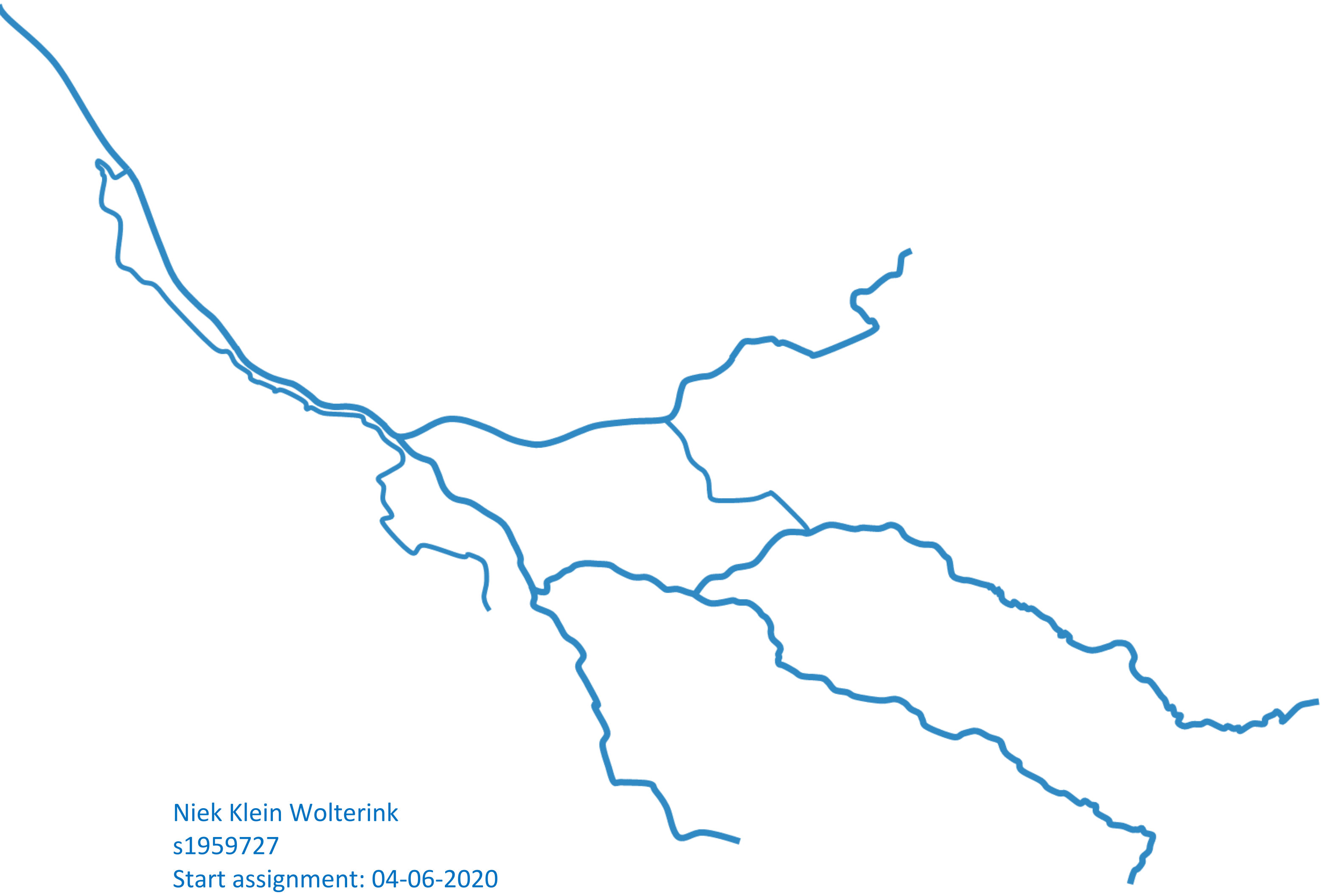
Water Retention in the Catchment of the Groenlose Slinge



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UNIVERSITY OF TWENTE.

Waterschap Rijn en IJssel

Preface

This paper will conclude my Bachelor Civil Engineering at the faculty of Engineering Technology (ET) at the University of Twente. During this study, the effects of climate change on the hydrological cycles of the Netherlands became more prominent. This grasped my interest and led to the decision of going after a bachelor's thesis that would contribute to adapting to the effect of a changing climate on water systems. During my mountain biking trips around my hometown of Aalten it occurred to me that this part of the Achterhoek, with its large aquifers and little rain, does suffer from drier summers.

With this knowledge in mind, I contacted Waterschap Rijn en IJssel, the Water Authority that determines and implements policies in the area that I had in mind. As it turned out, Waterschap Rijn en IJssel (WRIJ) were just as interested in this matter as I was, and a match was found. WRIJ wanted to understand the hydrological system in the upper reaches of the Groenlose Slinge better and liked to know what could be done to overcome the problems with a declining groundwater table, high peak discharges and a (too) small base discharge. This assignment was an exact match with what I was searching for. The cooperation led to this report, the report is directed at policy makers for the project area.

This preface would not be complete without mentioning Covid-19. The pandemic also affected this bachelor's thesis, as it was not possible to work from the office in Doetinchem. Improvisation was needed, but thanks to the efforts from Waterschap Rijn en IJssel and the University, the assignment could continue. Therefore, I would like to express special thanks to my supervisors. First, Rutger Engelbertink, my main supervisor at WRIJ, who provided the expertise on the project area and the surface water system. Second, I want to thank my second supervisor Nila Taminiau at WRIJ, who provided knowledge on groundwater systems. The weekly meeting with Rutger and Nila to discuss the progress on the thesis gave me a lot of insights and understanding of the matter. Third, I want to thank Martijn Booij, my supervisor from the University of Twente, whose knowledge about water systems and reporting contributed significantly to this report. Lastly, I want to thank Gerry Roelofs for his input on the use of models and providing several model results. Enjoy reading the report!

Niek Klein Wolterink, Aalten, 19-6-2020

Summary

This report addresses the hydrological problems in the catchment of the Groenlose Slinge in the East of the Netherlands and gives insights into how these problems can be decreased. The aim of the report is to provide a better understanding of the hydrological, geohydrological, and hydromorphological functioning of the catchment area around the upper reaches of the Groenlose Slinge. Using the knowledge on the hydrological system, the report aims to map possible water-retaining measures that are effective at decreasing the three main problems in the area. The first problem is the declination of groundwater tables in the dry years of 2018 and 2019, which were as much as 10 centimetres lower than the years before. The second problem is the high peak discharge during sudden rain bursts, especially during winter. These peak discharges were much rarer before. The third problem is a (too) small base discharge during the driest time of the year, as several watercourses ran empty in 2018 and 2019, which did barely happen before. This aim will be reached by answering three research questions.

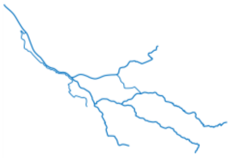
The result of the first research question are six hydrological response units (HRUs), which are areas with homogeneous rainfall-discharging behaviours. These are found by first conducting a system analysis to understand the hydrological functioning of the system in the project area. With this system analysis, hydrological, geohydrological and geomorphological characteristics of the area are discussed. The main characteristics used for the classification of the units are the thickness of the aquifer in the area, which varies from 1 to more than 100 meters below ground level, and the natural course of the waterways, which became apparent in several different aspects of the system analysis. Further distinctions were made based on the slope and the freeboard in the area.

These 6 areas are input for the second research question, in which literature will be used to determine which water-retaining measures can be effective at decreasing the three main problems in the area. Each of the 6 sub-areas within the project area has a different rainfall-discharging behaviour, hence every area does have other promising measures. Based on the characteristics of each area and the knowledge from earlier research on the different measures, the most promising measures per hydrological response unit are determined. The result of the second research question is a table that indicates the most promising measures per hydrological response unit.

The effects of these promising measures per area on groundwater storages, peak (winter) discharges and on the base discharge during the drier times of the year are quantified with the third research question. The effects of the water-retaining measures on the groundwater storages during the drier summer months are determined using earlier research from KnowH2O, et al. (2019), Landbouw op Peil (2014) and Sietzema (2016). The effects on the winter discharges and the base discharge are determined for the dry year 2018 with a conceptual hydrological MATLAB model, with precipitation and evapotranspiration data as input and output the discharge. This model is calibrated with a part of the catchment that overlaps with all 6 hydrological response units, measured discharging data and measured groundwater tables. With this calibrated model, HRU-specific models could be built, by adjusting the parameters such that the model represented the areas specifically, by for example adjusting the maximum soil moisture content and adding the amount of drainage that each HRU has. For every area, the promising measures from research question 2 are modelled, to determine the difference in discharges due to the implementation of measures. For every season during the dry year of 2018, the percentage change in discharges is determined.

The analysis lead to the conclusion that the peak discharges could be decreased and the small base-discharge could be increased in the areas with a shallow aquifer (<10 meter). Winter (peak) discharges could be decreased by 12% in these areas, while the summer (base) discharge at these locations could be increased by as much as 11%. The measures that were most effective in these shallow areas are the transformation from conventional drainage to controlled drainage and improving the soil structure in these areas. The problem of declining groundwater levels in the project area could be alleviated in the areas with a thicker aquifer. In these areas, the groundwater storages during the driest time of the year (31st of July) could be increased by 30 up to 76 mm in the areas with a thick aquifer.

Table of Contents



1. Introduction

In this chapter, the motivation and the current knowledge (and knowledge gap) of the area and of water-retaining measures will be elaborated, after which the problem context is stated. This will be used to introduce the boundaries and the aim of the research. From the aim of the research, the research questions for this study will be stated.

1.1 Research motivation

The discharge of the catchment of the Groenlose Slinge on the East-Dutch Plateau (Oost-Nederlands Plateau) in the area between Winterswijk and Groenlo (see project area in Figure 1) fluctuates over the year. One moment the system discharges a lot of water, while in other periods brooks (almost) run dry (Waterschap Rijn en IJssel, 2020a). Next to that, the area is sensitive to drought (Welink, 2019). Waterschap Rijn en IJssel wants to get a clearer picture of what the underlying factors for the problems in the area are (how the water system functions) and what can be done to decrease these problems by using the characteristics of the area (how the functioning of the system can be utilized (better)).

