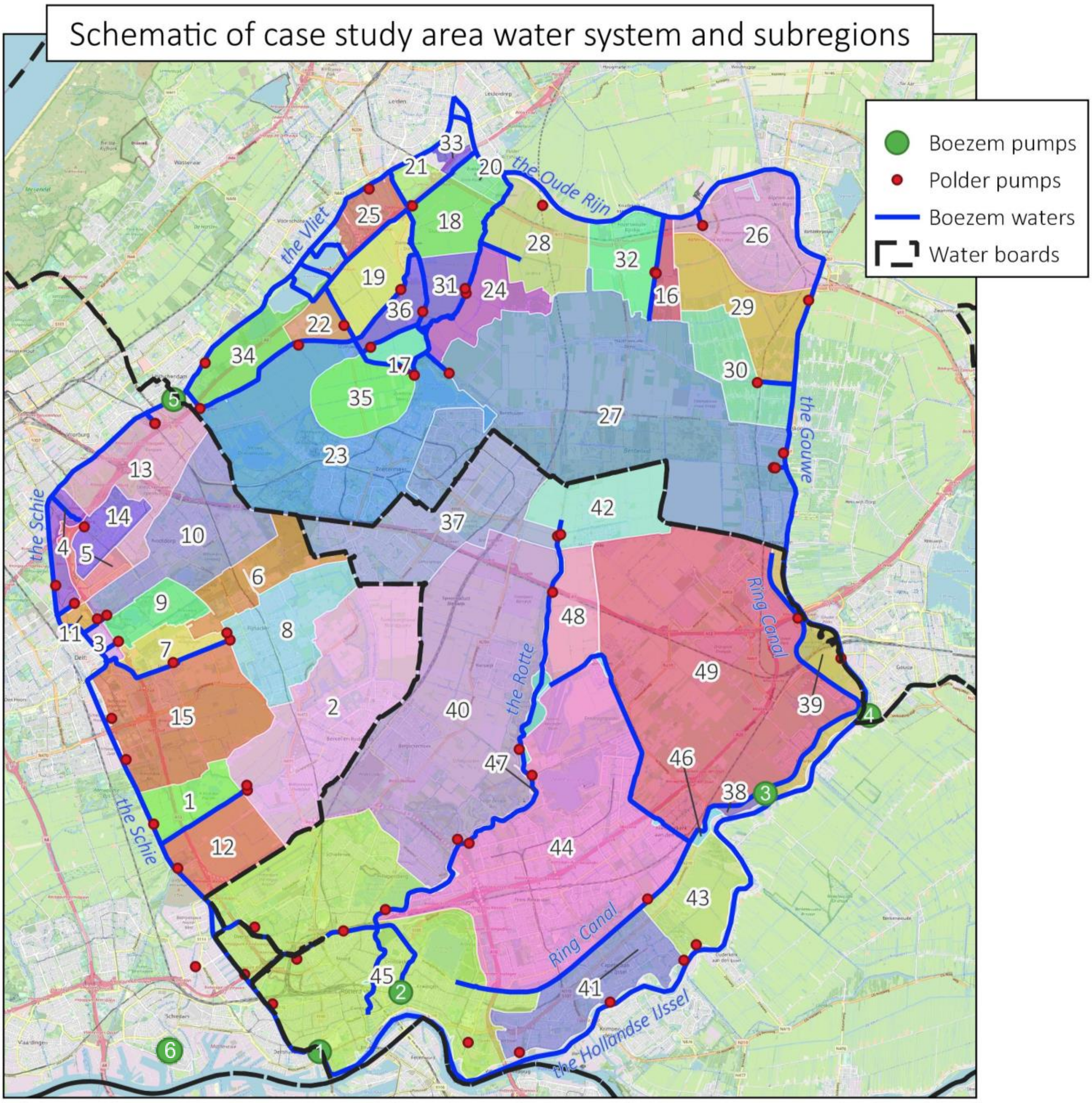
Appendix A –CSA overview

A.1 – Overview of Case Study Area and water system components

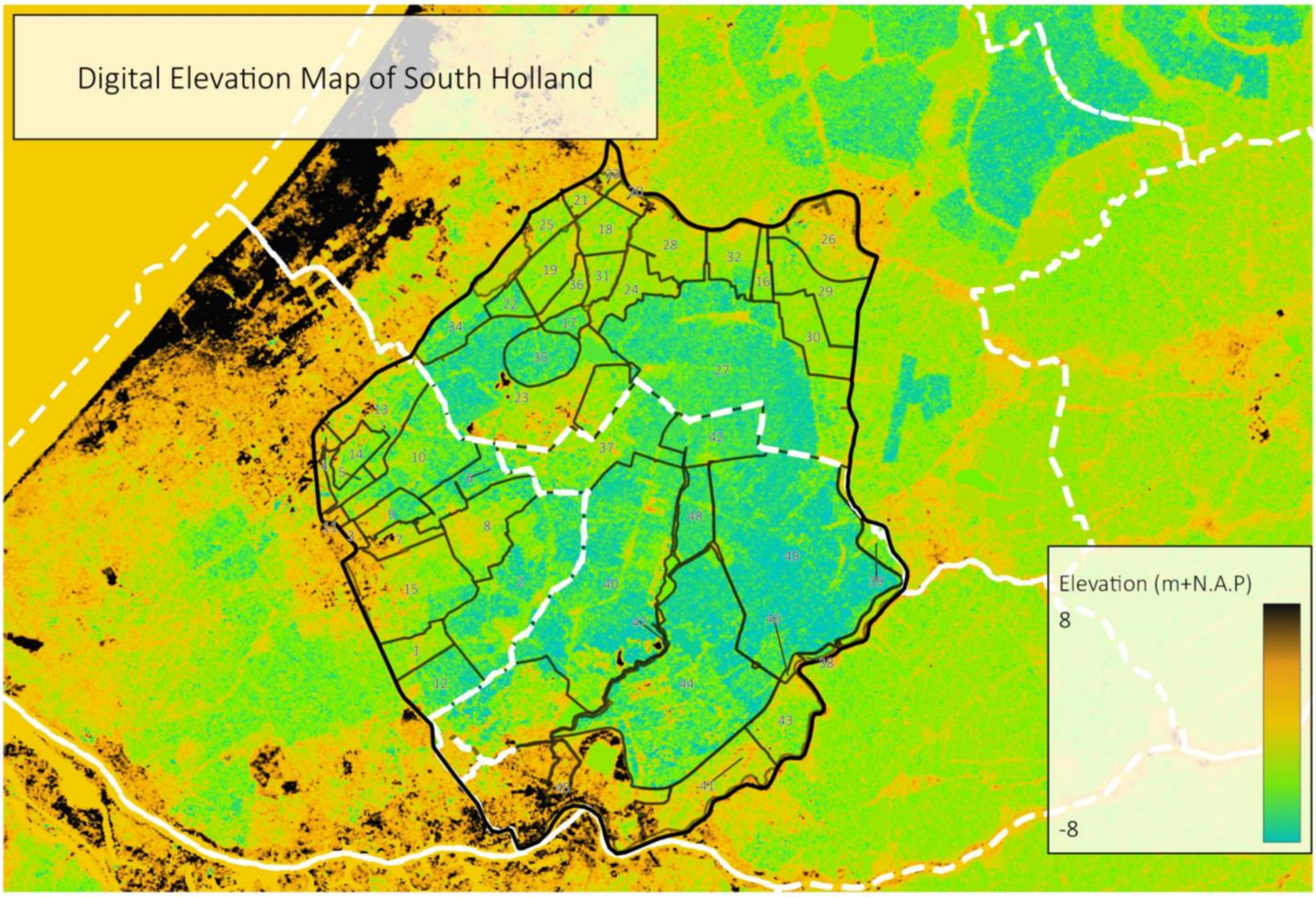


Data from (De Nederlandse Gemalen Stichting, sd)

Nr.	Boezem pump name	Capacity [m³/min]	Waterboard	Inlet Capacity [m³/min]	Drains	Discharges into
1	Gemaal Parksluis	1200	Delfland		the Schie	Nieuwe Maas
2	Mr. U.G. Schilthuis	1350	Schieland		the Rotte	Nieuwe Maas
3	Abraham Kroes	800	Schieland		Ring Canal	Hollandsche IJssel
4	Mr. P.A. Pijnacker Hordijkgemaal	2400	Rijnland	2100	the Gouwe	Hollandsche IJssel
5	mr. dr. Th. F.D.A. Dolk	480	Delfland		the Vliet	the Schie
6	Schiegemaal	450	Delfland		the Schie	Nieuwe Maas

Nr.	*Subregion name*	25	Oostvliet- Hof- en Spekpolder
	Water Board of Delfland	26	Polder Alpherhoorn
1	Akkerdijksche polder	27	Polder de Noordplas and Ambachtspolder
2	Berkel	28	Polder Groenendijk
3	Delft-Oost	29	Polder Het Zaanse Rietveld
4	Hoge Broekpolder	30	Polder Laag Boskoop and Rietveldse Polder
5	Lage Broekpolder	31	Polder Westbroek
6	Nieuwe of Drooggemaakte Polder	32	Rhijnenburgerpolder
7	Noordpolder van Delfgauw	33	Room- of Meerburgerpolder
8	Oude Polder van Pijnacker	34	Starrevaart- en Damhouderpolder and Vlietland
9	Polder van Biesland en Bovenpolder	35	Zoetermeerse Meerpolder
10	Polder van Nootdorp	36	Zwet- en Grote Blankaartpolder
11	Polder Vrijenban		*Water Board of Schieland and the Krimpenerwaard*
12	Schieveen	37	Binnenwegse polder
13	Tedingerbroekpolder	38	Boezemland
14	Ypenburg	39	Oostpolder
15	Zuidpolder van Delfgauw and Wippolder	40	Polder Bleiswijk
	Water Board of Rijnland	41	Polder Capelle aan den IJssel
16	Geer- en Buurtpolder	42	Polder de Wilde Veenen
17	Geer- en Kleine Blankaardpolder	43	Polder Esse Gans- en Blaardorp
18	Grote Polder	44	Polder Prins Alexander and Eendragtspolder
19	Grote Westeindse Polder	45	Polders of Rotterdam
20	Industrieterrein Grote Polder	46	Ringvaart / Ring Canal
21	Kleine Cronesteinse- of Knotterpolder	47	Rotte
22	Meeslouwerpolder	48	Tweemanspolder
23	Nieuwe Driemanspolder and Drooggemaakte Grote Polder	49	Zuidplaspolder
24	Oostbroekpolder		

A.2 – Digital Elevation Map of South Holland



Data from (PDOK, 2019)