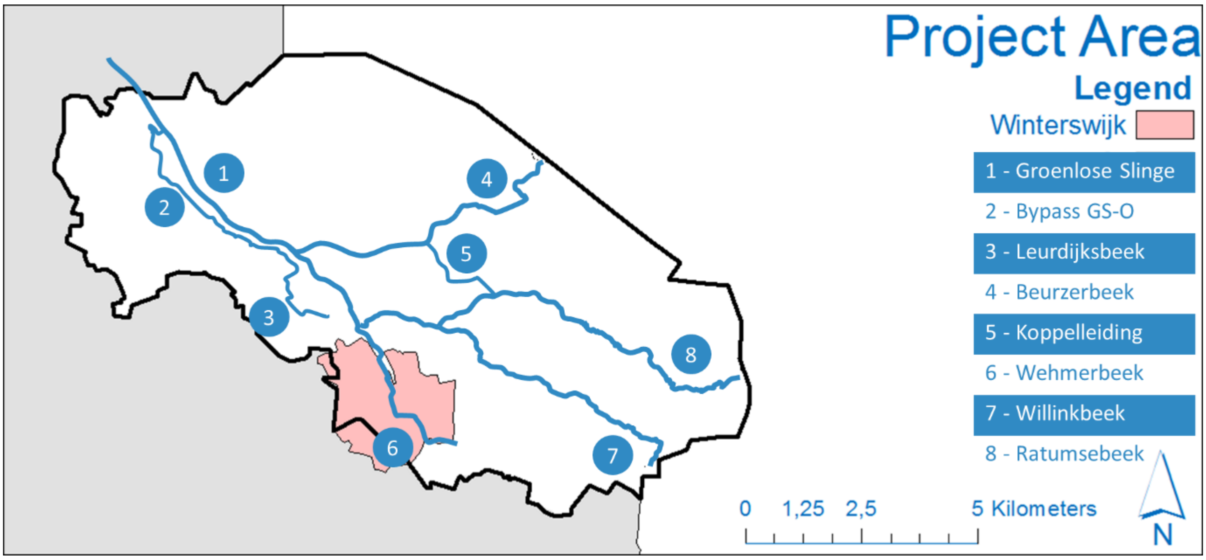


Figure 1 - Project area

The first two problems in the project area have to do with the discharging behaviour of the project area. In research from Lenssen, et al. (2018), it was found that the project area does not meet its ecological KRW-ENV and HEN- and SED-goals. The KRW-ENV (KaderRichtlijn Water) goals aim to safeguard the quality of surface- and groundwater (Rijksinstituut voor Volksgezondheid en Milieu, 2020) and the HEN- and SED-goals aim to protect the ecological values of rivers and brooks (Waterschap Rijn en IJssel, 2020b). One of the ecological goals that is not met is the discharge of the brooks and streams in the project area. There are two problems that are related to this discharging behaviour of the streams connected to the Groenlose Slinge; high peak discharges during sudden rain bursts, especially during winter, these peak discharges have occurred more often over the last couple of years (Waterschap Rijn en IJssel, 2020c), and a (too) small base discharge, as several streams ran empty during the summer of 2018 and 2019, which did not happen before (Waterschap Rijn en IJssel, 2020d). Determining possible solutions for these two problems can help the surface water department of Waterschap Rijn en IJssel at reaching their ecological goals.

The third problem is the declination of groundwater levels over the last couple of years. During the dry years 2018 and 2019, the groundwater tables in the project area were as much as 10 centimetres lower than the average lowest groundwater table during the years before (Vitens, 2020a). With the prospect of a changing climate, more of such dry years will occur (KNMI, 2015) and the groundwater levels will continually decline. From declining groundwater levels, all kinds of problems can arise, for example soil subsidence and drought damages to agriculture and nature (Van Lanen & Peters, 2000).

In order to overcome these problems, measures can be implemented. The solution that Waterschap Rijn en IJssel has in mind, is retaining water in the project area for a longer period. The water retention fits well within the vision on groundwater resources management that Waterschap Rijn en IJssel is going to draw up because of the drought periods in 2018 and 2019. However, it is not yet determined which retaining measures can be implemented at which locations in the project area. Not only would solutions to the three problems help the project area itself, but several climate goals of the Dutch water authorities (in Dutch: Waterschappen) can also partly be achieved, for example the goals of spreading discharge peaks and retaining more water.

The last couple of years, some insights have been gathered into the hydrological system of the project area. Hanhart & Schorn (2019) have conducted a general system analysis (in Dutch: LESA) and thought about a vision on the water distribution in the brooks around Winterswijk in order to get some initial ideas on how to overcome the three problems for the project area. This study is concise and contains expert judgement, further research is needed to deepen the knowledge and get more insights into the matter. Next to that, Witteveen+Bos have conducted research into the possibilities of implementing several measures to overcome some of these problems in a much larger area (Phernambucq, et al., 2019). The total area that is discussed in the paper from Phernambucq, et al. is depicted in Figure 2, which indicates the chance of success of several measures. The project area of this report is outlined with blue. It can be noted that the project area generally has a green colour compared to other parts of the area. Therefore, it is concluded that several water retaining measures will be able to solve drought problems and increase the water availability in the project area.

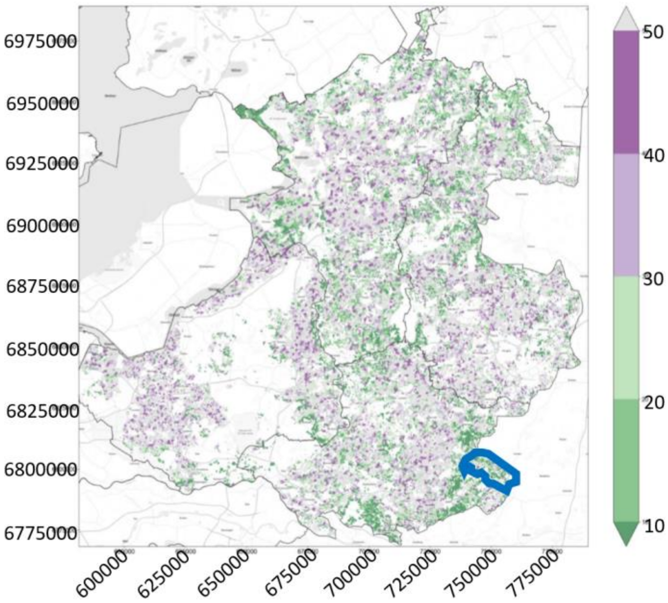


Figure 2 - Chance of success map of measures that decrease drought problems and increase the water availability, most promising is green (0-10th percentile), which indicates the 10% of the area in which the measures are most promising (Phernambucq, et al., 2019), project area indicated with blue

Phernambucq, et al. (2019) conducted a spatial analysis with GIS which indicated where several measures could be effective at combating droughts. This analysis considered the land-use of the area, catchments, brook valleys and the locations of coniferous forests, and based on this data the research concluded in which areas the water-retaining measures could work. Next to that, based on literature, experience and expert judgement, a quantitative indication is given on what the effects would be on the groundwater levels. The researched area covers a large area, which gives a broad view, but does not deliver a lot of specific knowledge for the project area. Based on the papers of Hanhart & Schorn (2019) and Phernambucq, et al. (2019), no policy decisions can be taken. However, earlier research can be used to paint a picture of what kind of water-retaining measures have been implemented in the past and which of these measures turned out to be effective at decreasing the problems of declining groundwater tables, high peak discharges and a (too) small base-discharge.

1.2 State of the Art

In this section, the current knowledge of water retention and water retention in the project area specifically will be discussed, based on earlier research on the water-retaining measures. It will be determined how and why water retention can help to solve the three problems in the project area based on theory. It will be examined whether water retention is capable of decreasing the problems in the area, as well as which measures have already been implemented in the project area.

1.2.1 Water retention

As stated in *1.1 Research motivation*, the solution to the three problems in the area that Waterschap Rijn en IJssel is contemplating, is the retention of water in the project area for a longer period. In the upcoming sub-sections, the literature will be discussed on whether increased water retention can (partly) solve the problems in the area and some co-benefits of water retention that were found in other projects. With retaining surface water for a longer period, no matter which measures are taken, the discharging speed will decrease, and the surface water will have more time to percolate towards the groundwater (Waterschap Vechtstromen, 2019). With this increased amount of percolation of water, the groundwater table will rise (Waterschap Scheldstromen, 2020). Here we arrive at the first of the three main problems in the area, the declining groundwater levels. As the water retention results in an increase of the groundwater table, the groundwater level problem can be tackled with water retention. The increased groundwater levels have several direct positive effects on the project area, as increased groundwater tables due to more retained water can help to overcome drought periods similar to the droughts in 2018 and 2019 (Waterschap Noorderzijlvest, 2020). Crops can take up water for a longer period (Gou, et al., 2020), which results in monetary profits of farmers and more purified water (Querner, et al., 2008). This reduction of nutrients in the groundwater will also contribute to other ecological KRW-goals that are not discussed in this paper.

Price (2011) states that with increased percolation, the base discharge of the river will increase. This base flow is barely directly influenced by rainfall events, rather by the groundwater table. With a larger groundwater storage due to increased percolation, the base discharge can be maintained for a longer period. So, the second main problem can also be overcome with the retention of water, the base discharge can be increased. This is not the only discharging problem that will be tackled with the retention of water, as it will also reduce water nuisance as Hilberts, et al. (2007) state that rainfall discharges slower if it percolates into the ground. In other words, discharging peaks can be reduced by retaining water underground. Other positive side-effects of water retention include pressure relief on the sewage systems (Amsterdam Rainproof, 2020) and nature can turn back into its original state as human dewatering systems will be countered (Jansen, et al., 2011). This section was about water retention in general, the focus will now shift to the steps that have been taken to retain water in the project area.

1.2.2 Water retention in the Groenlose Slinge catchment

Over the years, Waterschap Rijn en IJssel has already taken several measures in the Groenlose Slinge. These measures were all aimed at ecological goals, while barely any measures were taken to improve the groundwater and discharging situations. Due to the attention to the ecological problems, these are now close to getting solved. However, as the discharging has been neglected, this now turns out to be the main problem in the brooks in the area (Waterschap Rijn en IJssel, 2015). Waterschap Rijn en IJssel has implemented few measures to increase retention times downstream of this project area, but barely any measures have been implemented in this project area. The water retention measures downstream of this area include a reintroduction of the meandering of the Groenlose Slinge and the construction of several acres of land that are reserved to store water during discharging peaks (Waterschap Rijn en IJssel, 2015).

The measures in the project area itself that combat the three main problems are the weirs and the Bypass Groenlose Slinge-Oosterholt. Waterschap Rijn en IJssel (2015) states that the main function of these weirs is to keep a steady target level of the water of the Groenlose Slinge and its upper reaches. A co-benefit is that weirs allow for more infiltration of water, such that the groundwater levels do not decline as much (Programma Alumbricus, 2020). The main function of the Bypass Groenlose Slinge-Oosterholt (for location, see Figure 1) is to provide a kind of a buffer zone between the Slinge and the agricultural areas. In order to do that, the water flow must be constant (Kwak & Stortelder, 2020), which leads to a constant discharge over the year. However, after these measures were implemented, the problems that occur in the area are still not resolved. The measures even made ecological aspects worse at several locations (Waterschap Rijn en IJssel, 2015). Therefore, the knowledge about the area and possible water-retaining measures needs to be deepened. Before that can be done, it should be known what the current knowledge about the area is.

In order to solve the three main problems in the area, no measures have been taken outside of the river system itself, only measures in the surface water system of the Groenlose Slinge. However, it is possible that the solution to the groundwater- and the discharging problems is outside of the river system, in the rest of the project area. Water retention does not only happen in the rivers and streams, but also in the areas around these watercourses. However, the current understanding of the hydrological system in the area is not large enough to determine which measures can be effective at battling the three problems in this project area and therefore no water-retaining measures can be implemented. The current knowledge of the study area will be discussed in *2. Study area*, but this knowledge is not enough to implement water-retention measures in this catchment.

1.3 Knowledge gap

Currently, there is too little knowledge about the hydrological, geohydrological, and hydromorphological functioning of the system in and around the upper reaches of the Groenlose Slinge. Next to that, the project area can be described as a geological mosaic implying a lot of variation in the subsurface. Because of this, it is difficult to model the area, and therefore there is no clear indication of which measures can solve several of the problems and where these measures would be most effective.

Now, there is a very rough estimation of which measure could be implemented in which location to retain water, over the whole High Sandgrounds (in Dutch: Hoge Zandgronden) in the Netherlands (Phernambucq, et al., 2019). This is not specific enough to base a policy on in the project area. The knowledge should be extended to an indication of measures and effects on the level of hydrological response units, which are areas within the project area with a homogeneous rainfall-discharging behaviour, before policies can be drawn up and implemented.

1.4 Research aim

The aim of this research is to create a more specific picture of the hydrological, geohydrological, and hydromorphological functioning of the project area and effective measures that counteract the three main problems in the project area; the decline of the groundwater levels, high peak discharges and a (too) small base discharge. This implies that a picture will be made of which measures will be effective in which locations within the project area.

The current knowledge of the area that is described in *2. Study area* is not enough to base policies on, the functioning should be mapped more specific, to the detail of hydrological response units. The clarified picture of the hydrological, geohydrological, and hydromorphological aspects of the project area will help with the goal of creating measures for the project area that will decrease the current problems that are faced. With these results, the research aims to contribute to several policy assignments and climate goals.

1.5 Research questions

In order to reach the aim of the research, the research will be structured with three research questions. First, it will be checked where different measures can potentially be implemented. At some locations, the spatial characteristics will be more suitable for some measures than for others. In order to find suitable locations, the current system should be understood. Hence, the first research question:

Which hydrological response units can be defined based on the hydrological, geohydrological, and hydromorphological aspects of the project area?

In this first question, the characteristics of the whole area will be found. Based on that, several sub-areas within the project area will be defined. The characteristics of one such sub-area will be roughly homogeneous over the whole sub-area, such that one retention-measure can be implemented in this whole sub-area. In order to come to the optimal measure for each sub-area, it should be checked which of the stated measure(s) is promising in which sub-area.

Which measure(s) will contribute to solving (multiple of) the three stated problems in the sub-areas?

This will result in an indication of the most promising measures per sub-area. This will be the input for the next question. At this point we will have a rough idea which measures will work in the sub-areas. The last part of the research constitutes an analysis of the effects of the measures on the local groundwater level and on the discharge at the point where the Bypass enters the Groenlose Slinge. Therefore, the last question is:

What effects do the promising measures in the different sub-areas have on the groundwater levels during summer and on the downstream discharge of the Groenlose Slinge?

The increase in groundwater level will be determined for every hydrological response unit. This will cover the effects of measures against the decline of groundwater levels. The downstream discharge-part focusses on the effects on the other two problems in the area; high peak discharges and a (too) small base discharge. In this way, all problems in the area will be covered. After answering these research questions, a recommendation can be given about which measures at which locations would be most effective at decreasing the main problems in the area.

1.6 Reader's guide

In chapter 2, a description of the project area and the research that has been done before this paper is given. After that, chapter 3 contains the methods that will be used to answer each of the research questions. Chapter 4 shows the results of the analysis, a critical discussion of these results will be given in chapter 5. A conclusion will be drawn in chapter 6, after which chapter 7 will close with several recommendations for further research.

2. Study area

In this chapter, the current knowledge of the project area will be elaborated. The current understanding of the hydrological, geohydrological and hydromorphological functioning of the project area should be known, in order to create a more specific picture of these hydrological aspects in this report. Several characteristics will be discussed, and a table will be given of different maps of the area that existed before this research, with their sources. The knowledge mentioned in this chapter, and the maps that are provided, will be the basis for further research in this paper. From the knowledge in this chapter, a more specific picture of the hydrological, geohydrological and geomorphological understanding of the system will be made.

The scope of the project is focussed on the system of the upper reaches of the rivers and brooks of the Groenlose Slinge on the East-Dutch Plateau. The system of rivers and brooks of the Groenlose Slinge that will be looked at, are the Bypass Groenlose Slinge-Oosterholt, the Leurdijksbeek, the Beurzerbeek, the Koppelleiding, the Wehmerbeek, the Willinkbeek and the Ratumsebeek. The project area is the whole catchment of these streams within the borders of the management area of Waterschap Rijn en IJssel up to the point where the water from the Bypass Groenlose Slinge-Oosterholt enters the Groenlose Slinge, this area is around 85 km^2 and is depicted in Figure 3. In this figure, the elevation differences due to the East-Dutch Plateau are also visible. As this is map of the project area was available before this research, the source is also listed in Table 1, map 1 – AHN3.

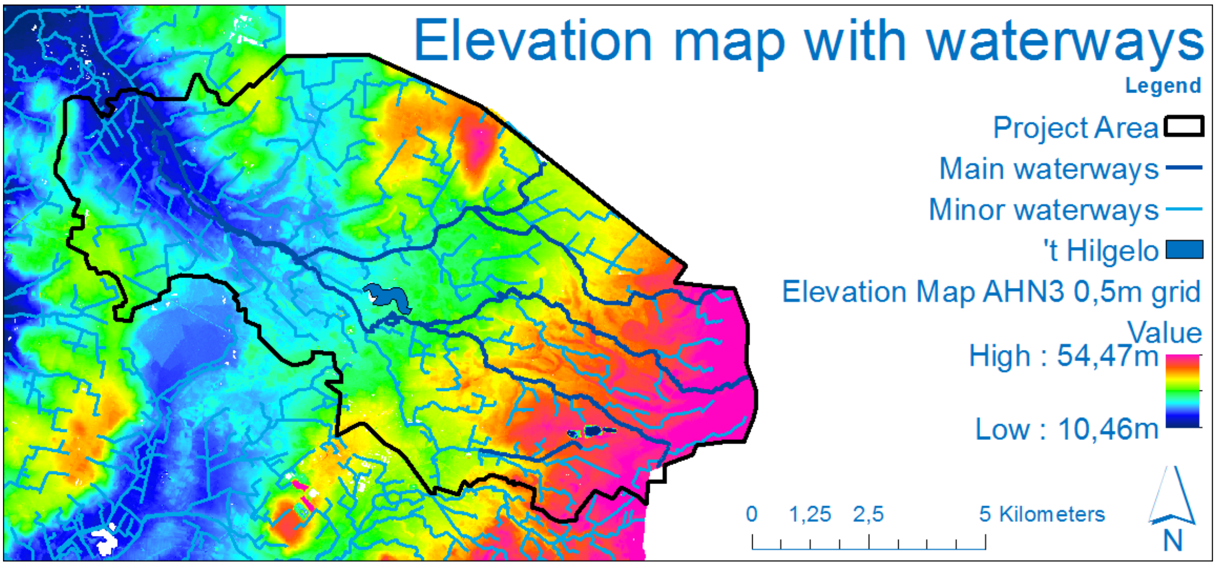


Figure 3 - Elevation map (AHN3, 0.5m grid) with the surface water system

The watercourses in the area follow the height differences through the area, they follow a path from the high parts in the (south-)east of the area towards the lower parts in the north-west. The surface water system fits well within the system that would be expected based on the height differences, most of the watercourses still flow through their natural course, through several valleys. The only unknown of the course of the surface water system is whether the natural course of the Ratumsebeek runs through the Koppelleiding or not. With peak discharges, the Koppelleiding is used to direct peak discharges from the Ratumsebeek to the Beurzerbeek (see Figure 1 for the exact location of these brooks) (Waterschap Rijn en IJssel, 2020a) It is not known whether this Koppelleiding has evolved over the years or whether it has been purposely built a long time ago (Driessen, et al., 2000).

The measures that turn out to be effective in this research, may well be effective in the German area of the catchment. Some findings may also be applicable in the south of the Municipality of Winterswijk, in the system of the Boven Slinge, as the East-Dutch Plateau extends to this catchment and has similar characteristics to the North, East and South of Winterswijk (Ernst, 2017). Due to this plateau, the upper reaches of the Groenlose Slinge cover a relatively large height difference over a short distance. During the Tertiary, rivers deposited large amounts of clay and sediments in a small sea (Eelerwoude, 2020). These layers of sand and clay have been pushed upwards by tectonic movements over the years and resulted in the current height differences in the project area (Ernst, 2017). The deposited clay layer has resulted in an impermeable subsurface clayey layer that sometimes is less than 1 meter below ground level (DINOloket, 2020). At other locations, this clay layer is known to be much deeper, up to an aquifer of more than 20 meters (map 2 in Table 1). This makes for a peculiar aquifer in the area. Douma & Prins (2008) even describe this area as the geological mosaic of the Netherlands, as there are a lot of geological layers in this relatively small area. This is also the reason that quite extensive research has been done into the subsurface layers (maps 3 to 7 in Table 1). This research has however not been extensive enough to understand the water flows.

Research has been done into the locations of deeper permeable soil layers (map 8 in Table 1), but the exact effects of these areas are not yet known. An AMIGO model has been built to model the groundwater flows in the study area. However, with the geological mosaic, it is not known whether the model predicts the water flows accurately. The maps that this AMIGO model has created are also available for this research (map 9 in Table 1).

The last two characteristics that are important to note in this chapter are a quarry in the area and a sewage plant. There is a limestone-quarry in the study area, this large hole in the ground is even visible in the elevation map in Figure 3. Such a quarry has a significant impact on the groundwater (TNO, 2015) and will therefore be excluded from this research. Next to that, the sewage plant RWZI-Winterswijk will be excluded from the analysis. The non-area-specific water discharge from this plant is not natural and nothing can be done about it with the water-retaining measures. In order to obtain the results of the water-retaining measures, the sewage plant will not be taken into consideration in the analysis.