Appendix B – Model results and Python code

B.1 – Inlet and outlet per polder for the current climate

	All units in [m3]	**Dry Year (2018)**			**Average year (all)**			**Wet year (2001)**		
Scale	**Area**	*Inlet*	*Outlet*	*Difference*	*Inlet*	*Outlet*	*Difference*	*Inlet*	*Outlet*	*Difference*
CSA	Heart of South Holland	5,32E+07	2,46E+08	1,92E+08	3,47E+07	2,42E+08	2,08E+08	2,57E+07	3,81E+08	3,55E+08
	Hoogheemraadschap Delfland	1,36E+07	5,41E+07	4,05E+07	8,96E+06	4,90E+07	4,00E+07	7,01E+06	7,67E+07	6,97E+07
Water Board	Hoogheemraadschap Rijnland	2,28E+07	8,10E+07	5,82E+07	1,60E+07	8,37E+07	6,77E+07	1,13E+07	1,35E+08	1,24E+08
	Hoogheemraadschap Schieland en de Krimp.	1,69E+07	1,11E+08	9,37E+07	9,77E+06	1,10E+08	9,97E+07	7,42E+06	1,69E+08	1,61E+08
	Akkerdijksche polder	1,27E+06	1,67E+06	4,00E+05	8,57E+05	1,51E+06	6,52E+05	6,99E+05	2,62E+06	1,92E+06
	Berkel	2,07E+06	1,07E+07	8,66E+06	1,02E+06	1,02E+07	9,17E+06	9,70E+05	1,65E+07	1,56E+07
	Delft-Oost	9,38E+04	3,51E+05	2,57E+05	8,15E+04	3,36E+05	2,54E+05	2,36E+04	5,40E+05	5,16E+05
	Hoge Broekpolder	3,22E+05	1,04E+06	7,18E+05	2,65E+05	9,41E+05	6,76E+05	1,49E+05	1,55E+06	1,40E+06
	Lage Broekpolder	6,28E+04	9,53E+05	8,90E+05	2,02E+04	8,60E+05	8,39E+05	1,93E+04	1,39E+06	1,37E+06
	Nieuwe of Drooggemaakte Polder	1,02E+06	3,59E+06	2,57E+06	6,02E+05	3,10E+06	2,50E+06	5,10E+05	4,79E+06	4,28E+06
	Noordpolder van Delfgauw	8,14E+05	1,31E+06	5,00E+05	6,24E+05	1,16E+06	5,33E+05	4,65E+05	1,96E+06	1,49E+06
	Oude Polder van Pijnacker	1,90E+06	4,66E+06	2,75E+06	1,27E+06	3,99E+06	2,72E+06	9,69E+05	6,71E+06	5,74E+06
	Polder van Biesland en Bovenpolder	3,58E+05	1,74E+06	1,38E+06	1,95E+05	1,60E+06	1,41E+06	1,81E+05	2,71E+06	2,53E+06
	Polder van Nootdorp	1,02E+06	8,46E+06	7,44E+06	8,75E+05	7,68E+06	6,81E+06	7,27E+05	1,08E+07	1,01E+07
	Polder Vrijenban	7,33E+04	2,73E+05	2,00E+05	6,21E+04	2,56E+05	1,94E+05	1,77E+04	4,25E+05	4,07E+05
	Schieveen	1,22E+06	3,62E+06	2,39E+06	8,03E+05	3,43E+06	2,63E+06	6,42E+05	5,32E+06	4,68E+06
	Tedingerbroekpolder	4,64E+05	5,88E+06	5,41E+06	2,23E+05	4,77E+06	4,55E+06	1,48E+05	6,85E+06	6,70E+06
	Ypenburg	2,58E+05	1,89E+06	1,63E+06	1,99E+05	1,68E+06	1,49E+06	1,63E+05	2,47E+06	2,31E+06
	Zuidpolder van Delfgauw en Wippolder	2,61E+06	7,95E+06	5,34E+06	1,87E+06	7,49E+06	5,63E+06	1,33E+06	1,20E+07	1,07E+07
	Geer- en Buurtpolder	3,93E+05	8,79E+05	4,86E+05	2,88E+05	9,05E+05	6,17E+05	1,95E+05	1,51E+06	1,32E+06
	Geer- en Kleine Blankaardpolder	3,14E+05	8,44E+05	5,29E+05	2,03E+05	8,55E+05	6,51E+05	1,60E+05	1,40E+06	1,24E+06
	Grote Polder	1,07E+06	2,11E+06	1,04E+06	7,46E+05	2,15E+06	1,40E+06	5,62E+05	3,71E+06	3,15E+06
	Grote Westeindse Polder	8,33E+05	2,48E+06	1,65E+06	6,04E+05	2,64E+06	2,04E+06	3,95E+05	4,51E+06	4,12E+06
	Industrieterrein Grote Polder	7,08E+04	6,27E+05	5,57E+05	5,58E+04	6,67E+05	6,11E+05	2,97E+04	1,09E+06	1,06E+06
	Kleine Cronesteinse- of Knotterpolder	2,06E+05	6,76E+05	4,70E+05	1,47E+05	7,16E+05	5,69E+05	9,96E+04	1,20E+06	1,10E+06
	Meeslouwerpolder	2,02E+05	1,18E+06	9,75E+05	1,30E+05	1,23E+06	1,10E+06	1,05E+05	1,92E+06	1,82E+06
	Nieuwe Driemanspolder	2,16E+06	1,33E+07	1,12E+07	1,22E+06	1,37E+07	1,25E+07	8,85E+05	2,21E+07	2,13E+07
	Oostbroekpolder	1,03E+06	2,35E+06	1,32E+06	7,71E+05	2,46E+06	1,69E+06	5,19E+05	4,17E+06	3,65E+06
	Oostvliet- Hof- en Spekpolder	4,21E+05	1,49E+06	1,07E+06	3,02E+05	1,58E+06	1,28E+06	2,07E+05	2,63E+06	2,42E+06
	Polder Alpherhoorn	1,13E+06	4,56E+06	3,43E+06	8,93E+05	4,79E+06	3,90E+06	3,97E+05	7,97E+06	7,57E+06
	Polder de Noordplas en Ambachtspolder	5,70E+06	2,88E+07	2,31E+07	3,94E+06	2,97E+07	2,57E+07	2,99E+06	4,59E+07	4,29E+07
	Polder Groenendijk	1,46E+06	3,51E+06	2,05E+06	1,06E+06	3,65E+06	2,59E+06	7,16E+05	6,20E+06	5,49E+06
Subregion	Polder Het Zaanse Rietveld	2,33E+06	3,53E+06	1,20E+06	1,69E+06	3,51E+06	1,82E+06	1,21E+06	6,02E+06	4,81E+06
	Polder Laag Boskoop en Rietveldse Polder	1,84E+06	2,33E+06	4,86E+05	1,46E+06	2,37E+06	9,18E+05	9,67E+05	4,13E+06	3,17E+06
	Polder Westbroek	4,85E+05	1,25E+06	7,65E+05	3,57E+05	1,32E+06	9,61E+05	2,36E+05	2,23E+06	1,99E+06
	Rhijnenburgerpolder	9,05E+05	2,59E+06	1,68E+06	6,44E+05	2,66E+06	2,02E+06	4,51E+05	4,39E+06	3,94E+06
	Room- of Meerburgerpolder	1,15E+05	2,82E+05	1,67E+05	8,36E+04	2,88E+05	2,04E+05	6,11E+04	5,09E+05	4,48E+05
	Starrevaart- en Damhouderpolder en Vlietland	5,08E+05	3,76E+06	3,25E+06	3,81E+05	4,00E+06	3,62E+06	3,37E+05	5,92E+06	5,59E+06
	Zoetermeerse Meerpolder	1,16E+06	3,36E+06	2,20E+06	7,44E+05	3,39E+06	2,65E+06	5,92E+05	5,47E+06	4,88E+06
	Zwet- en Grote Blankaartpolder	4,20E+05	1,10E+06	6,81E+05	3,04E+05	1,15E+06	8,46E+05	2,02E+05	1,96E+06	1,76E+06
	Binnenwegse polder	5,02E+05	8,71E+06	8,21E+06	2,06E+05	8,87E+06	8,67E+06	9,25E+04	1,38E+07	1,37E+07
	Boezemland	8,32E+04	1,76E+05	9,26E+04	6,43E+04	1,79E+05	1,15E+05	4,00E+04	2,93E+05	2,53E+05
	Oostpolder	1,15E+06	1,63E+06	4,81E+05	8,55E+05	1,55E+06	6,98E+05	6,39E+05	2,55E+06	1,91E+06
	Polder Bleiswijk	1,94E+06	2,23E+07	2,04E+07	7,77E+05	2,20E+07	2,12E+07	5,66E+05	3,40E+07	3,35E+07
	Polder Capelle aan den IJssel	6,34E+05	4,35E+06	3,71E+06	4,07E+05	4,35E+06	3,94E+06	1,81E+05	7,26E+06	7,08E+06
	Polder de Wilde Veenen	2,29E+06	3,47E+06	1,18E+06	1,48E+06	3,25E+06	1,77E+06	1,21E+06	5,69E+06	4,48E+06
	Polder Esse Gans- en Blaardorp	1,08E+06	2,42E+06	1,34E+06	8,01E+05	2,48E+06	1,68E+06	5,39E+05	4,41E+06	3,87E+06
	Polder Prins Alexander en Eendragtspolder	2,69E+06	2,29E+07	2,02E+07	1,53E+06	2,25E+07	2,10E+07	1,40E+06	3,34E+07	3,20E+07
	Polders van Rotterdam	2,91E+06	1,38E+07	1,09E+07	1,92E+06	1,33E+07	1,14E+07	1,51E+06	2,13E+07	1,97E+07
	Ringvaart	0,00E+00	3,01E+07	3,01E+07	4,26E+05	1,19E+07	1,15E+07	5,29E+05	1,26E+06	7,35E+05
	Rotte	4,95E+05	4,01E+07	3,96E+07	1,02E+06	1,24E+07	1,13E+07	1,30E+06	2,01E+06	7,11E+05
	Tweemanspolder	8,18E+05	2,39E+06	1,58E+06	5,35E+05	2,38E+06	1,85E+06	3,90E+05	3,98E+06	3,59E+06
	Zuidplaspolder	2,79E+06	2,84E+07	2,56E+07	1,19E+06	2,86E+07	2,74E+07	8,44E+05	4,22E+07	4,14E+07

B.2 – Central Python code of the Water Balance model

```
import pandas as pd
import matplotlib.pyplot as plt
import sys
import numpy as np
import datetime
from datetime import datetime, timedelta


def EVfactor(E, Dates, EVfactor):
    for i in range(len(E)):
        mn = Dates[i]
        month = mn.month
        if month > 5 and month < 9:
            E[i] = E[i] * EVfactor

    return E

def Day(P, E, E_pen, CSO, Vol_2_seepage, Vol_3_seepage, Vol_4_seepage,
        Apaved, Aunp, Awat, min_lvl, max_lvl, level,
        Volume_1, Volume_2, Volume_3, max_vol_1, max_vol_2, max_vol_3,
        PumpCap, wbh, min_gvf, f_in_undp, f_out_undp, f_in, f_out):

    # Bucket 1: Upper Paved
    neerslagoverschot_1 = (P - E) * Apaved / 1000
    runoff_1 = 0
    if Volume_1 + neerslagoverschot_1 > max_vol_1:
        runoff_1 = - 1 * (Volume_1 + neerslagoverschot_1 - max_vol_1)
    if Volume_1 + neerslagoverschot_1 > max_vol_1:
        nextVolume_1 = max_vol_1
    elif Volume_1 + neerslagoverschot_1 < 0:
        nextVolume_1 = 0
    else:
        nextVolume_1 = Volume_1 + neerslagoverschot_1

    # Bucket 2: Under Paved
    if Volume_2 < 0:
        SubFlow_2 = -1 * f_in_undp * Volume_2
    elif Volume_2 > 0:
        SubFlow_2 = -1 * f_out_undp * Volume_2
    else:
        SubFlow_2 = 0

    bruto_2 = Vol_2_seepage + SubFlow_2
    if Volume_2 + bruto_2 > max_vol_2:
        nextVolume_2 = max_vol_2
    else:
        nextVolume_2 = Volume_2 + bruto_2

    # Bucket 3: Sub1
    if Volume_3 < 0:
        SubFlow_3 = -1 * f_in * Volume_3
    elif Volume_3 > 0:
        SubFlow_3 = -1 * f_out * Volume_3
    else:
        SubFlow_3 = 0

    if Volume_3 < 0:
        neerslagoverschot_3 = (P - E * min_gvf) * Aunp / 1000
```

```
    else:
        neerslagoverschot_3 = (P - E) * Aunp / 1000

    bruto_3 = Vol_3_seepage + neerslagoverschot_3 + SubFlow_3
    runoff_3 = 0
    if Volume_3 + bruto_3 > max_vol_3:
        nextVolume_3 = max_vol_3
        runoff_3 = -1 * (Volume_3 + bruto_3 - max_vol_3)
    else:
        nextVolume_3 = Volume_3 + bruto_3

    # Bucket 4: Water
    P_4 = P / 1000 * Awat
    E_4 = E_pen / 1000 * Awat
    SubFlow_4 = -1 * (SubFlow_2 + SubFlow_3)
    runoff_4 = -1 * (runoff_1 + runoff_3)

    netto_4 = P_4 - E_4 + SubFlow_4 + runoff_4 + CSO + Vol_4_seepage

    calc_inlet, calc_outlet = 0, 0

    if level + netto_4 / Awat < min_lvl:
        calc_inlet = (min_lvl - level) * Awat - netto_4

    if level + netto_4 / Awat > max_lvl:
        calc_outlet = np.min((PumpCap, (level - max_lvl) * Awat + netto_4))

    storage = netto_4 + calc_inlet - calc_outlet

    next_lvl = level + storage / Awat
    nextVolume_4 = (next_lvl - wbh) * Awat

    return runoff_1, runoff_3, runoff_4, SubFlow_2, SubFlow_3, SubFlow_4,
nextVolume_1, nextVolume_2, nextVolume_3, nextVolume_4, next_lvl,
calc_outlet, calc_inlet, netto_4


def WB(Dates, Asep, Acom, Asem, Anat, Awat, P, E, K, CSO, Levels, PumpCap,
Pump1, Pump2 = 0, Pump3 = 0, EV_factor = 1):
    # Parameters
    wbh = np.min(Levels) - 2
    max_gw_uppav = 0.002
    f_out_undp = 0.001
    f_in_undp = 0.001
    storage_undp = 0.55
    max_gw_undp = 0.55
    f_out = 0.3
    f_in = 0.15
    storage = 0.55
    max_gw = 0.5

    init_level = (Levels[2] + Levels[3]) / 2



    min_gvf = 0.7

    # Surfaces
    Apaved = Asep + 0.5 * Asem
    Aunderpav = Apaved
    Aunp = Anat + 0.5 * Asem
```

```
    # Adjusting evaportation and CSO
    E = EVfactor(E, Dates, EV_factor)
    E_pen = Evaporator(E, Dates)
    CSO = Acom / 10000 * CSO

    # Bucket 1: Upper Paved
    max_vol_1 = max_gw_uppav * Apaved
    Volume_1 = np.zeros(len(E))
    neerslagoverschot_1 = np.zeros(len(E))
    runoff_1 = np.zeros(len(E))


    # Bucket 2: Under Paved
    max_vol_2 = max_gw_undp * Aunderpav * storage_undp
    Volume_2 = np.zeros(len(E))
    Vol_2_seepage = K * Aunderpav / 1000
    SubFlow_2 = np.zeros(len(E))


    # Bucket 3: Sub1
    max_vol_3 = Aunp * storage * max_gw
    Vol_3_seepage = K * Aunp / 1000
    SubFlow_3 = np.zeros(len(E))
    Volume_3 = np.zeros(len(E))
    runoff_3 = np.zeros(len(E))

    # Bucket 4: Water
    level = np.zeros(len(E))
    Volume_4 = np.zeros(len(E))
    runoff_4 = np.zeros(len(E))

    ## water IN:
    Vol_4_seepage = K / 1000 * Awat
    SubFlow_4 = np.zeros(len(E))
    calc_inlet = np.zeros(len(E))


    ## water OUT:
    evapotranspiration = E_pen / 1000 * Awat
    precipitation = P / 1000 * Awat
    calc_outlet = np.zeros(len(E))

    # function returns:
    #runoff_1, runoff_3, runoff_4, SubFlow_2, SubFlow_3, SubFlow_4,
    #nextVolume_1, nextVolume_2, nextVolume_3, nextVolume_4, next_lvl,
calc_outlet, calc_inlet
    netto_4 = np.zeros(len(E))
    for i in range(len(Dates)):
        mn = Dates[i]
        month = mn.month
        day = mn.day

        if month > 3 and month < 8 or month == 3 and day > 14 or month == 8
and day < 16:
            min_lvl = Levels[0]
            max_lvl = Levels[1]
        else:
            min_lvl = Levels[2]
            max_lvl = Levels[3]
```

```
        if i == 0:
            result = Day(P[i], E[i], E_pen[i], CSO[i], Vol_2_seepage,
Vol_3_seepage, Vol_4_seepage, Apaved, Aunp, Awat, min_lvl, max_lvl,
init_level, 0, 0, 0, max_vol_1, max_vol_2, max_vol_3, PumpCap, wbh,
min_gvf, f_in_undp, f_out_undp, f_in, f_out)

            runoff_1[i] = result[0]
            runoff_3[i] = result[1]
            runoff_4[i] = result[2]
            SubFlow_2[i] = result[3]
            SubFlow_3[i] = result[4]
            SubFlow_4[i] = result[5]
            Volume_1[i] = result[6]
            Volume_2[i] = result[7]
            Volume_3[i] = result[8]
            Volume_4[i] = result[9]
            level[i] = result[10]
            calc_outlet[i] = result[11]
            calc_inlet[i] = result[12]
            netto_4[i] = result[13]

        else:
            result = Day(P[i], E[i], E_pen[i], CSO[i], Vol_2_seepage,
Vol_3_seepage, Vol_4_seepage, Apaved, Aunp, Awat, min_lvl, max_lvl,
level[i-1], Volume_1[i-1], Volume_2[i-1], Volume_3[i-1], max_vol_1,
max_vol_2, max_vol_3, PumpCap, wbh, min_gvf, f_in_undp, f_out_undp, f_in,
f_out)

            runoff_1[i] = result[0]
            runoff_3[i] = result[1]
            runoff_4[i] = result[2]
            SubFlow_2[i] = result[3]
            SubFlow_3[i] = result[4]
            SubFlow_4[i] = result[5]
            Volume_1[i] = result[6]
            Volume_2[i] = result[7]
            Volume_3[i] = result[8]
            Volume_4[i] = result[9]
            level[i] = result[10]
            calc_outlet[i] = result[11]
            calc_inlet[i] = result[12]
            netto_4[i] = result[13]

    calc_inlet *= -1
    Vol_4_seepage = Vol_4_seepage * np.ones(len(E))

    return calc_outlet, calc_inlet, level, evapotranspiration,
precipitation, runoff_4, SubFlow_4, CSO, Vol_4_seepage
```

B.3 – Yearly accumulated Water Balance Inputs and Outputs

Figures for the current climate									
All in [m³]	OUTPUT		INTPUT						
Year	*Outlet*	*Evapotranspiration*	*Inlet*	*Precipitation*	*Surface runoff*	*Subsurface flow*	*CSO*	*Seepage*
2001	3.8E+08	6.1E+04	2.6E+07	2.6E+07	5.3E+07	1.3E+08	1.9E+08	7.2E+06
2002	2.3E+08	6.1E+04	2.4E+07	2.6E+07	3.6E+07	8.2E+07	1.1E+08	3.8E+06
2003	1.6E+08	6.1E+04	4.8E+07	2.9E+07	2.8E+07	6.0E+07	5.4E+07	2.4E+06
2004	2.7E+08	6.1E+04	2.7E+07	2.6E+07	4.0E+07	9.3E+07	1.3E+08	5.7E+06
2005	1.9E+08	6.1E+04	2.2E+07	2.7E+07	3.3E+07	6.9E+07	8.7E+07	4.0E+06
2006	2.1E+08	6.1E+04	4.2E+07	2.8E+07	3.2E+07	7.2E+07	8.6E+07	5.9E+06
2007	3.2E+08	6.1E+04	2.8E+07	2.7E+07	4.6E+07	1.1E+08	1.5E+08	6.2E+06
2008	2.2E+08	6.1E+04	2.6E+07	2.6E+07	3.6E+07	8.0E+07	1.0E+08	3.9E+06
2009	1.8E+08	6.1E+04	3.5E+07	2.8E+07	3.0E+07	6.5E+07	7.5E+07	1.8E+06
2010	2.8E+08	6.1E+04	3.2E+07	2.7E+07	4.1E+07	9.7E+07	1.3E+08	4.1E+06
2011	2.7E+08	6.1E+04	4.0E+07	2.7E+07	3.8E+07	8.9E+07	1.2E+08	5.4E+06
2012	2.0E+08	6.1E+04	2.3E+07	2.6E+07	3.5E+07	7.4E+07	9.5E+07	2.4E+06
2013	2.4E+08	6.1E+04	3.6E+07	2.6E+07	3.6E+07	8.4E+07	1.1E+08	3.2E+06
2014	2.5E+08	6.1E+04	3.3E+07	2.8E+07	3.8E+07	8.7E+07	1.1E+08	4.2E+06
2015	2.5E+08	6.1E+04	3.5E+07	2.8E+07	3.8E+07	8.6E+07	1.1E+08	3.5E+06
2016	2.5E+08	6.1E+04	3.1E+07	2.8E+07	3.9E+07	8.8E+07	1.1E+08	3.4E+06
2017	2.3E+08	6.1E+04	3.1E+07	2.8E+07	3.7E+07	8.3E+07	1.0E+08	6.2E+06
2018	2.5E+08	6.1E+04	5.3E+07	3.0E+07	3.6E+07	8.6E+07	9.4E+07	5.0E+06
2019	2.0E+08	6.1E+04	3.7E+07	2.9E+07	3.4E+07	7.5E+07	7.8E+07	3.7E+06
2020	2.8E+08	6.1E+04	4.9E+07	3.0E+07	4.0E+07	9.3E+07	1.2E+08	4.6E+06
2021	2.5E+08	6.1E+04	3.3E+07	2.7E+07	3.7E+07	8.6E+07	1.1E+08	4.1E+06
2022	2.3E+08	6.1E+04	5.3E+07	3.1E+07	3.5E+07	8.2E+07	8.3E+07	5.3E+06
All quantities are defined as entering or exiting the water system of the case study area								

Figures for scenario GL								
in [m3]	OUTPUT		INPUT					
Year	*Outlet*	*Evapotranspiration*	*Inlet*	*Precipitation*	*Surface runoff*	*Subsurface flow*	*CSO*	*Seepage*
2084	2.1E+08	6.1E+04	2.7E+07	2.8E+07	3.5E+07	8.6E+07	8.9E+07	1.3E+05
2085	2.0E+08	6.1E+04	4.2E+07	2.9E+07	3.1E+07	7.4E+07	8.0E+07	1.1E+05
2086	3.0E+08	6.1E+04	1.6E+07	2.6E+07	4.4E+07	1.1E+08	1.5E+08	2.8E+05
2087	2.7E+08	6.1E+04	2.3E+07	2.7E+07	4.2E+07	1.1E+08	1.3E+08	1.9E+05
2088	3.4E+08	6.1E+04	1.7E+07	2.6E+07	4.8E+07	1.3E+08	1.8E+08	3.1E+05
2089	2.6E+08	6.1E+04	4.0E+07	2.6E+07	3.5E+07	9.4E+07	1.2E+08	1.7E+05
2090	1.3E+08	6.1E+04	2.6E+07	2.9E+07	2.7E+07	5.4E+07	4.8E+07	4.0E+04
2091	2.4E+08	6.1E+04	2.7E+07	2.6E+07	3.6E+07	9.1E+07	1.1E+08	2.9E+05
2092	4.3E+08	6.1E+04	9.8E+06	2.7E+07	5.9E+07	1.6E+08	2.3E+08	3.7E+05
2093	2.9E+08	6.1E+04	1.8E+07	2.5E+07	4.2E+07	1.1E+08	1.4E+08	1.6E+05
2094	2.6E+08	6.1E+04	1.3E+07	2.7E+07	4.2E+07	9.8E+07	1.3E+08	1.4E+05
2095	3.3E+08	6.1E+04	1.3E+07	2.6E+07	4.8E+07	1.2E+08	1.7E+08	2.1E+05
2096	2.9E+08	6.1E+04	2.0E+07	2.7E+07	4.4E+07	1.1E+08	1.4E+08	2.3E+05
2097	1.7E+08	6.1E+04	3.8E+07	2.7E+07	2.6E+07	6.3E+07	6.4E+07	8.9E+04
2098	2.4E+08	6.1E+04	2.2E+07	3.0E+07	4.0E+07	9.4E+07	1.2E+08	2.2E+05
2099	2.7E+08	6.0E+04	1.9E+07	2.7E+07	4.2E+07	1.1E+08	1.3E+08	3.9E+05
2100	2.4E+08	6.1E+04	2.7E+07	2.7E+07	3.7E+07	9.4E+07	1.1E+08	1.5E+05
2101	3.0E+08	6.1E+04	2.6E+07	2.9E+07	4.4E+07	1.1E+08	1.4E+08	2.6E+05
2102	2.4E+08	6.1E+04	1.3E+07	2.7E+07	4.0E+07	9.4E+07	1.2E+08	1.9E+05
2103	2.1E+08	6.1E+04	2.5E+07	2.7E+07	3.4E+07	7.9E+07	9.3E+07	1.3E+05
2104	2.4E+08	6.1E+04	2.1E+07	2.9E+07	3.9E+07	9.5E+07	1.1E+08	2.6E+05
2105	2.7E+08	6.0E+04	2.3E+07	2.7E+07	4.2E+07	1.0E+08	1.3E+08	3.1E+05
All quantities are defined as entering or exiting the water system of the case study area								

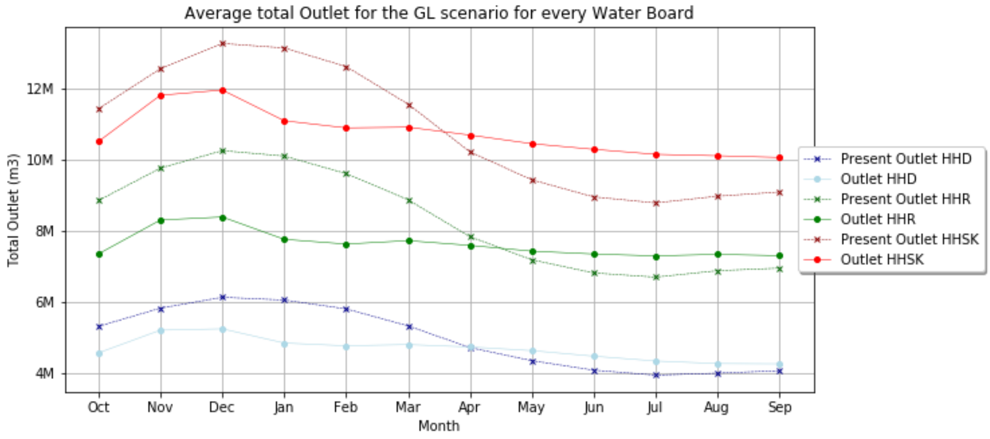
Figures for scenario GH								
in [m3]	OUTPUT		INPUT					
Year	*Outlet*	*Evapotranspiration*	*Inlet*	*Precipitation*	*Surface runoff*	*Subsurface flow*	*CSO*	*Seepage*
2084	2.0E+08	6.1E+04	4.6E+07	2.8E+07	3.1E+07	7.7E+07	7.2E+07	1.0E+05
2085	2.7E+08	6.1E+04	2.9E+07	2.9E+07	3.9E+07	1.0E+08	1.2E+08	2.7E+05
2086	3.0E+08	6.1E+04	2.5E+07	2.6E+07	4.2E+07	1.1E+08	1.4E+08	1.6E+05
2087	3.3E+08	6.1E+04	3.0E+07	2.7E+07	4.5E+07	1.2E+08	1.6E+08	2.5E+05
2088	3.3E+08	6.1E+04	2.8E+07	2.6E+07	4.5E+07	1.3E+08	1.6E+08	2.4E+05
2089	1.0E+08	6.1E+04	4.7E+07	2.6E+07	1.9E+07	4.0E+07	1.9E+07	3.6E+04
2090	2.5E+08	6.1E+04	3.1E+07	2.9E+07	3.7E+07	9.4E+07	1.1E+08	2.4E+05
2091	3.6E+08	6.0E+04	1.5E+07	2.6E+07	5.1E+07	1.3E+08	1.9E+08	3.8E+05
2092	3.6E+08	6.1E+04	2.3E+07	2.7E+07	5.0E+07	1.3E+08	1.8E+08	2.2E+05
2093	2.6E+08	6.1E+04	1.9E+07	2.5E+07	3.9E+07	9.9E+07	1.3E+08	1.5E+05
2094	3.8E+08	6.1E+04	2.1E+07	2.7E+07	5.2E+07	1.4E+08	1.9E+08	2.4E+05
2095	2.9E+08	6.1E+04	2.1E+07	2.6E+07	4.1E+07	1.1E+08	1.4E+08	2.0E+05
2096	2.1E+08	6.1E+04	4.2E+07	2.7E+07	3.2E+07	8.0E+07	8.5E+07	1.2E+05
2097	2.9E+08	6.1E+04	2.4E+07	2.7E+07	4.2E+07	1.1E+08	1.4E+08	2.4E+05
2098	2.5E+08	6.1E+04	2.2E+07	3.0E+07	4.1E+07	9.9E+07	1.2E+08	3.7E+05
2099	2.3E+08	6.1E+04	3.6E+07	2.7E+07	3.4E+07	8.5E+07	9.6E+07	1.4E+05
2100	3.6E+08	6.1E+04	2.2E+07	2.7E+07	5.0E+07	1.3E+08	1.8E+08	3.1E+05
2101	2.3E+08	6.1E+04	2.8E+07	2.9E+07	3.7E+07	9.1E+07	1.0E+08	1.8E+05
2102	2.0E+08	6.1E+04	2.9E+07	2.7E+07	3.1E+07	7.6E+07	8.6E+07	1.1E+05
2103	3.0E+08	6.1E+04	3.1E+07	2.7E+07	4.2E+07	1.1E+08	1.4E+08	2.6E+05
2104	2.6E+08	6.1E+04	3.5E+07	2.9E+07	3.9E+07	9.9E+07	1.2E+08	2.7E+05
2105	2.2E+08	6.1E+04	1.9E+07	2.7E+07	3.6E+07	8.7E+07	1.0E+08	1.3E+05
All quantities are defined as entering or exiting the water system of the case study area								