Table 1 - Maps of the study area that were available before this research

Name map	Grid size/resolution	Source + possible remark(s)
1 - AHN3 Elevation map	100x100m	AHN. (2014). *Actueel Hoogtebestand Nederland.*
2 - Location waterways compared to thickness aquifer (loam depth)	N/A	Bosch, v. d. (1994). Geologisch Veldlaboratorium. Arnhem: EcoQuest. **Remark**: Not yet georeferenced in ArcMap
3 - Geomorphological map	N/A	Koomen, A., & Maas, G. (2004). Geomorfologische Kaart Nederland (GKN). Wageningen: Alterra.
4 - Soil map the Netherlands 1-50 000	1:50.000	Onderstal, J. (. (2009). Bodemkaart van Nederland 1:50 000. Wageningen: Alterra.
5 - Soil map 1-10 000 Winterswijk-Oost	1:10.000	Kleijer, H., & Cate, J. (1998). De bodemgesteldheid van het herinrichtingsgebied Winterswijk-Oost: resultaten van een bodemgeografisch onderzoek. Wageningen: DLO-Staring Centrum.
6 - Soil map 1-10 000 Winterswijk-West	1:10.000	Kleijer, H. (2001). De bodemgesteldheid van de gebieden Winterswijk-Plateau en Winterswijk-West. Resultaten van een bodemgeografisch onderzoek. Wageningen: Alterra.
7 - Soil map 1-10 000 Hupsel-Zwolle	1:10.000	Brouwer, F. (1994). De bodemgesteldheid van het ruilverkavelingsgebied Hupsel-Zwolle, Resultaten van een bodemgeografisch onderzoek. Wageningen: DLO-Staring Centrum.
8 - Deposit underneath Quaternary and tectonics	1:25.000	Bosch, v. d., & Brouwer, F. (2009). Bodemkundig-geologische inventarisatie van de gemeente Winterswijk. Wageningen: Alterra.
9 - Groundwater-ladders	250x250m	Vermeulen, P., et al. (2020). iMOD User Manual. Version 5.1. The Netherlands: Deltares.

3. Methods

The research has been structured with research questions. In every paragraph, the methods for one research question will be elaborated.

3.1 Method research question 1

Which hydrological response units can be defined based on the hydrological, geohydrological, and hydromorphological aspects of the project area?

This research question will be answered in two steps, first a system analysis will be done to understand the hydrological aspects of the project area, after which the second step is to determine which aspects will be used to define hydrological response units. STOWA provides clear instructions for system analyses (Besselink, et al., 2017), these will also be used in this research. All hydrological, geohydrological and hydromorphological aspects in the first research question can be evaluated with the framework provided by STOWA. STOWA provides clear steps in conducting system analyses for several purposes, in this research the steps for the purpose "retaining water" will be used, as this is the main purpose of the measures that will be checked. This part of the analysis will contribute to determining spatial relationships between variables in the area. The methods to analyse these aspects are elaborated in STOWA, page 38-167 (Besselink, et al., 2017).

The system analysis will provide insights into the hydrological functioning of the system within the project area. Several hydrological aspects of the area will be dominant in the rainfall-discharge behaviour in the area, these will become clear during the system analysis. These dominant characteristics will be used to determine hydrological response units. These units are areas within the project area that have a distinctly different rainfall-discharge relation than other areas. The dominant characteristics found in the system analysis will be the basis for the classification.

3.2 Method research question 2

Which measure(s) will contribute to solving (multiple of) the three stated problems in the sub-areas?

The results of the first research question will be input for the second research question. For every sub-area, the second research question will cover the initial indication whether the proposed measures in Table 2 would be able to decrease (at least) one of the three main problems in the area. These measures do not all function under the same hydrological and geological conditions, some measures will be more effective in one sub-area than in another. The measures that will be examined in this research follow from an earlier research from Witteveen+Bos, mentioned in *1.1 Research motivation,* into promising measures that will decrease drought problems and increase the available water storage in the High Sandgrounds in the Netherlands (Phernambucq, et al., 2019). The catchment of the Groenlose Slinge is included in this study area of Witteveen+Bos, therefore the measures that seem the most promising in the research from Phernambucq, et al. (2019) for the Groenlose Slinge catchment are determined for the upcoming research and stated in Table 2.

Table 2 - Measures that will be tested in this paper

Measure	Explanation
Removal of drainage	Removing the conventional drainage in the area.
Transforming conventional drainage into controlled drainage	The level of drainage can be varied over the year.
Raising riverbeds	Shallower (-30 cm) waterways and less local discharges can lead to more infiltration.
Raising weirs	Slowing discharge down by raising weir levels by 30 cm to maintain the water in the area for longer.
Improving soil structure	Removing compaction and raising the organic matter content.
Changing land-use	Vegetation that uses less water during the driest times.
Percolation trenches	This measure makes sure that water does not get into the main discharging systems, but infiltrates into the soil.

For every measure in Table 2, it will be determined in which sub-areas it might be applicable. The opportunities for the removal of drainage will be mapped by comparing the location of the hydrological response units with the location of the Green Development Zones that have been defined by the Province of Gelderland. In these areas, agriculture should become more natural, the removal of drainage will be a step towards a more natural agriculture. Areas with a large overlap (>30% of the HRU) with the Development Zones will be suitable for the measure removal of drainage. The second measure is the transformation of the conventional drainage in the area into controlled drainage. This measure will work in areas with a large amount of conventional drainage. Waterschap Rijn en IJssel keeps track of the amount of drainage in its management area, the known drainage locations will be compared to the HRUs that are determined in research question 1. In the sub-areas where more than 30% of the total HRU is drained, this measure will be included in the promising measures.

The next two measures, raising riverbeds and raising weir levels have similar effects. The distinction between these two measures will be made based on the slope of the HRU and the average freeboard. Areas with a steeper slope and a larger freeboard are more suitable for raising riverbeds (more room to increase the riverbed), while the areas with a smaller slope and freeboard have more potential for the raising of weir levels (less weirs are needed per stretch of waterway). For the definition of where these measures will be promising, the slope and freeboard will be determined using the Zonal Statistics tool in ArcMap, which calculates the average grid-value of the slope and freeboard within the polygon of the HRU. Based on those values, it will be determined in which areas the measures will be effective.

The fifth measure is improving the soil structure, which consists of the removal of compaction and the increase of organic matter content. In order to determine the effectiveness of this measure, the compaction in the area will be obtained from earlier research from Sietzema (2016) and the average organic matter content will be calculated per HRU with the Zonal Statistics tool in ArcMap. Areas with less than 30% compacted area will not be suitable for this measure and areas with a larger organic matter content than 6% will also be excluded. The sixth measure, changing the land-use, will only be beneficial in areas in which the groundwater storage can run empty, so for this measure the size of the groundwater storage will be compared. Lastly, the implementation of percolation trenches. This measure does only work if it is not located in an area with a high clay content and there should be surface runoff. Therefore, the clay content will be determined in each HRU using the soil map of the area and the slope map will be used to determine whether surface runoff can take place. Based on these results, the HRUs in which this measure is promising can be determined.

3.3 Method research question 3

What effects do the promising measures in the different sub-areas have on the groundwater levels during summer and on the downstream discharge of the Groenlose Slinge?

The results from the second research question will be the input for the last research question. For every sub-area, the promising measures will be quantified. What we in the end want to know is what effects the measures will have on the groundwater storage in each HRU and what effects the measures will have on the discharges in the Groenlose Slinge over the year. In order to determine the effects of the promising measures on the groundwater levels in the different HRUs, existing literature will be consulted. For the measures raising of weir-levels and the raising of riverbeds, research from KnowH2O, et al. (2019) will be used. The results of KnowH2O, et al. are grid-maps with calculated changes in groundwater tables after implementing several measures, among which the raising of riverbeds and weir-levels. The Zonal Analysis tool on ArcMap will be used to calculate the average change in groundwater tables after implementing these measures. This tool calculates the average value of a grid within a polygon, so the average change in groundwater tables within the HRU-polygon.

The effects of improving the soil structure will be determined for the two factors that will be tackled with this measure, the removal of compaction and the increase of organic matter contents in the soil. In earlier research from Sietzema (2016), the calculation of water retention in compacted and non-compacted areas is described, based on those calculations, the differences in soil retention capacities between compacted and non-compacted soils can be determined. The other factor that will be tackled, is the amount of organic matter in the soil. Rozemeijer, et al. (2012) provides the numbers for determining the increase in the amount of soil moisture that can be stored due to an increase in organic matter; this will also be used for this analysis. The other effects on groundwater levels will be estimated based on the findings in Landbouw op Peil (2014), in which the measures of removing drainage, controlled drainage, changing land-uses and the percolation trenches are discussed. For each of the measures, Landbouw op Peil (2014) indicates the applicability and effects based on the characteristics of areas. Based on the characteristics of the hydrological response units that will be defined, it can be determined what the effects of the measures will be on each area.

The effects on the discharges of the different HRUs will be determined using a conceptual hydrological model (Booij, 2019), depicted in Figure 4, as this model determines the rainfall-discharging behaviour in an area, which can be used as the precipitation data is available for this area. The model is implemented in MATLAB. First, the model will be constructed for a sub-catchment in the area that overlaps with all the HRUs to obtain an average model of the area, which will be calibrated with measured discharges at measurement location Jonkersbrug (Waterschap Rijn en IJssel, 2020c) and groundwater tables. The parameters that are obtained from literature are the infiltration rate (Berhanu, et al., 2012), the capillary rise (Brady & Weil, 2008) and the maximum soil moisture (Rozemeijer, et al., 2012), while the parameters that are calibrated are the percolation rate, the ground- and surface water discharging speed and the initial storages in the different 'buckets' of the model.

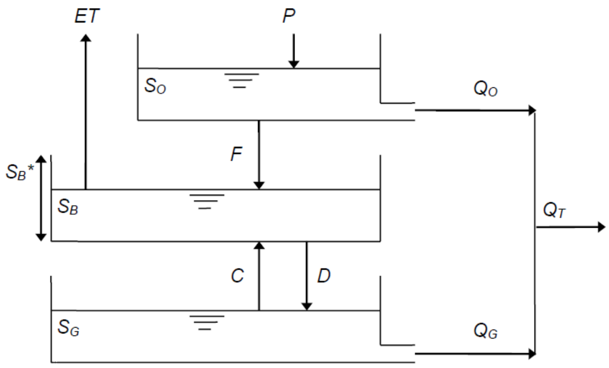


Figure 4 - Conceptual hydrological model (Booij, 2019)

Based on this model, the parameters will be adjusted per sub-area and a drainage level is implemented in the drained parts of the unit to resemble each of the HRUs. The drainage level is a maximum groundwater storage, above this maximum, groundwater will get discharged instantly. After this, the measures are modelled in each HRU, the exact implementation is shown in Table 3.

Table 3 - Implementation measures in conceptual hydrological model

Measure	Implementation in model
Removal of drainage	Removing the drainage level in the drained part of the HRU.
Transforming drainage into controlled drainage	Removing the drainage level in the drained part of the HRU, to obtain the maximum possible effects.
Raising riverbeds	Decreasing the surface water discharging speed.
Raising weir levels	Decreasing the surface water discharging speed.
Improving soil structure	Increasing the infiltration-rate and the maximum soil-moisture content.
Changing land-use	Changing the evapotranspiration factors from corn to grain.
Percolation trenches	Decreasing the surface water discharging speed.

The calculated discharges of the current situation and the situation with measures in place will be compared to determine the effects of the measures on the discharges during the four different seasons of the dry year of 2018, to obtain the effects on the discharges during a dry year, which would occur more often as climate change continues (KNMI, 2015).

4. Results

The results of the research that has been conducted is discussed in this chapter. First, the main results of the system analysis are shown in 4*.1 System analysis*, in which the most prominent characteristics will be used to determine 6 hydrological response units. For every HRU, the most promising measures will be determined in *4.2 Effective measures*. In the last section, *4.3 Effects measures on groundwater storage and discharges*, the effects on groundwater storages and discharges will be quantified. Further elaboration of the results is included in the appendices.