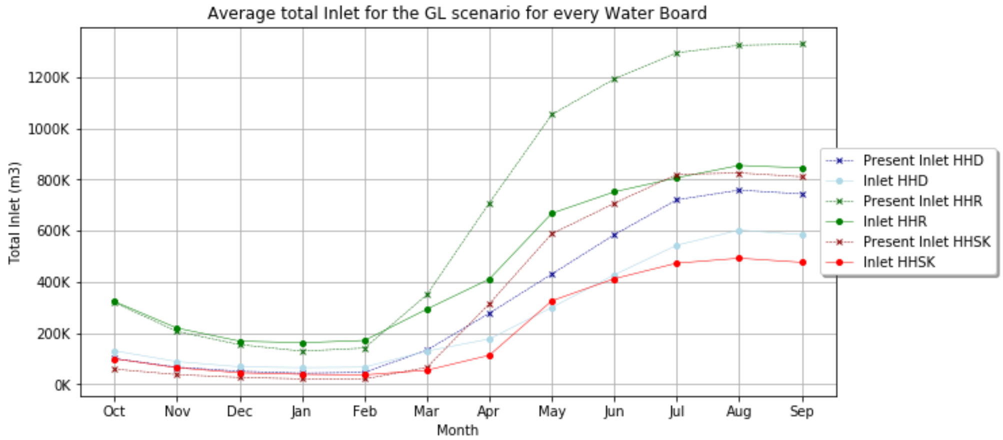
Figures for scenario WL									
in [m3]	OUTPUT		INPUT						
Year	*Outlet*	*Evapotranspiration*	*Inlet*	*Precipitation*	*Surface runoff*	*Subsurface flow*	*CSO*	*Seepage*
2084	2.1E+08	6.1E+04	4.5E+07	2.7E+07	3.2E+07	8.4E+07	8.0E+07	1.4E+05
2085	3.1E+08	6.1E+04	3.5E+07	2.8E+07	4.2E+07	1.2E+08	1.4E+08	3.6E+05
2086	3.0E+08	6.1E+04	2.8E+07	2.6E+07	4.2E+07	1.2E+08	1.4E+08	1.9E+05
2087	3.9E+08	6.0E+04	3.3E+07	2.7E+07	5.0E+07	1.4E+08	1.9E+08	4.3E+05
2088	3.5E+08	6.1E+04	4.4E+07	2.9E+07	4.7E+07	1.3E+08	1.5E+08	3.3E+05
2089	1.0E+08	6.1E+04	4.8E+07	2.7E+07	1.9E+07	4.3E+07	1.7E+07	5.2E+04
2090	2.7E+08	6.1E+04	3.3E+07	2.8E+07	3.8E+07	1.0E+08	1.2E+08	3.1E+05
2091	4.1E+08	6.0E+04	2.4E+07	2.6E+07	5.4E+07	1.5E+08	2.1E+08	5.1E+05
2092	3.9E+08	6.1E+04	3.3E+07	2.8E+07	5.1E+07	1.5E+08	1.8E+08	3.1E+05
2093	2.8E+08	6.1E+04	2.1E+07	2.6E+07	4.1E+07	1.1E+08	1.3E+08	2.1E+05
2094	4.0E+08	6.1E+04	2.5E+07	2.8E+07	5.4E+07	1.5E+08	2.0E+08	3.2E+05
2095	3.0E+08	6.1E+04	2.6E+07	2.8E+07	4.2E+07	1.2E+08	1.4E+08	2.6E+05
2096	2.0E+08	6.1E+04	5.4E+07	3.0E+07	3.1E+07	8.1E+07	6.8E+07	1.4E+05
2097	2.9E+08	6.1E+04	3.1E+07	2.8E+07	4.1E+07	1.1E+08	1.3E+08	2.6E+05
2098	2.8E+08	6.0E+04	2.5E+07	2.8E+07	4.1E+07	1.1E+08	1.3E+08	4.5E+05
2099	2.5E+08	6.1E+04	4.9E+07	2.9E+07	3.5E+07	9.4E+07	9.6E+07	2.0E+05
2100	3.9E+08	6.1E+04	3.0E+07	2.8E+07	5.2E+07	1.5E+08	1.9E+08	4.2E+05
2101	2.6E+08	6.1E+04	3.1E+07	2.8E+07	3.9E+07	1.0E+08	1.1E+08	2.6E+05
2102	2.0E+08	6.1E+04	3.6E+07	3.0E+07	3.2E+07	8.1E+07	8.1E+07	1.6E+05
2103	3.1E+08	6.1E+04	3.7E+07	2.8E+07	4.2E+07	1.2E+08	1.4E+08	3.8E+05
2104	2.8E+08	6.1E+04	3.5E+07	3.1E+07	4.2E+07	1.1E+08	1.3E+08	3.6E+05
2105	2.2E+08	6.1E+04	2.2E+07	2.9E+07	3.7E+07	9.0E+07	1.0E+08	1.9E+05
All quantities are defined as entering or exiting the water system of the case study area									

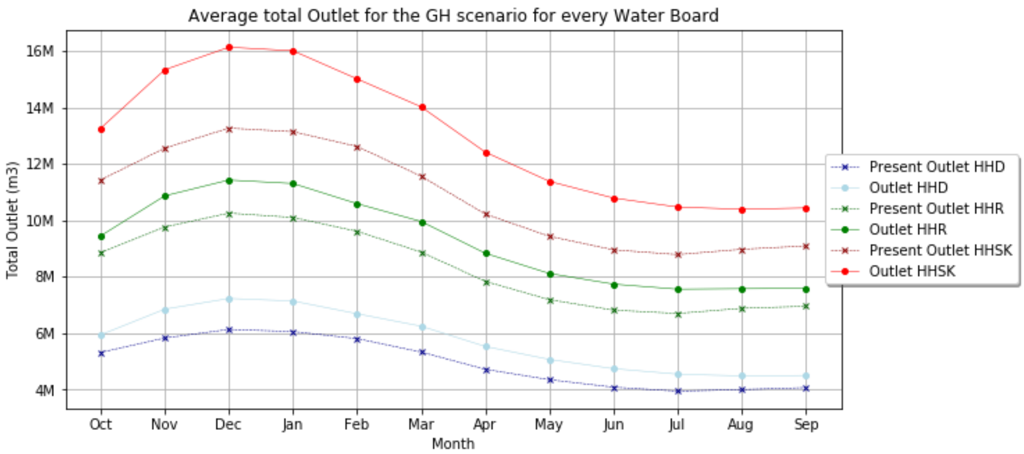
Figures for scenario WH								
in [m3]	OUTPUT		INPUT					
Year	*Outlet*	*Evapotranspiration*	*Inlet*	*Precipitation*	*Surface runoff*	*Subsurface flow*	*CSO*	*Seepage*
2084	2.1E+08	6.1E+04	4.5E+07	2.7E+07	3.2E+07	8.4E+07	8.0E+07	1.4E+05
2085	3.1E+08	6.1E+04	3.5E+07	2.8E+07	4.2E+07	1.2E+08	1.4E+08	3.6E+05
2086	3.0E+08	6.1E+04	2.8E+07	2.6E+07	4.2E+07	1.2E+08	1.4E+08	1.9E+05
2087	3.9E+08	6.0E+04	3.3E+07	2.7E+07	5.0E+07	1.4E+08	1.9E+08	4.3E+05
2088	3.5E+08	6.1E+04	4.4E+07	2.9E+07	4.7E+07	1.3E+08	1.5E+08	3.3E+05
2089	1.0E+08	6.1E+04	4.8E+07	2.7E+07	1.9E+07	4.3E+07	1.7E+07	5.2E+04
2090	2.7E+08	6.1E+04	3.3E+07	2.8E+07	3.8E+07	1.0E+08	1.2E+08	3.1E+05
2091	4.1E+08	6.0E+04	2.4E+07	2.6E+07	5.4E+07	1.5E+08	2.1E+08	5.1E+05
2092	3.9E+08	6.1E+04	3.3E+07	2.8E+07	5.1E+07	1.5E+08	1.8E+08	3.1E+05
2093	2.8E+08	6.1E+04	2.1E+07	2.6E+07	4.1E+07	1.1E+08	1.3E+08	2.1E+05
2094	4.0E+08	6.1E+04	2.5E+07	2.8E+07	5.4E+07	1.5E+08	2.0E+08	3.2E+05
2095	3.0E+08	6.1E+04	2.6E+07	2.8E+07	4.2E+07	1.2E+08	1.4E+08	2.6E+05
2096	2.0E+08	6.1E+04	5.4E+07	3.0E+07	3.1E+07	8.1E+07	6.8E+07	1.4E+05
2097	2.9E+08	6.1E+04	3.1E+07	2.8E+07	4.1E+07	1.1E+08	1.3E+08	2.6E+05
2098	2.8E+08	6.0E+04	2.5E+07	2.8E+07	4.1E+07	1.1E+08	1.3E+08	4.5E+05
2099	2.5E+08	6.1E+04	4.9E+07	2.9E+07	3.5E+07	9.4E+07	9.6E+07	2.0E+05
2100	3.9E+08	6.1E+04	3.0E+07	2.8E+07	5.2E+07	1.5E+08	1.9E+08	4.2E+05
2101	2.6E+08	6.1E+04	3.1E+07	2.8E+07	3.9E+07	1.0E+08	1.1E+08	2.6E+05
2102	2.0E+08	6.1E+04	3.6E+07	3.0E+07	3.2E+07	8.1E+07	8.1E+07	1.6E+05
2103	3.1E+08	6.1E+04	3.7E+07	2.8E+07	4.2E+07	1.2E+08	1.4E+08	3.8E+05
2104	2.8E+08	6.1E+04	3.5E+07	3.1E+07	4.2E+07	1.1E+08	1.3E+08	3.6E+05
2105	2.2E+08	6.1E+04	2.2E+07	2.9E+07	3.7E+07	9.0E+07	1.0E+08	1.9E+05
All quantities are defined as entering or exiting the water system of the case study area								

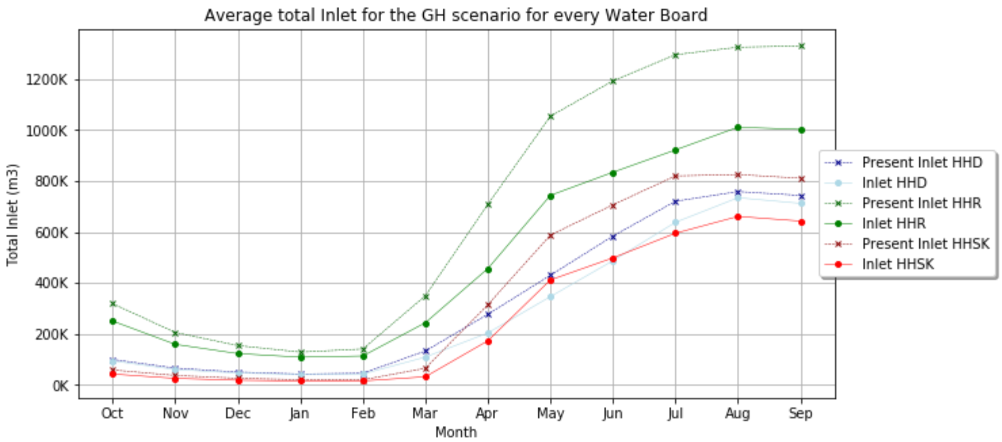
Appendix C – Simulation results for climate scenarios

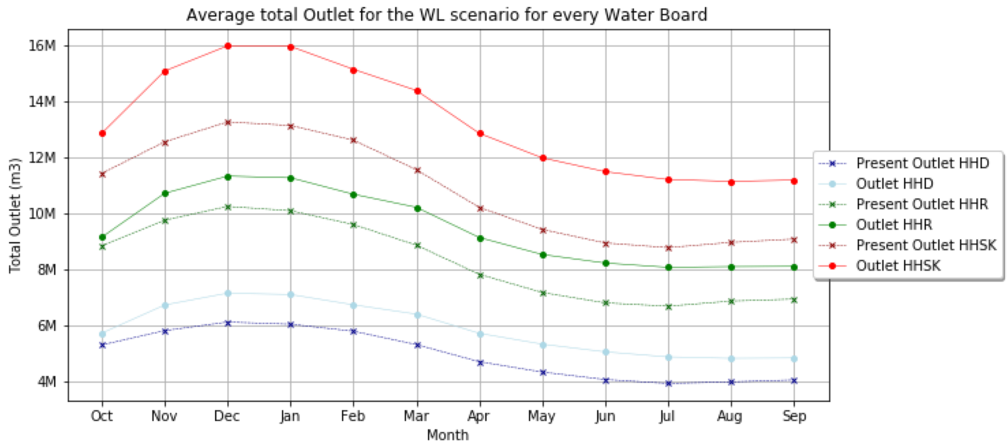
C.1 – Monthly average Inlet and Outlet per scenario

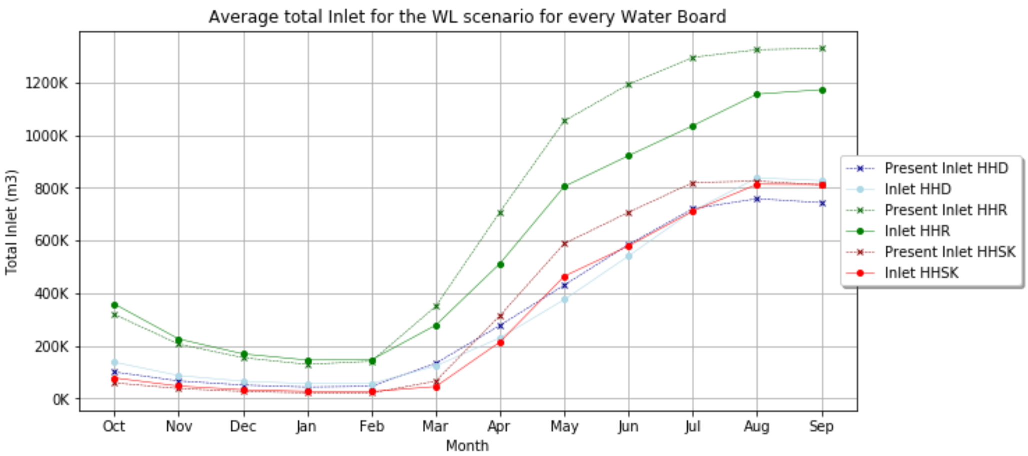


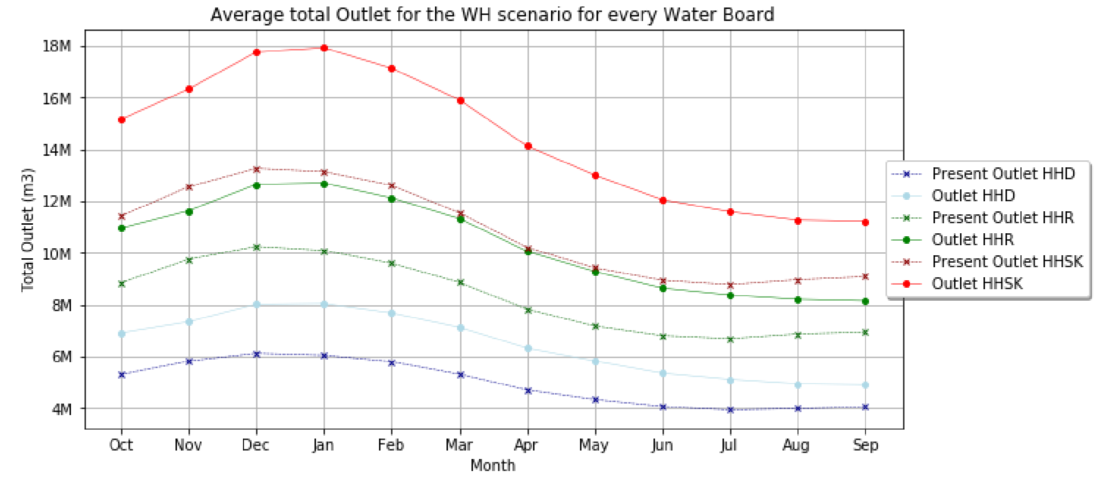


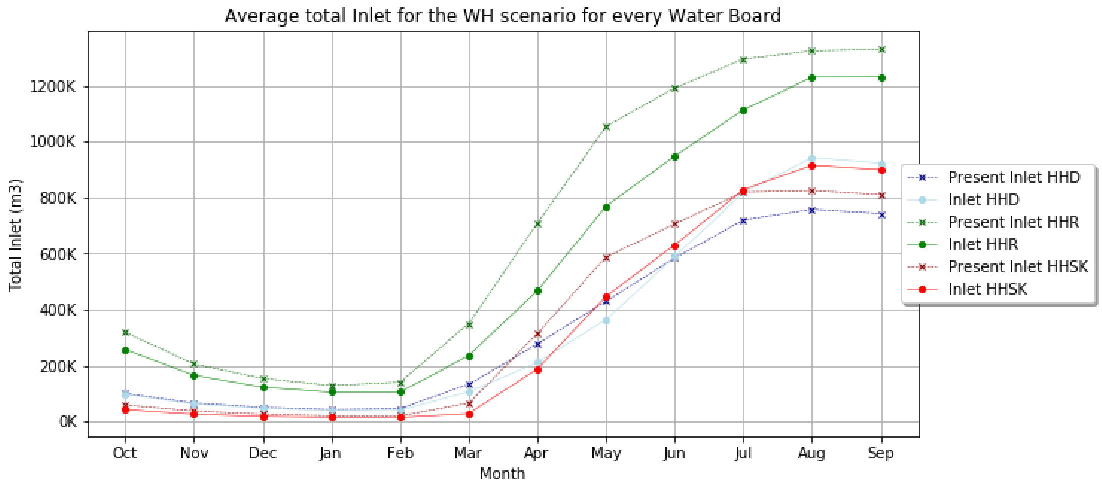



Average total Inlet for the GH scenario for every Water Board
Total Inlet (m3)
1200K
1000K
800K
600K
400K
200K
0K
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Month
Present Inlet HHD
Inlet HHD
Present Inlet HHR
Inlet HHR
Present Inlet HHSK
Inlet HHSK

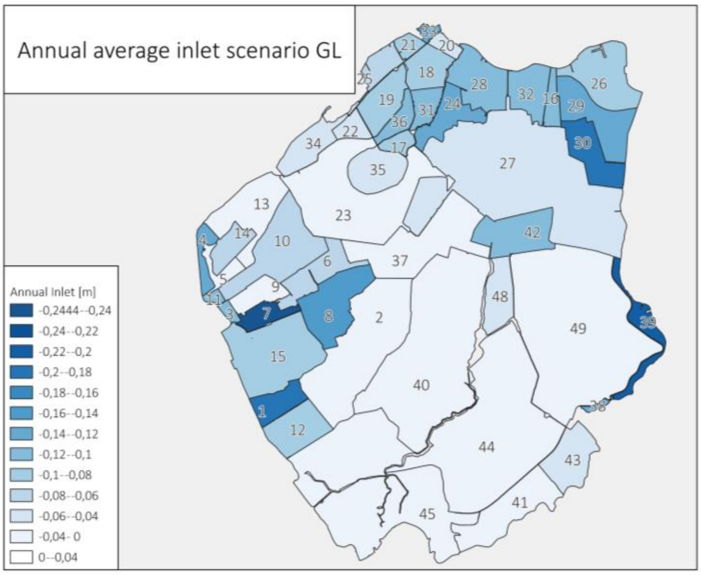

Average total Outlet for the WL scenario for every Water Board
Total Outlet (m3)
16M
14M
12M
10M
8M
6M
4M
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Month
Present Outlet HHD
Outlet HHD
Present Outlet HHR
Outlet HHR
Present Outlet HHSK
Outlet HHSK

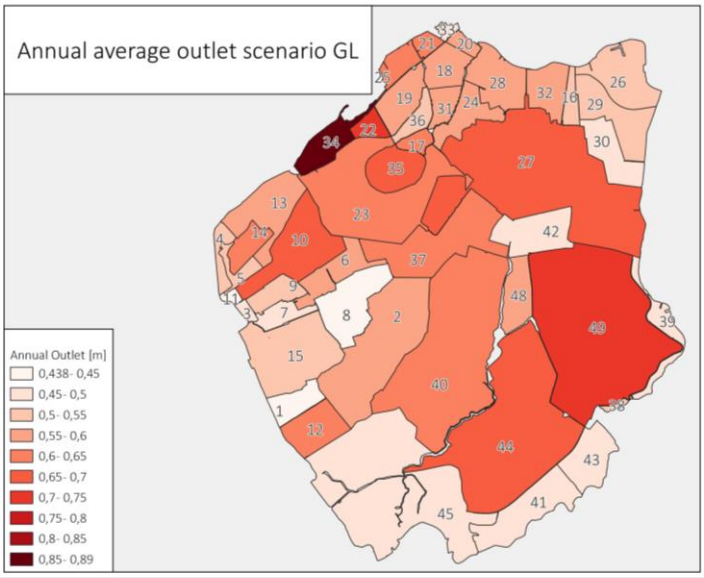

Average total Inlet for the WL scenario for every Water Board
Total Inlet (m3)
1200K
1000K
800K
600K
400K
200K
0K
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Month
Present Inlet HHD
Inlet HHD
Present Inlet HHR
Inlet HHR
Present Inlet HHSK
Inlet HHSK

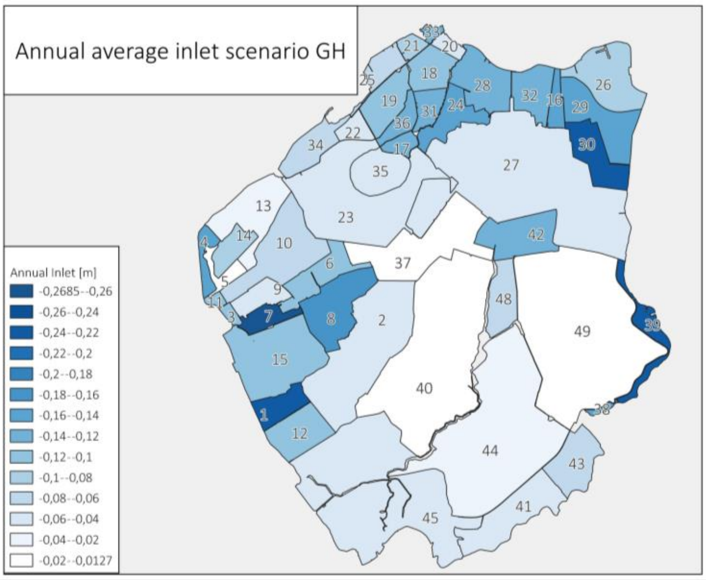

Average total Outlet for the WH scenario for every Water Board
Total Outlet (m3)
18M
16M
14M
12M
10M
8M
6M
4M
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Month
Present Outlet HHD
Outlet HHD
Present Outlet HHR
Outlet HHR
Present Outlet HHSK
Outlet HHSK

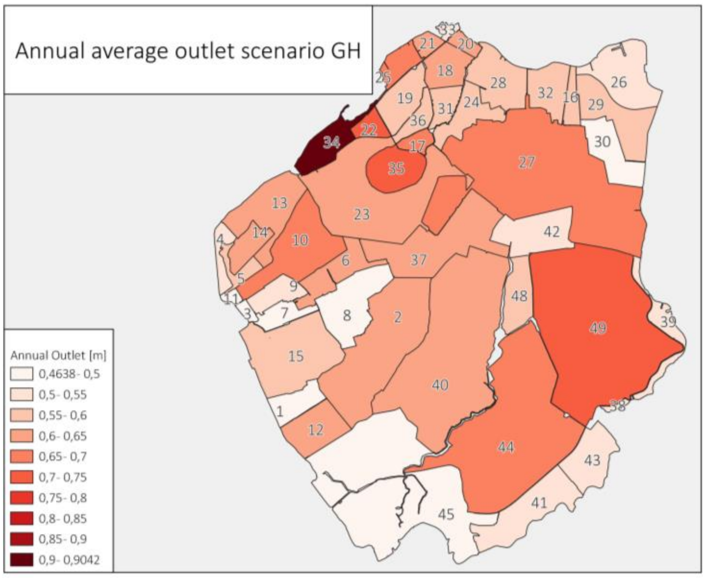

Average total Inlet for the WH scenario for every Water Board
Total Inlet (m3)
1200K
1000K
800K
600K
400K
200K
0K
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Month
Present Inlet HHD
Inlet HHD
Present Inlet HHR
Inlet HHR
Present Inlet HHSK
Inlet HHSK