4.1 Defining HRUs

In order to define the hydrological response units, first the system will be discussed and understood. At the end of this section, the hydrological response units will be defined. The geological understanding of the subsurface of the project area will be extended with several maps and an explanation of them. A few maps come from earlier research; the maps that were available before this research are listed in *2. Study area*. But, in order to understand the explanation of the subsurface better, the maps are visualized here. For each map, remarkable features will be discussed and explained, to obtain a better understanding of the system. Next to that, similarities between different maps will be mentioned, to see the interconnectedness of different aspects of the subsurface- and water system.

4.1.1 Subsurface structures

The geomorphological map in Figure 5 shows a variety of features. The higher elevated areas on the Plateau are build up from remnants of earlier higher elevated parts (3L23) and several locations where those remnants have formed plains of sand (2M1). The lower areas generally consist of sand ridges (3L5) and washed out plains of sand that once belonged to these sand ridges (2M9) but have been blown onto the plains by the wind. Next to that, several sand ridges (3K14 & 4K14) are visible, these geomorphological units correspond to the smaller elevated areas in Figure 5.

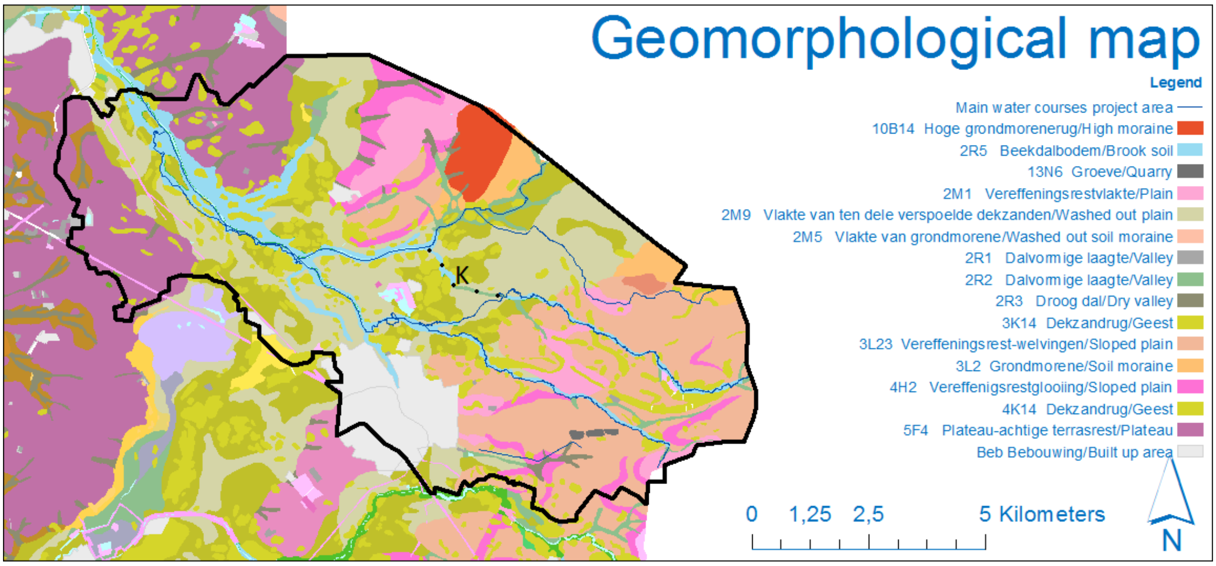


Figure 5 - Geomorphological map (Koomen & Maas, 2004), the black dots at "K" indicate the location of the Koppelleiding

The main feature that pops up in Figure 5 is the location of the natural courses of the waterways. The brook soil (2R5) runs along the Groenlose Slinge via the Willinkbeek and the Ratumsebeek all the way to the border with Germany. Next to that, several smaller deposits of brook soil can be spotted. The course of the Koppelleiding is visible in Figure 5 as brook soil has been found in the subsoil, this indicates that the natural course of the Ratumsebeek runs through the Koppelleiding (indicated with K in Figure 5) and not via the stretch of water between the Ratumsebeek and the Willinkbeek. At the connection between the Ratumsebeek and the Willinkbeek, Figure 5 indicates that no brook soil is found, therefore it is concluded that humans have created this connection to redirect water from the Ratumsebeek, while the Koppelleiding is the natural course of the Ratumsebeek.

The location of the natural course of the waterways also pops up in the soil map of the area. At roughly the locations of the brook soil in Figure 5, the soil map indicates brook earth-soils (in Dutch: beekeerdgrond), which is a remnant of current or past riverbeds. Again, the Koppelleiding is observed to run over soils deposited by waterways. For the exact locations of brook earth-soils, the soil map is included in Appendix A. The soil map indicates several other soil types in the area. The main being the podzol soils that are located around the whole project area, 31% of the total project area even has soil type podzol soil. This type of soil can be found on all elevation levels and geomorphological locations.

It is important to mention that almost all soil types have at least a small content of clay in it, most soil is clayey fine sand or weak clayey fine sand (Onderstal, 2009). Next to that, there is one distinctive soil type in this area that is completely clay. This clay layer is the shallow boulder clay. This soil map-unit indicates the existence of a very shallow (<40 cm beneath ground level) impermeable clay layer. These locations of shallow boulder clay are not the only location in which the aquifer is relatively shallow. Bosch (1994) came up with a map indicating the thickness of the aquifer in the project area. This map, together with the locations of the shallow clay layer, is shown in Figure 6. The aquifer thickness can extend to more than 20 meters beneath ground level. Underneath this topsoil layer, there is generally an impermeable layer.

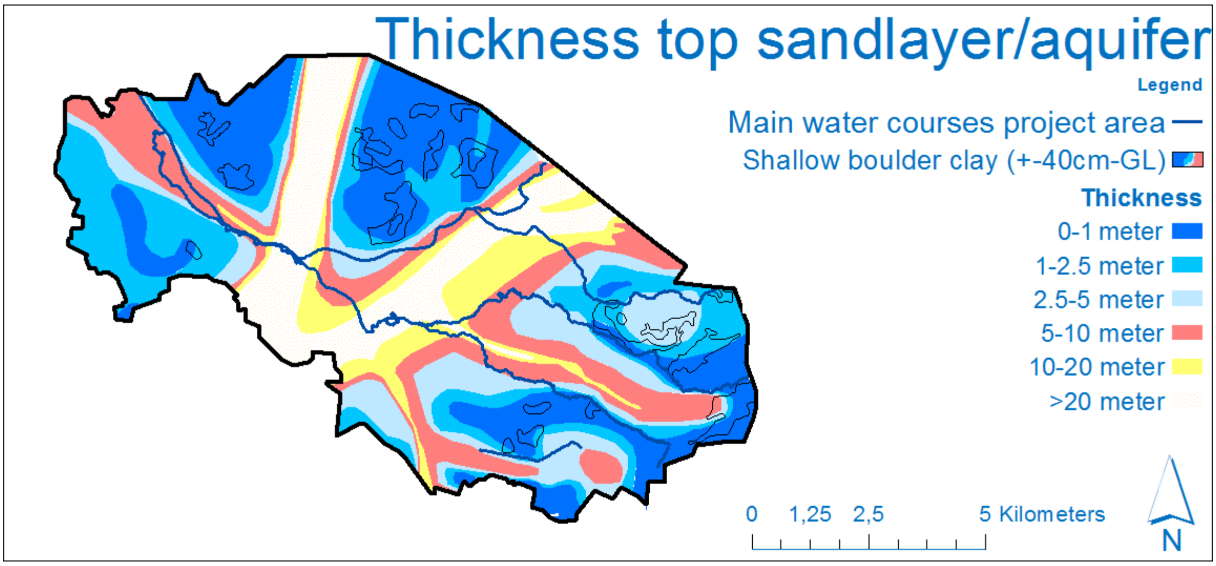


Figure 6 - Thickness aquifer (Bosch, Geologisch Veldlaboratorium, 1994)

The shallow boulder clay largely overlaps with the aquifer thickness of less than 1 meter, therefore the locations of the shallow boulder clay and the area with aquifer thickness <1 meter will be considered as one and the same area. Comparing Figure 6 with the elevation map in Figure 3, it should be noted that the general trend is that the higher the Plateau, the shallower the aquifer will be. Between the shallow areas with a small aquifer in Figure 6, two valleys are visible. The thickness of the aquifer in these areas is larger than 20 meters. The thickness of the aquifer in the area varies over a large range in the project area. The main water courses in the area tend to run along the edges of these channels. These two channels can extend to 100m –NAP and have been eroded by melt water (Bosch & Kleijer, 2003).

Underneath the aquifer, the mosaic of the subsurface continues, during the period from 144 to 2.5 million years ago, different layers of materials have been deposited around the project area (Eelerwoude, 2020). Most of these materials consisted of clays, but some parts are sandy (and therefore more permeable). At the end of this period, the surroundings of Winterswijk rose a little, while the rest of the Netherlands declined, due to that, the deposits came back to the surface under an angle and the various layers are now directly underneath the topsoil, resulting in several locations in which the deeper permeable layers reach the aquifer. These locations are however very small and scattered around the project area, which does not make them suitable for hydrological response units.

4.1.2 Surface water system

The surface water system with the major and minor water courses in the area is shown in Figure 3. This figure is elaborated in Appendix A with the sub-catchments and the smallest units, the trenches. The surface water system in the project area consists of 4 surface water types. The first type is the main watercourse, which are the streams that are wider than 3 meters. Second, the smaller brooks that discharge into these larger streams (1 to 3 meters wide), which are in turn fed by the smallest units (width of 0-1 meter) in the area, the trenches. Next to these three types, there is a lake called ‘t Hilgelo, which is in the middle of the project area, see Figure 3.

‘t Hilgelo seems to be drained by two sub-catchments, so the lake discharges into two sub-catchments. This is due to the non-natural nature of the lake, as it is used to obtain sand for construction projects (Werf, 2013). In summer, due to the stream that drains the lake, the lake can act more like a stream than a lake in which water stagnates (Gerner, 2020). The other feature that does not account for the natural borders of the catchments (which generally tend to run over the highest ridges visible in Figure 3), is the trenches, which are also human made. Both anthropogenic changes led to an area that is now characterized by an extensive draining system of streams, brooks and trenches (Michalska, 2016). Combined with the topographical features of the area, this does deliver desiccation problems in the higher elevated parts of the project area (Vries, 1997).

The upper reaches of the Slinge, the Ratumsebeek, Willinkbeek and Beurzerbeek all spring across the border in Germany. Right when the brooks cross the Dutch border, the transition from the plateau to the lower areas starts. At the higher elevated areas, the brooks turn out to lie deep within their surroundings, as visualized in Figure 7. The map in Figure 7 shows the difference between ground level of every location in the area and the water level of the water course that location discharges into, this is called the freeboard (in Dutch: drooglegging). It can be noted that at the plateau, the difference between ground level and the water level in the watercourses is generally larger than in the lower, downstream areas.

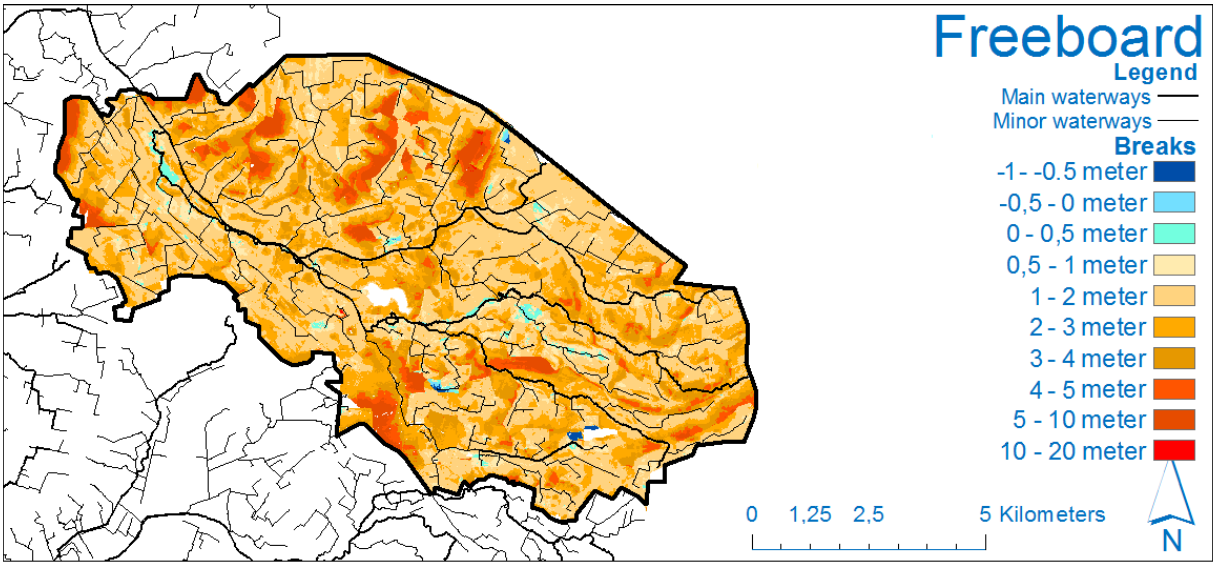


Figure 7 - Freeboard (elevation level location compared to the water level that location discharges into). Calculated with ArcMap tool Sobek Inundatie Analyse

In several areas where the aquifer thickness is smaller than a meter, the freeboard is larger than one meter, this indicates that several watercourses cut into the impermeable boulder clay. In an area with a larger freeboard, drainage can be constructed. Only when the plots of land are high enough above the water table in the discharging water course, water can be directed out of the area, into the discharging streams. Looking at Figure 7, it is therefore no surprise that the drainage in the project area is mainly located at the Plateau. Between 80 to 90% of all agricultural plots of land on the Plateau are known to be drained, compared to 10-20% of the agricultural lands in the areas with a thick aquifer. The exact locations of plots of land that have been drained are shown in Appendix A. The reason that the areas with a thinner aquifer are generally more heavily drained is that the farmers do not want to get puddles of water on their land. As with a thin aquifer the soil does not have enough capacity to store all water in the ground, farmers opted for a system to get water into discharging streams quicker. A negative side effect of this quick discharge of water via drainage is that the pressure on the surface water system becomes larger, as this drainage makes for a quicker discharge once precipitation falls onto the plots of land. This results in a larger peak discharge.

As it is expected that summers will become drier due to climate change (KNMI, 2015), the precipitation and discharges for the dry years of 2018 and 2019 will be discussed, to get an idea of the system in drier times. The precipitation and water levels for several locations are shown in Figure 8. The locations of the measurement points are indicated in Appendix B. There is too little data on the discharges (in m^3/s) in the area to base the analysis on, and no Q-h relation is determined for the different streams in the area, hence only the water levels +NAP are shown. The locations themselves are at different altitudes, hence the different graphs are not at the same levels.

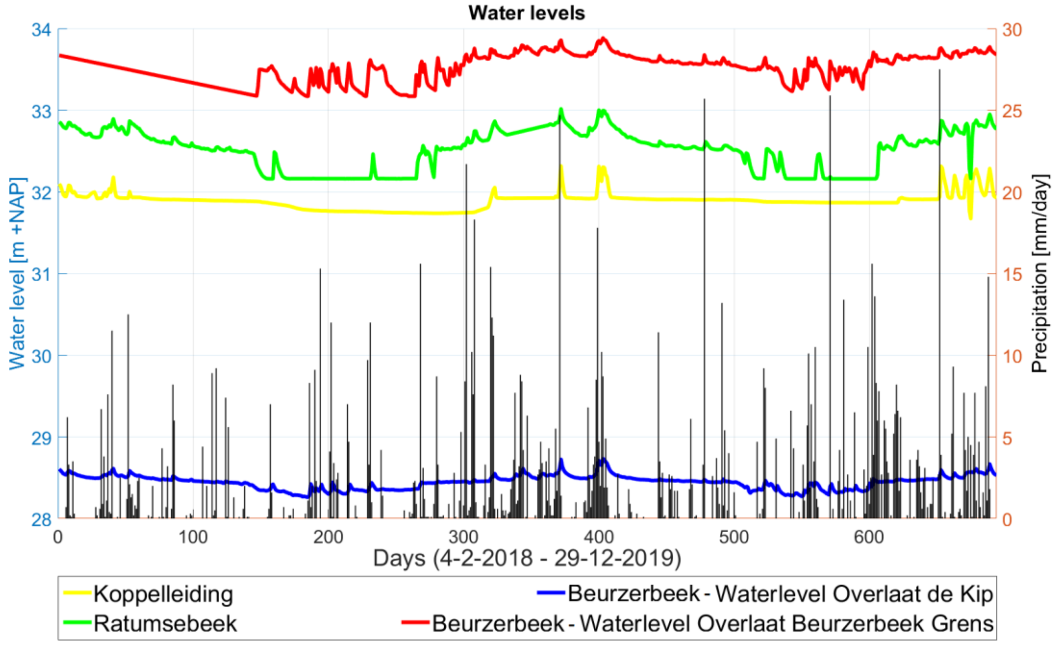


Figure 8 – Water levels of different waterways, compared to precipitation events that are indicated with black bars

There is quite a difference between the general shapes of the water levels. First, the two measurement locations in the Beurzerbeek. At measurement point Beurzerbeek Grens, the system reacts very quickly to precipitation events, even to relatively small events (<5 mm/day). It is expected that this quick response is due to the surface water system across the border, as the Beurzerbeek springs in the industrial area in Vreden, which is paved and drained. The quick response time is less visible in the downstream measurement location in the Beurzerbeek. There can be multiple explanations for this, as the Beurzerbeek gets much wider downstream of the border, and the Beurzerbeek runs alongside a sand channel, which can make for a loss of water (see Appendix D). In these sand channels, there is capacity to store excess amounts of water.

The peaks at Overlaat de Kip tend to happen when the Koppelleiding is activated. This Koppelleiding only gets used if the Ratumsebeek reaches its capacity. This excess amount of water discharges into the Beurzerbeek and ends up at measurement location Overlaat de Kip. The opposite effects occur during dry conditions. During the dry summer of 2018 (which only occurs once every 20 years (KNMI, 2020)), several precipitation events occurred, but almost none of them resulted in an increase in water levels in the Ratumsebeek. Peaks are visible in the Beurzerbeek at 15-7-2018 and 15-9-2018 (around day 200 in Figure 8), but the Ratumsebeek lacks this increase in water levels after the precipitation events. It is expected that this precipitation only percolates into the soil to add to the groundwater table. Around the Ratumsebeek, there is enough permeable soil for the water to infiltrate into, as it is on the edge of a sand channel. Therefore, it is concluded that the Ratumsebeek loses water to the subsurface during very dry times.

4.1.3 Groundwater system

The loss of water in the surface water system results in an increase in groundwater levels, which will now be discussed. Just as the surface water system, the general direction of the groundwater is from southeast to northwest in the project area (Waterschap Rijn en IJssel, 2020). Only in the deep sand channels, the flows follow the direction of the sand channel (Willemsen, 1998).

An AMIGO-model (Vermeulen, et al., 2020) was used to determine the groundwater variation in the deep sand channels and in the shallow part of the aquifer. It turns out that the groundwater table in the deep channel does fluctuate much more than the table in the shallow aquifer. The exact fluctuation is visualized in Appendix C. The conclusion is that the fluctuation in the deep valley reaches almost 2 meters, while the shallower aquifer fluctuates over a much smaller range, around 60 centimetres. As mentioned earlier, there is a lot of drainage in the shallow areas. The variation that has been determined with AMIGO is calculated in areas where it is known that there is no drainage. This resulted in an indication of the natural groundwater variation. During the wet time in 2010 the groundwater level rose almost 2 meters in the deep valleys, while the groundwater level in the shallow area varied less than 60 centimetres. The groundwater level in the shallow area also lowers at a more constant rate, so water discharges slower than in the deep valley.

The other groundwater levels in Appendix C indicate locations in which it is expected that upward seepage (De Kip) and downward seepage (Jonkersbrug) takes place in dry times. A check has been conducted as to know whether downward seepage takes place around Jonkersbrug. The analysis can be found in Appendix D, the conclusion is that during dry times, the Groenlose Slinge loses water to the sand channels below. This further backs up the claims of Michalska (2016), who states that during summer months, the upper reaches of the Groenlose Slinge have a higher discharge than the downstream stretch of the stream, which suggested that the Groenlose Slinge is a losing stream around the buried glacial channel. This also influences the groundwater tables, as is also indicated in Appendix C, the area with upward seepage has a much more constant groundwater table.

4.1.4 Land-use and nutrients

The last aspect that will be discussed in the system analysis, is the land-use in the project area. The main use of land is agriculture, which has several effects on the hydrological system in the area. Earlier land-uses can explain several characteristics that became apparent in the elevation analysis and the soil analysis, as several elevated areas have risen due to people enriching the soils with nutrient-rich soils over the years, which resulted in higher plots of land, which are still visible in the elevation maps and soil maps, and are called enk earth-soils (in Dutch: enkeerdgronden). Second, agriculture involves the use of heavy machinery. Working with heavy machinery on plots of land can lead to the compaction of soils. A compacted soil means that the soil is denser than its natural state, which leads to a smaller capacity of storing water in the unsaturated zone. On average, 30 to 45% of the project area has been compacted, with the shallow boulder clay areas having a smaller amount of compaction (15-30%) and the podzol soils having a larger amount of compaction, up to 53% of the podzol soil has been compacted (Sietzema, 2016).