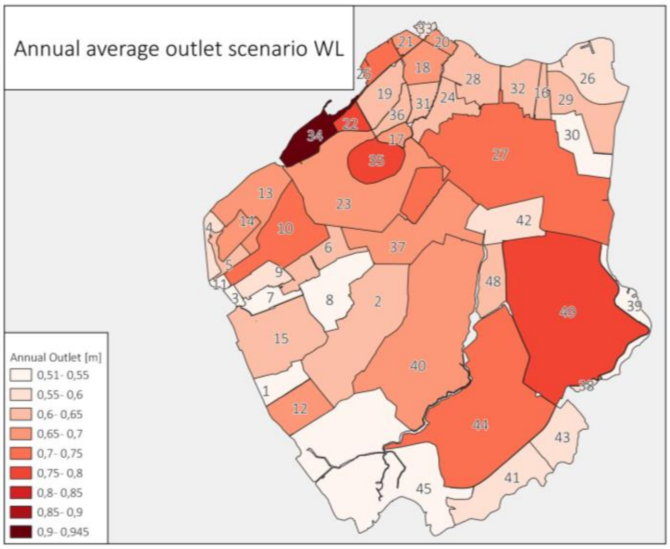
C.2 – Overview of annual Inlet and Outlet per polder for every climate scenario

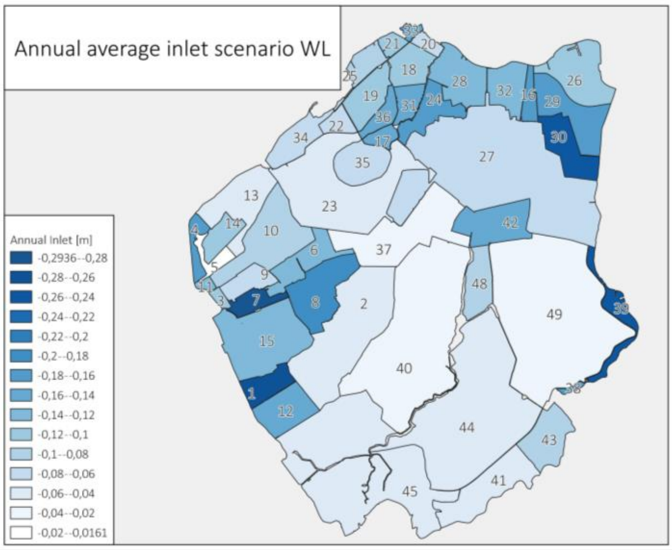


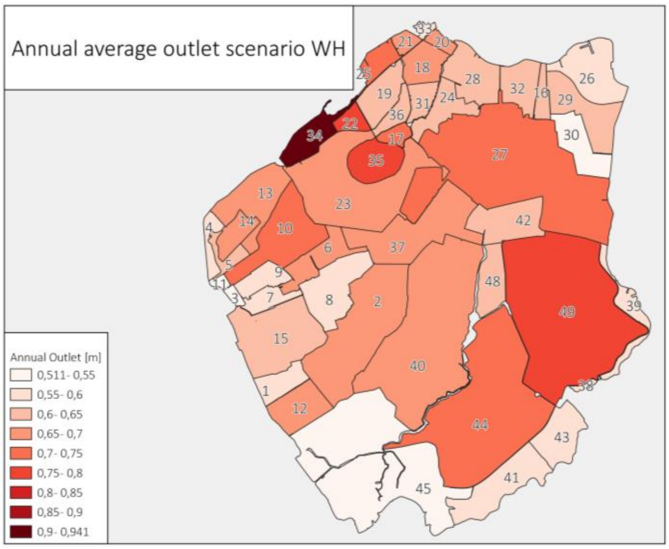


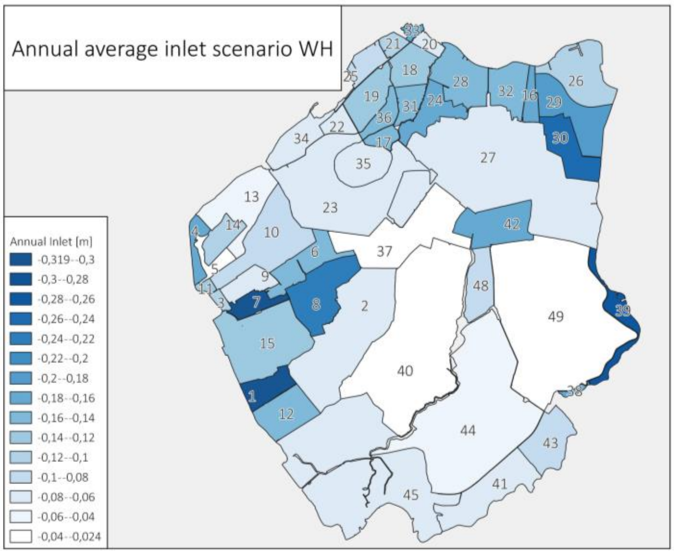





Annual average outlet scenario WL
Annual Outlet [m]
0,51- 0,55
0,55- 0,6
0,6- 0,65
0,65- 0,7
0,7- 0,75
0,75- 0,8
0,8- 0,85
0,85- 0,9
0,9- 0,945

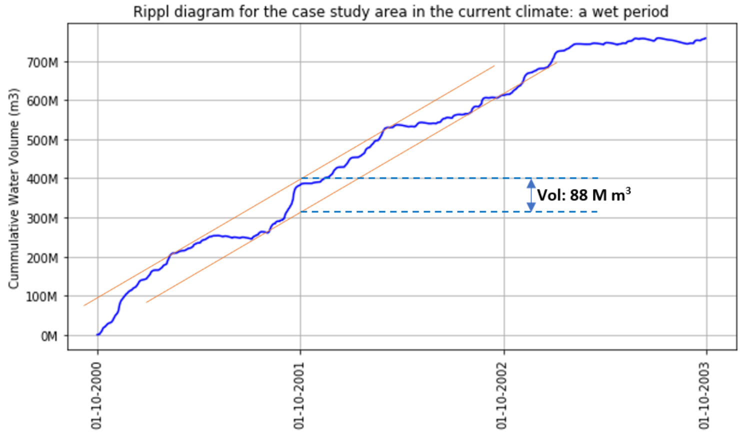

Annual average inlet scenario WL
Annual Inlet [m]
-0,2936--0,28
-0,28--0,26
-0,26--0,24
-0,24--0,22
-0,22--0,2
-0,2--0,18
-0,18--0,16
-0,16--0,14
-0,14--0,12
-0,12--0,1
-0,1--0,08
-0,08--0,06
-0,06--0,04
-0,04--0,02
-0,02--0,0161

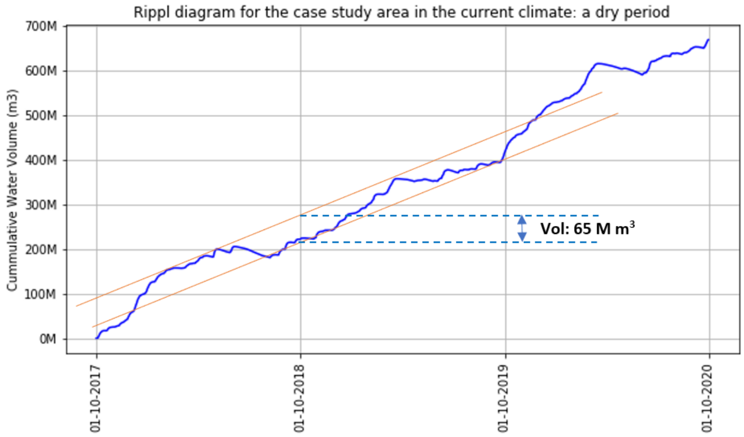

Annual average outlet scenario WH
Annual Outlet [m]
0,511- 0,55
0,55- 0,6
0,6- 0,65
0,65- 0,7
0,7- 0,75
0,75- 0,8
0,8- 0,85
0,85- 0,9
0,9- 0,941

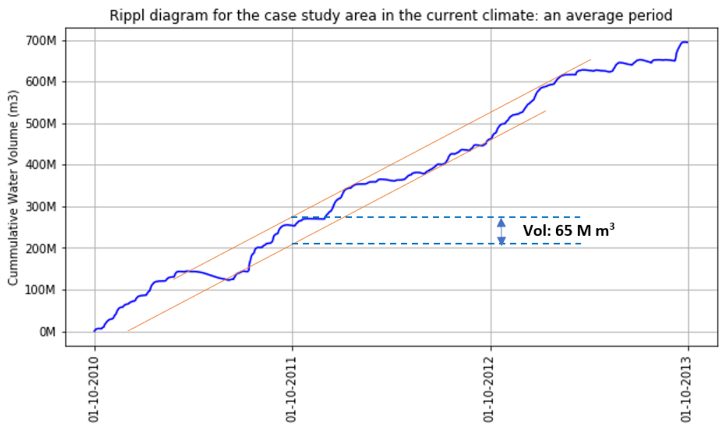

Annual average inlet scenario WH
Annual Inlet [m]
-0,319--0,3
-0,3--0,28
-0,28--0,26
-0,26--0,24
-0,24--0,22
-0,22--0,2
-0,2--0,18
-0,18--0,16
-0,16--0,14
-0,14--0,12
-0,12--0,1
-0,1--0,08
-0,08--0,06
-0,06--0,04
-0,04--0,024

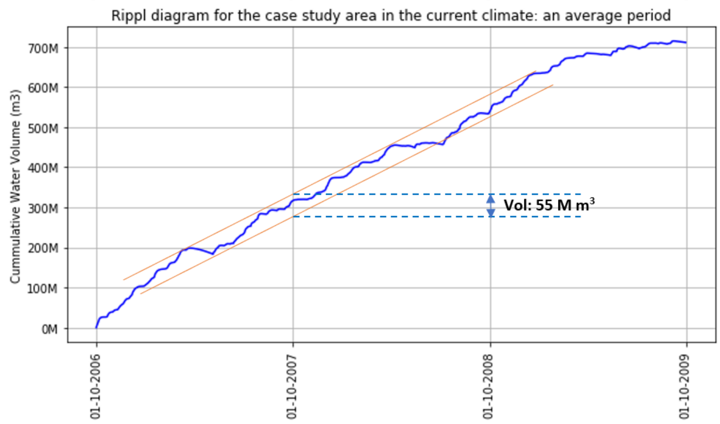
Appendix D – Rippl diagrams

D.1 – Rippl diagrams for the current climate

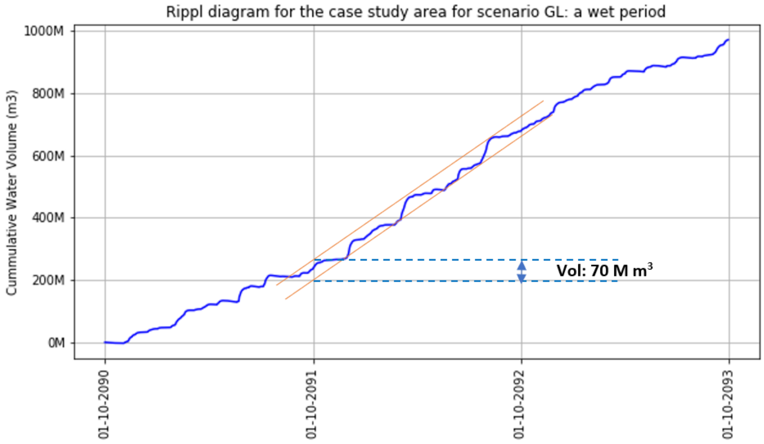


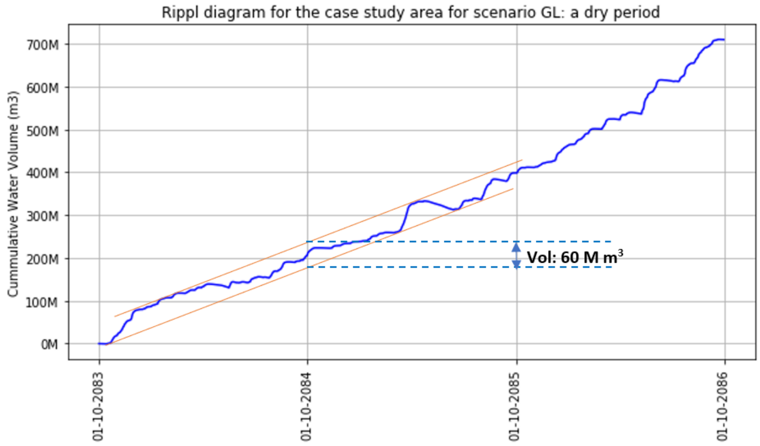


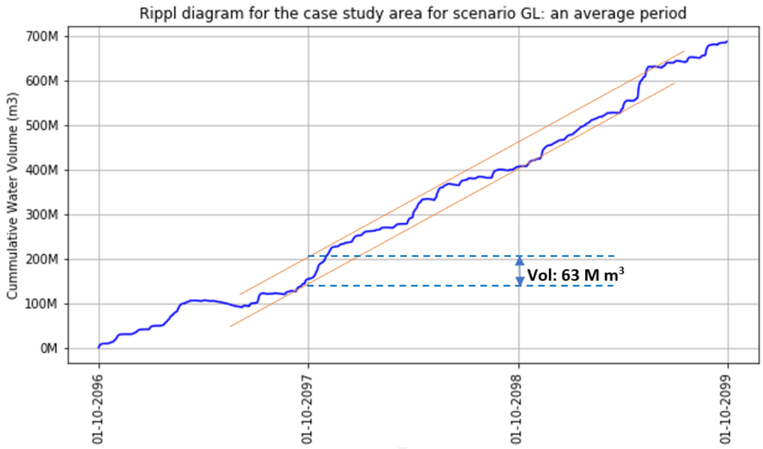


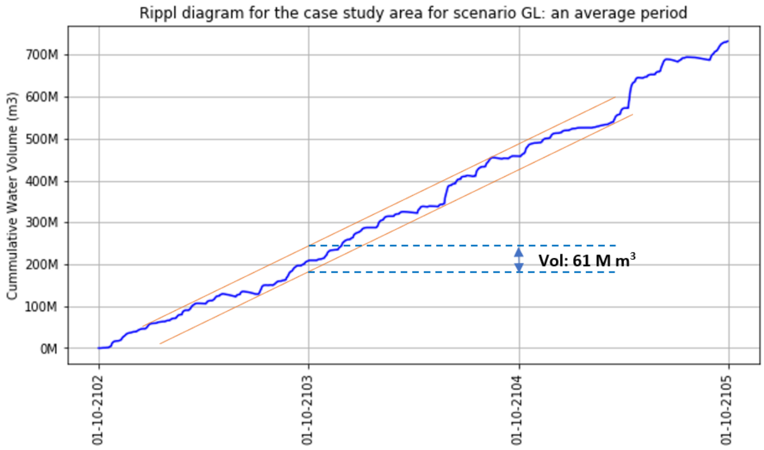


D.2 - Rippl diagrams for the GL scenario

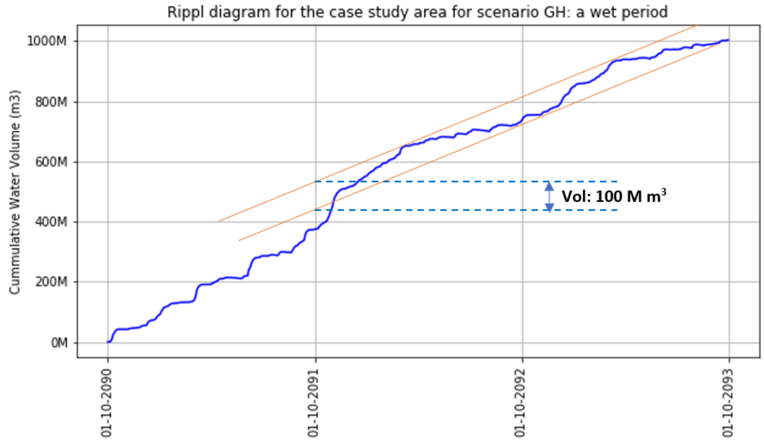


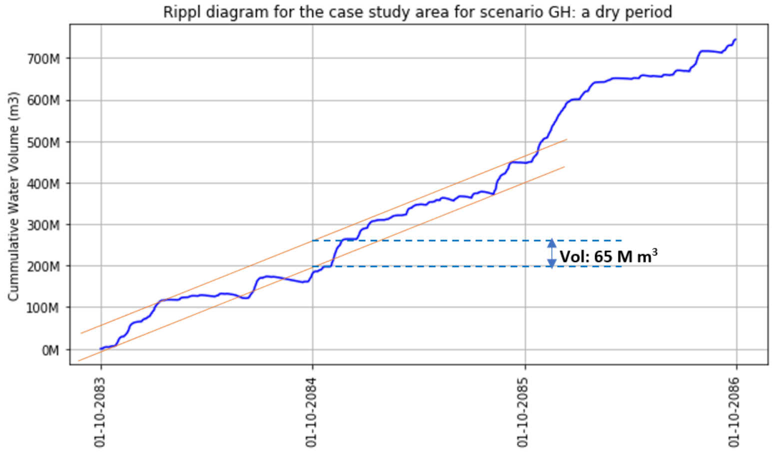


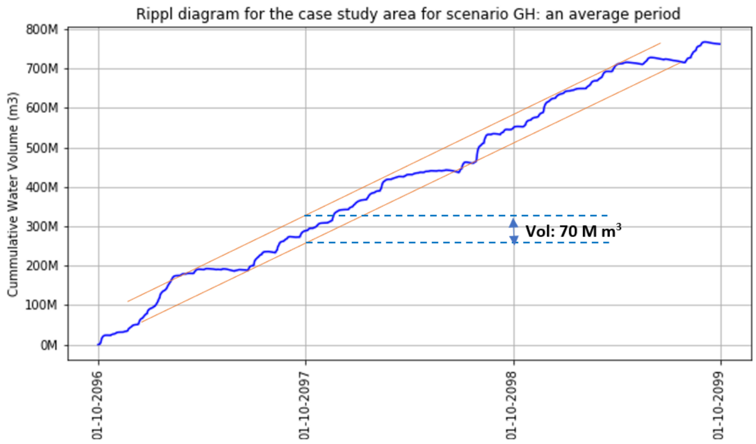


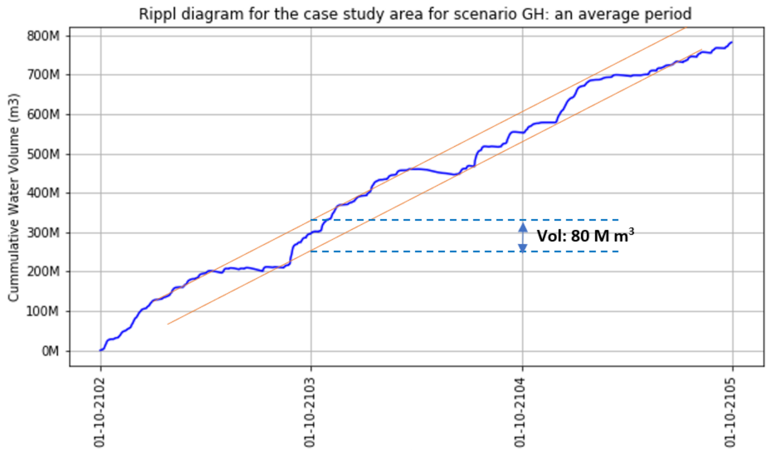


D.3 - Rippl diagrams for the GH scenario

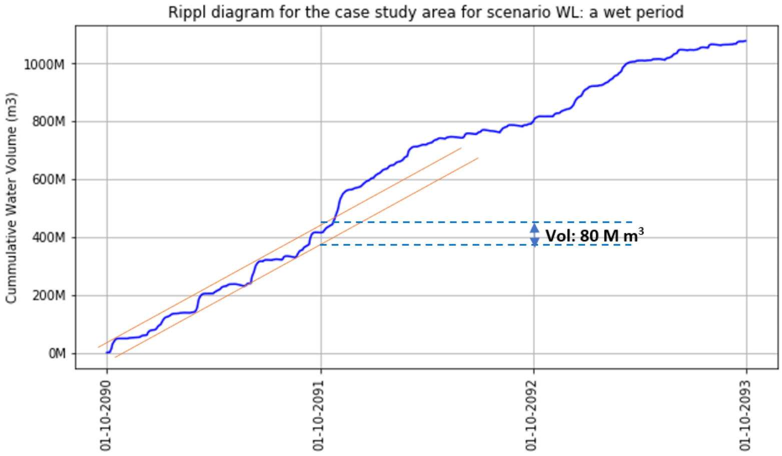


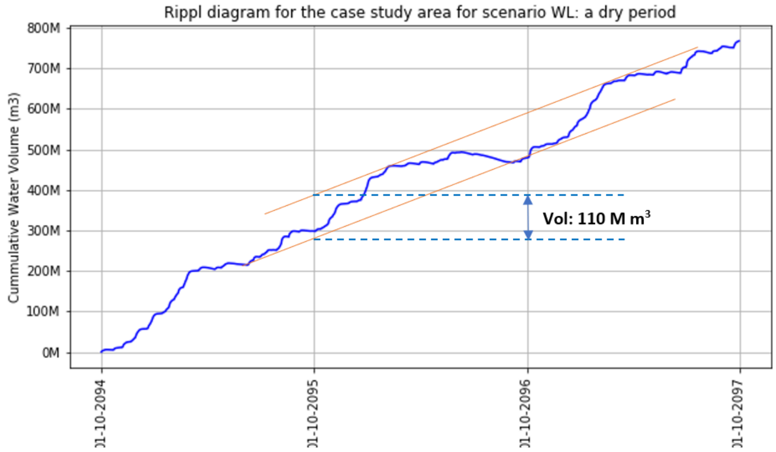


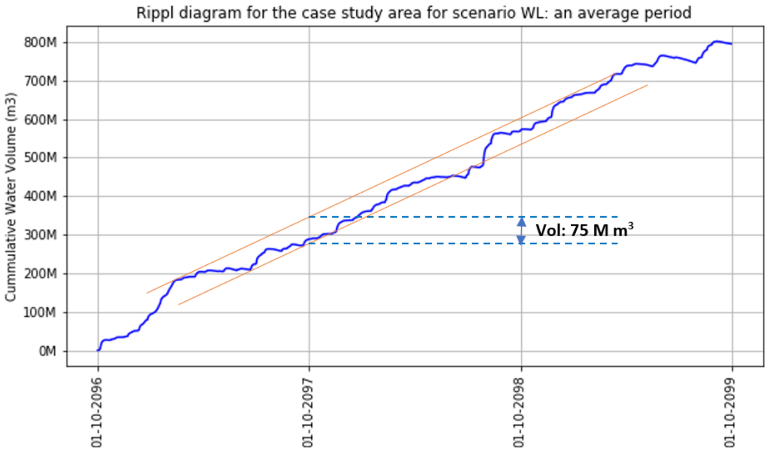