The land-use also affects organic matter contents of the soil. While the aforementioned enk earth-soils have been enriched in the past with organic-rich soil, this has not led to a structural change, as these earth-soils currently have a lower than average organic matter content compared to the rest of the project area (2.5-5%), while the general trend is around 5 to 8% organic matter content. Next to that, the organic matter content of the geomorphological brook soil of Figure 5 turns out to be only 2.5 to 5% as well.

4.1.5 Hydrological Response Units

One feature that stood out across multiple aspects of the system analysis, is the natural course of the surface water flows in the area. The natural course of the brooks comes back in the elevation map, in the geomorphological map, the soil map and even in the organic matter content of the soils. Combining this knowledge, the decision is made that the area that is denoted as brook soil (2R5) in the geomorphological map in Figure 5 will be the first hydrological response unit; Brook Valley, indicated in green in Figure 9. This also means that the Koppelleiding will be considered as part of the river system and not the connection between the Ratumsebeek and the Willinkbeek.

Another main characteristic that became apparent was the varying depth of the aquifer in the area. The thickness of the aquifer is of considerable importance for the hydrological functioning of the system in the area, it had significant impact on the groundwater levels and the potential to retain water in the soil. Therefore, the next HRUs will be defined with the thickness of the aquifer in mind. A clear distinct area is the thinnest parts of the aquifer, with a depth of less than 1 meter. The areas with such small space for groundwater, such large freeboard and such large amounts of drainage will be considered as the second hydrological response unit; Shallow, indicated in dark blue in Figure 9. This area consists of the aquifer thickness of 0-1 meter in Figure 6 and the shallow boulder clay areas from the soil maps of the area (Bodemkaart 1-50 000 and 1-10 000 Winterswijk-Oost). After this 1 meter, the depth of the aquifer increases rapidly, hence the cut at a thickness of 1 meter.

The next distinction based on aquifer-thickness is at a thickness of 1 to 10 meters of aquifer, the intermediate step between very shallow and very deep aquifers. This area is generally homogeneous in dealing with water, except for the built-up area of Winterswijk, which behaves entirely different and will therefore be excluded from this HRU. The soil map indicates that the area does largely consist of podzol soils. Next to that, the slope of the area is generally quite low, only at the locations where this area meets the Shallow HRU, the slope tends to get steeper. However, as this steep area is that small, the decision is made to not exclude the steep parts of this HRU. Therefore, the third HRU will be: Podzol, which consists of the complete area that has an aquifer thickness between 1 and 10 meters, excluding the areas with geomorphological value brook soil and built-up area. This HRU is indicated in Figure 9 in rose. The built-up area simply has too little data to conclude that this is like the rest of the Podzol HRU.

For the podzol HRU, the decision was made to combine the non-steep and the steeper parts. For the next two units, a distinction has been made based on the slope of the area. After the Podzol HRU is defined, only the aquifer thickness of more than 10 meters remains. This area is generally quite homogeneous except for two factors. The area can be separated in two parts by comparing the soil types, freeboard and the relief in the area. The first hydrological response unit will be the HRU with a relatively steep slope due to the sand ridges, a large freeboard and does consist of podzol soils and enk earth-soils; Geest (in Dutch: Dekzandcomplex), indicated in Figure 9 in red.

The other HRU with an aquifer-thickness of more than 10 meters, will be Outwash Plain. This area is characterized by relatively flat surface compared to Geest. This area consists of the remnants of former geests that have been transported by aeolian transport. Another main difference with the Geest is that instead of enk earth-soils, this area has more brook earth-soils and podzol soils. The area is really characterized by sediments that have been washed out from other locations and formed a flat plain, hence the name Outwash Plain. The flat plain also resulted in a smaller average freeboard in the area. The area is depicted in yellow in Figure 9.

The last unit is the Human HRU. Humans have altered the area by constructing the built-up area of Winterswijk and several other structures in the project area. Combining these structures into one HRU makes for an almost complete covering of the project area, which was the target of this research question. Therefore, the last HRU is Human, which is indicated in light blue in Figure 9.

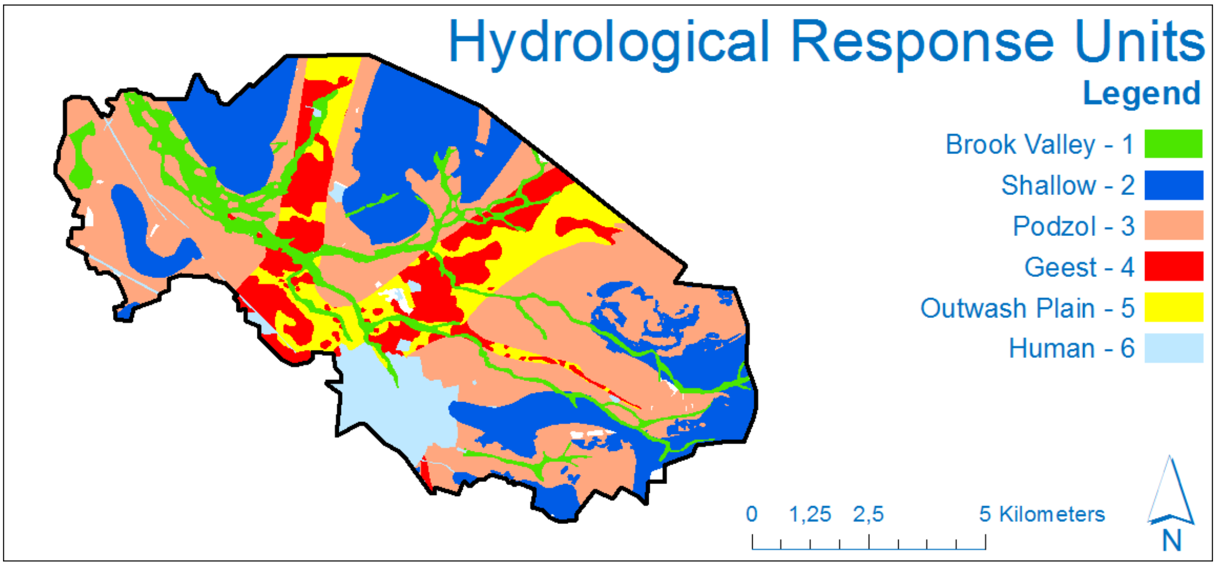


Figure 9 - Hydrological Response Units

Note that with this classification, the quarry in the area is not included, as mentioned in *2. Study area*. Several characterizing aspects of the HRUs are listed in Table 4. Other characteristics such as the average organic matter content and the groundwater ladders are listed in Appendix E.

Table 4 - Defining characteristics HRUs (1) Main waterways not included)

Hydrological Response Unit	Surface area [ha]	Percentage area drained [%]	Depth aquifer [m]	Total length trenches [m]	Average slope [%] (100x100m grid)	Average freeboard [m]
Shallow	2,258	58	d ≤ 1	211,324	0.40	2.5
Brook Valley	743	30	d > 1	69,650[1)]	0.23	1.6
Podzol	3,393	37	1 < d ≤ 10	267,029	0.30	2.1
Geest	841	18	d > 10	45,367	0.20	2.1
Outwash Plain	765	30	d > 10	51,217	0.17	1.6
Human	577	-	d > 1	21,822	0.22	2.9

4.2 Effective measures

4.2.1 Removal of drainage

In order to obtain a water system that is as natural as possible, every piece of drainage-pipe would be removed. However, this does often conflict with a lot of other goals with respect to, for example, agriculture and water safety. Areas in which this measure can be implemented can be limited. This measure will only work in areas where there is currently a significant amount of drainage. The amount of drainage per hydrological response unit is given in Table 4.

In order to see the effects of removing the drainage on discharges, only the HRUs with a drained area that is more than 25% of the total area qualify for this measure. However, not in every one of these four units this measure can be implemented. There is only one response unit in which provincial legislation would allow for the removal of drainage, which is the Brook Valley. The Province of Gelderland has defined Green Development Zones (in Dutch: Groene Ontwikkelingszones) which are areas with another zoning plan than nature, but serve the purpose of connecting nature reserves (GNN) (Provincie Gelderland, 2018). In the upcoming years, steps must be taken to accomplish the nature-goals for these areas. The Green Development Zones, the Nature Reserves and the outline of the Brook Valley are depicted in Figure 10 and there is an obvious overlap between the HRU and the GDZs and GNN, 66% of the total Brook Valley is located in these natural zones, while the other HRUs have less than 30% overlap. Therefore, Brook Valley will be suitable for the removal of drainage.

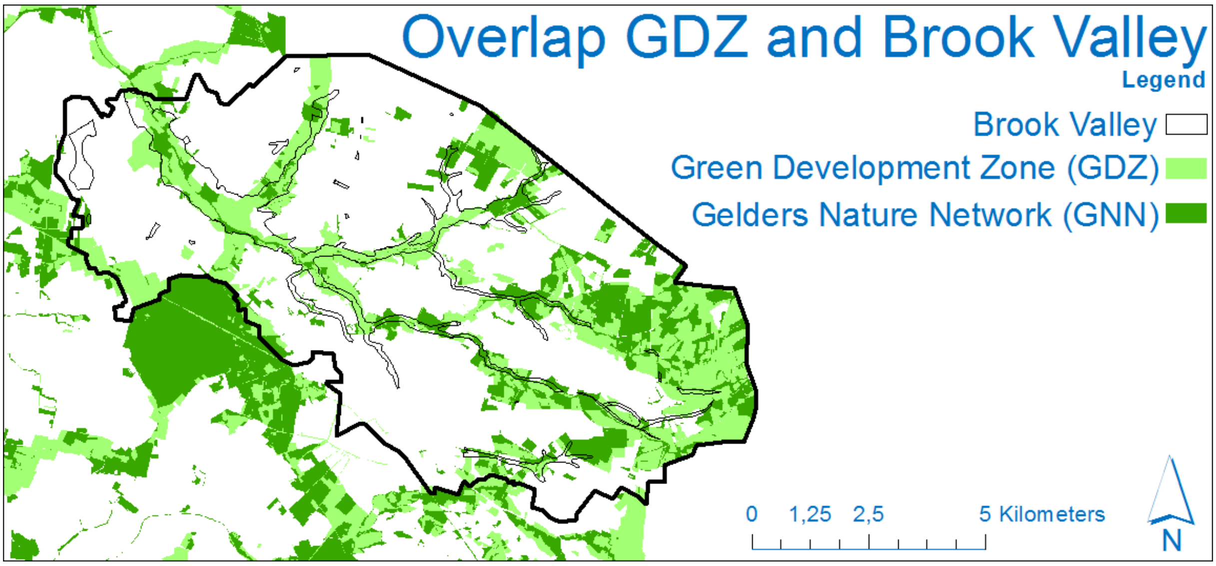


Figure 10 - Overlap Green Development Zones with Brook Valley HRU

4.2.2 Transforming conventional drainage into controlled drainage

There are still three response units in which with more than 30% of drained area within the HRU in Table 4. The risk of water nuisance is simply too large in these three HRUs to remove the drainage completely. In order to find a middle ground between conventional drainage and the removal of drainage, controlled drainage is created. The remaining three response units will be suitable for this measure, so this measure will be calculated for the Shallow HRU, the Podzol HRU and the Outwash Plain HRU. Deltaprogramma Agrarisch Waterbeheer (2020) states that there is little to control in thin aquifers and controlled drainage can barely work in areas where there is no water supply (Schaap & Essen, 2013), but this is focussed at implementing controlled drainage at plots of land that are not yet drained. Controlled drainage will at least improve the situation of conventional drainage.