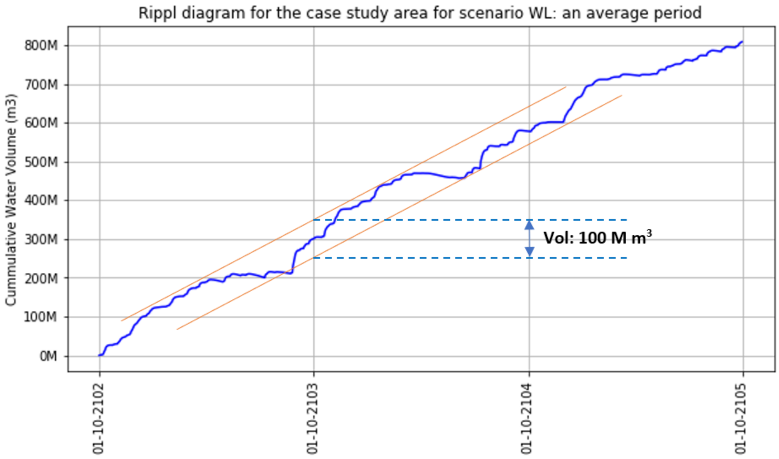


D.4 - Rippl diagrams for the WL scenario

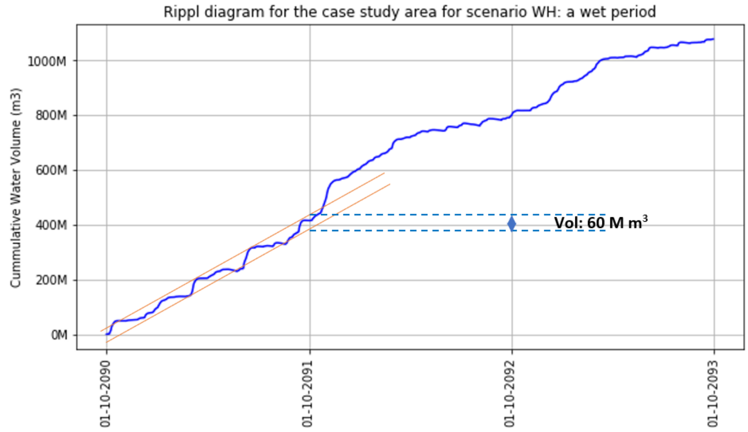


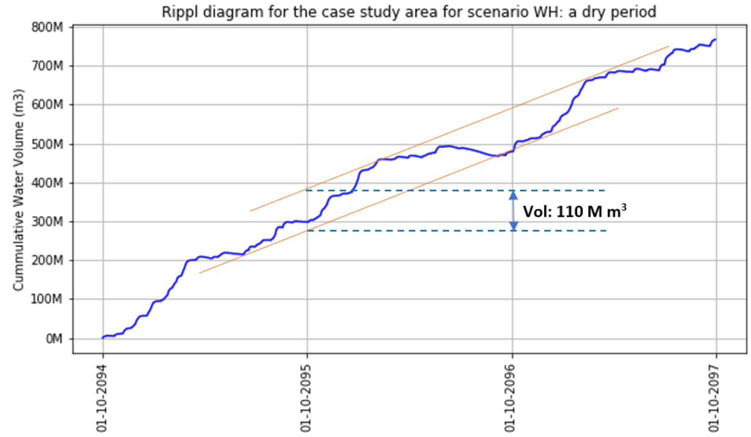


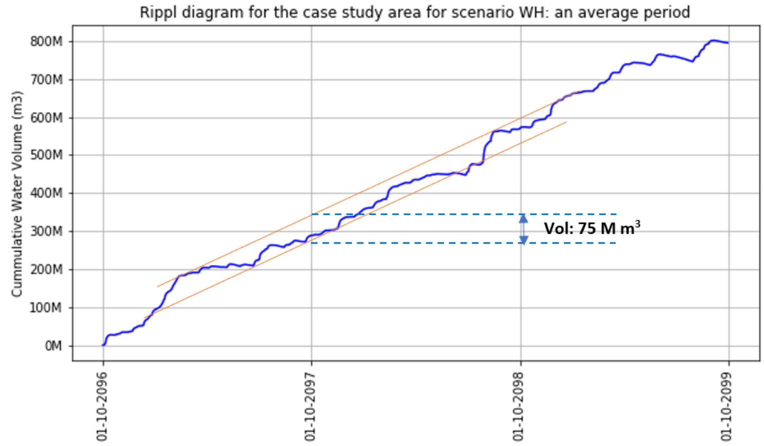


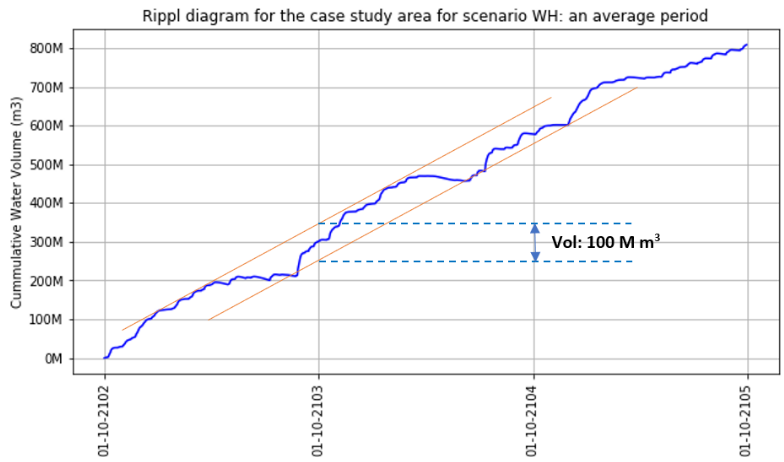


D.5 - Rippl diagrams for the WH scenario



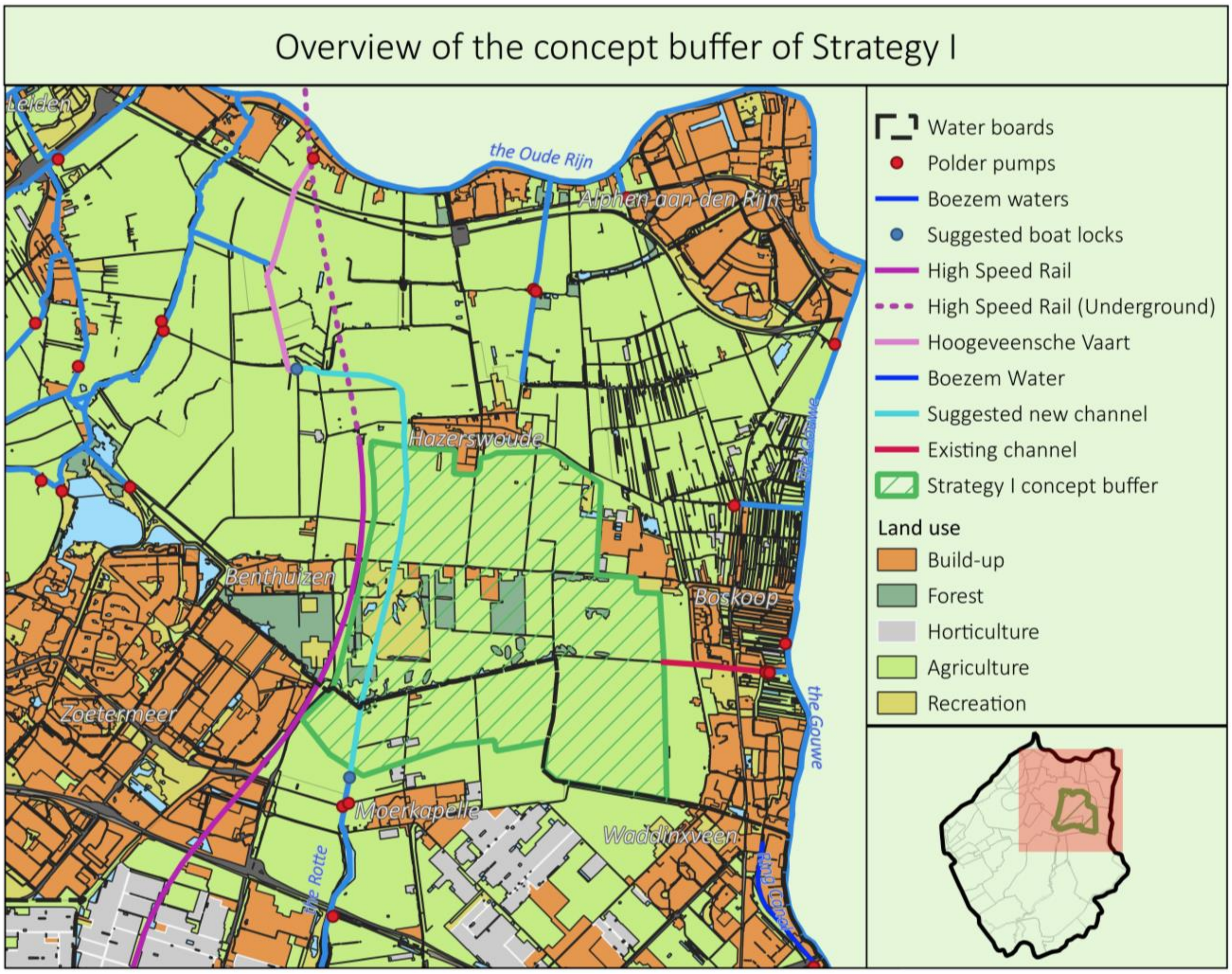


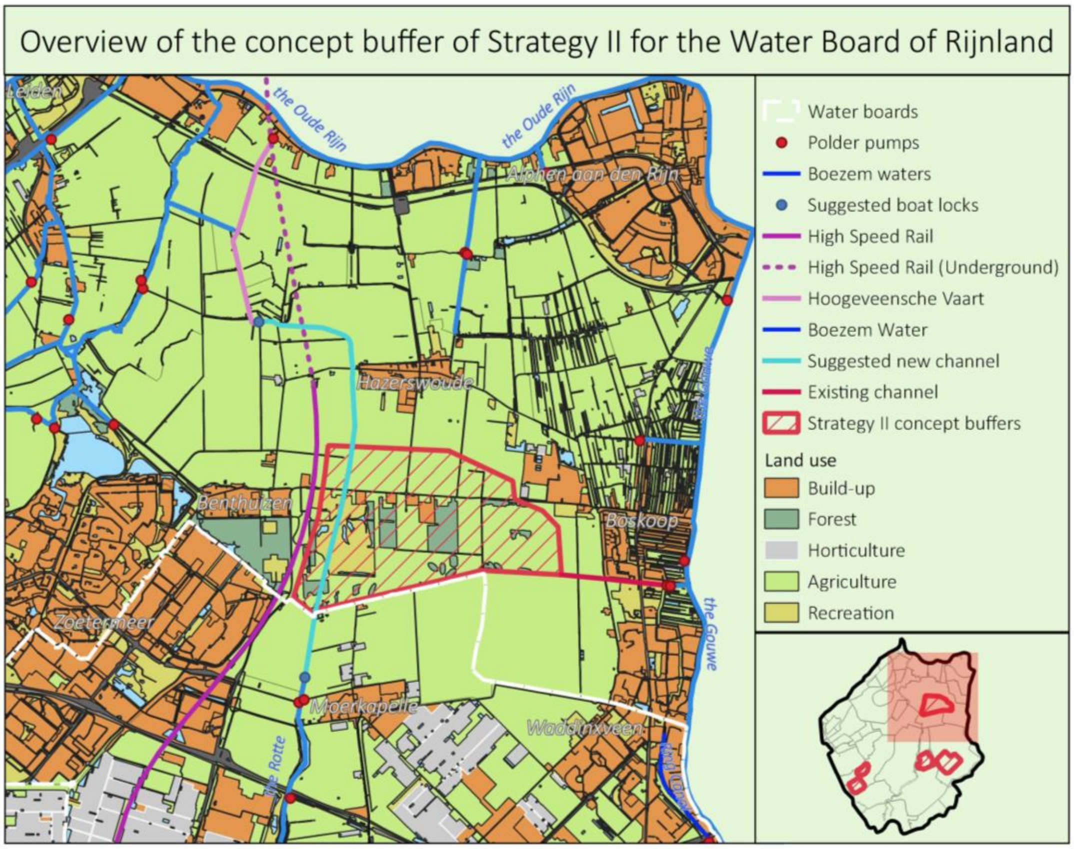




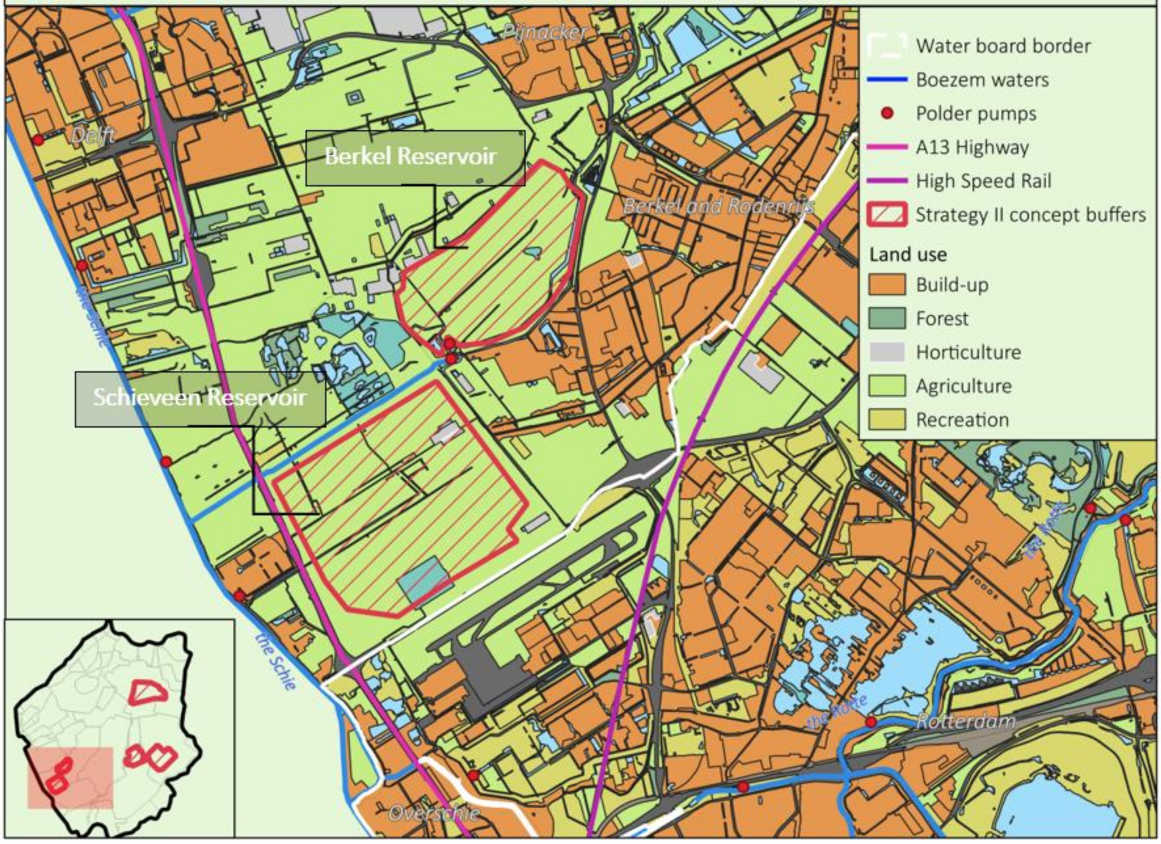
Appendix E – Buffer concept images

E.1 – Maps of concepts of Strategies I and II





Overview of the concept buffers of Strategy II for the Water Board of Delfland



Overview of the concept buffer of Strategy II for the Water Board of Schieland and the Krimpenerwaard