4.2.3 Raising weir levels

The construction of weirs and raising riverbeds (the next measure) are comparable, as both measures tend to slow down discharges. However, the effects of weirs are on a more local scale, while increasing riverbeds affects a larger region. As the implementation of weirs has mainly local effects, this measure works best in flatter areas, to spread the effects a little more. Another point worth mentioning is that areas with a larger freeboard allow for an increase in riverbeds, while a smaller freeboard has a smaller potential to raise the beds. So, in order to make a distinction between the two measures, the slope of the area and the freeboard will be used. With a larger slope, more weirs must be used over the same length of brook. In order to obtain significant results and determine the sensitivity of the area to this measure, the decision is made to raise the weir-levels by 30 centimetres.

For an increase in weir-levels by 30 cm in an area with a slope of 0.1%, every 300 meters a weir would be needed. For every increase by 0.1%, the distance between weirs would decrease by a half (300 m, 150m, 75m, etc.). This results in more weirs per stretch of watercourse. Hence, the decision is made to raise weirs in the flatter areas, while the steeper areas will provide space for the raising of riverbeds. Based on the slope-map in Appendix A, this decision will be made. This is a grid that is based on Hoogtekaart AHN 100m grid, which gives a general indication of the slope in an area. The average slope in each HRU is given in Table 5.

Table 5 - Average slope and freeboard in each HRU, determined with Zonal Statistics tool in ArcMap

Hydrological Response Unit	Average slope area [%]	Average freeboard [m]
Shallow	0.40	2.5
Brook Valley	0.23	1.6
Podzol	0.30	2.1
Geest	0.20	2.1
Outwash Plain	0.17	1.6
Human	0.22	2.9

Combining the results of Table 5, the Brook Valley- and Outwash Plain-HRU are most suitable for the locations for the increase of weir-levels. In these HRUs, the slopes are relatively flat (<0.25%). In Brook Valley, the number of meters per weir would be 130 and, in the Outwash Plain, 1 weir would be needed per 179 meters. This is much less than the one weir per 74 meters in the Shallow HRU (0.403%). Next to that, there is less space for increasing the bed of the brooks (freeboard ≈ 1.6 m).

4.2.4 Raising riverbeds

As discussed in the previous measure, the raising of the riverbeds would be more suitable for sloped areas with a relatively large freeboard. Two response units stand out in Table 5, with relatively high freeboards. These are the Shallow and the Human HRU. However, these units will not be suitable for the raising of riverbeds. In the Human area, the water courses flow through pipes and over paved surfaces, it would not be effective to raise the bed by adding sand on top of these impermeable riverbeds, hence this measure would not be effective in the Human HRU. In the Shallow HRU, there is another problem, there is simply too little medium in which the water can infiltrate, as the waterways already cut into the boulder clay. In the areas where the effects will be determined, the riverbeds will be raised by 30 centimetres, to determine the sensitivity of the area to this measure.

The first hydrological response unit in which this measure might be effective, is the Podzol HRU. This area has a relatively steep average slope and the freeboard in the area is larger than 2 meters. Next to that, there is a medium in which water can infiltrate. The second HRU that could benefit from the raising of the riverbeds is Geest, which has a lot of small relief changes as well as an average freeboard of more than 2 meters. In both HRUs there is room for increasing the riverbeds and in each of the areas, there are enough watercourses to have an impact on the ground- and surface-water. The last unit in which this measure can work, is again the Brook Valley. Although the measure of increasing weir-levels will also be quantified, this measure is that interesting for this HRU that the raising of riverbeds is also included in this unit. This is due to the mentioned Green Development Zones. In order to become more natural, the raising of riverbeds is a better option than raising weir levels.

4.2.5 Improving soil structure

For a decision on which HRU might benefit from an improved soil structure, the data on compaction and organic matter content will be used. The project area has a relatively compacted topsoil layer, with an average compacted area of 30-45% of the project area, only in the Shallow unit, the compacted area is smaller than 30%. Sietzema (2016) concluded that the compaction of the podzol-areas is even larger, 53% of the podzol areas in the project area is compacted. In this project area, the organic matter content of the soil is examined, based on that, it will be determined which HRUs are in need of an increase in organic matter content. The required data is shown in Table 6.

Table 6 - Average organic matter content in each HRU (= No data)*

Hydrological Response Unit	Average organic matter content (%)
Shallow	5.1
Brook Valley	4.2
Podzol	5.2
Geest	5.1
Outwash Plain	6.7
Human	-*

Of the remaining response units, the Podzol unit needs a refurbished soil structure, as the percentage of compacted soil is high, and the organic matter content can be improved. From Table 6, it can be noted that Brook Valley has a small organic matter content and it can use an improved soil structure, hence this measure will also be incorporated in the Brook Valley unit. Of the remaining HRUs the Geest and Shallow areas can also use an increased organic matter content and decreased soil compaction. The Outwash Plain and Human HRU do not get an upgrade, as these units have either a good soil structure already or there is too little data. The technical implementation of this measure on how much the organic matter content will be increased is indicated in Appendix F.

4.2.6 Changing land-use

Changing from crops that thrive in dry times (corn) to crops that are used to a wetter time of year (grain) works best in areas where the amount of water in the summer becomes small. This is mainly the case in the Shallow HRU, as this area has little groundwater storage. In order to save some storage during summer, this measure could be implemented.

4.2.7 Percolation trenches

This measure does work best if it is not located near discharging streams (Phernambucq, et al., 2019). With discharging streams close, the percolation trenches would get drained by the streams. In order to make sure that water ends up in the trenches, there should be surface runoff. The last criterion is that the soil around the trench may not have a high clay content, as this can result in the clogging of said trench (Water Environment Federation, 1998). The HRUs with little clay content and have enough surface runoff are the Geest HRU and Human HRU, therefore the measure will be calculated for these two areas.

4.2.8 Promising measures per HRU

The results of section 4.2.1 to 4.2.7 are given in Table 7.

Table 7 - Promising measures in each HRU indicated in blue

	Shallow	Brook Valley	Podzol	Geest	Outwash Plain	Human
Removal of drainage		■				
Controlled drainage	■		■		■	
Improving soil structure	■	■	■	■		
Changing land-use	■					
Raising riverbeds		■	■	■		
Raising weir levels		■			■	
Percolation trenches				■		■

4.3 Effects measures on groundwater storage and discharges

The effects of measures on each hydrological response unit have been calculated and are listed in Table 8. The effects of the water-retaining measures on the groundwater storages during summer have been determined with the literature listed in *3.3 Method research question 3*. This determination of effects is elaborated in Appendix G. Next, the effects of measures on the discharges over the year is determined using the conceptual-hydrological MATLAB model that is shown in *3.3 Method research question 3*. First, a calibration catchment that runs through all 6 HRUs is chosen, to calibrate the model on an area that has the average rainfall-discharging behaviour of the area. The model is calibrated on the measured discharging data at Jonkersbrug and the inputs are rainfall data in the project area and evaporation data. The calibrated base-model is adjusted to match each of the 6 HRUs, by adjusting parameters based on literature. In Appendix H, the method will be elaborated more technically and the bandwidth of the effects of the measures on the discharges during different seasons are shown.

For every HRU, the increase in summer (around the 31st of July) groundwater storages is indicated in the first brackets in Table 8. The 31st of July is usually the day of the year at which the most sprinkling water is needed, as the groundwater tables are the lowest at that day of the year (KnowH2O, et al., 2019). At this driest time of year, the effects of the measures would be most needed, hence the effects on the lowest groundwater tables of the year are given. The second brackets provide information on the seasonal effects on the discharges. Between the second set of brackets, the in/decrease of discharges have been expressed in percentages of the current discharge during that season. The order of effects on the seasons is: [winter 2017-2018, spring 2018, summer 2018, autumn 2018], the exact dates of each season is based on the meteorological seasons, which are indicated in Appendix H. A positive percentage means that the discharge will increase with the stated percentage compared to the current discharges and a minus indicates a decrease in discharges with the indicated percentage.

The third to last row of Table 8 indicates which measures are deemed to be effective at battling the three main problems in the project area. “Effective” means significantly improving one of the three problems, while not deteriorating the other problems with more than 1 or 2%. The row below shows the effects that such a combination has on the groundwater tables and discharges. Table 8 is concluded with the effects on the groundwater tables and discharges in the total project area. The bandwidth of the results of the combinations of measures in each HRU is given in Appendix I. The calculations of the effects on the complete project area are shown in Appendix J.

Table 8 - Effects of different measures on the different HRUs and on the total project area (the first brackets in each cell indicate the effects of measures on the groundwater storage in summer and the second brackets indicate the effects of measures on the [winter, spring, summer, autumn]-discharges of the Groenlose Slinge, in percentage change with respect to the current discharges)

	Shallow	**Brook Valley**	**Podzol**	**Geest**	**Outwash Plain**	**Human**
Removal of drainage		[+50 mm] [-3, 0, +2, +1%]				
Controlled drainage	[+10 mm] [-8, 0, +10, +10%]		[+15 mm] [-4, +1, +3, +2%]		[+20 mm] [-2, 0, +2, +1%]	
Improving soil structure	[+7.8 mm] [-4, +11, +2, -4%]	[+2.6 mm] [-2, +3, 0, -1%]	[+7.8 mm] [-4, +8, 0, -3%]	[+3.9 mm] [-2, +3, 0, -2%]		
Changing land-use	[+10 mm] [+2, -2, -4, +13%]					
Raising riverbeds		[+3 mm] [0, +2, +1, 0%]	[+4 mm] [0, +2, +1, 0%]	[+3.5 mm] [0, +2, +1, 0%]		
Raising weir levels		[+26 mm] [+1, +3, +2, 0%]			[+32 mm] [0, +6, +4, -1%]	
Percolation trenches				[+20 mm] [+1, +5, +3, -1%]		[+15 mm] [+2, +8, +5, -1%]
Effective measures	Contr. drainage & Soil structure	Raising weirs	Contr. drainage & Soil structure	Percolation trenches	Contr. drainage & Raising weirs	Percolation trenches
Effects combination effective measures	[+17.8 mm] [-12, +7, +11, +6%]	[+76 mm] [-2, +1, +2, 0%]	[+22.8 mm] [-7, +7, +3, -1%]	[+20 mm] [+1, +5, +3, -1%]	[+52 mm] [-2, +6, +7, +0%]	[+15 mm] [+2, +8, +5, -1%]
Effective measures total project area	[Minimum increase groundwater storage: +15 mm, maximum increase groundwater storage: +76 mm] [Winter: -6%, Spring: +6%, Summer: +5%, Autumn: +1%]					

The expected increase in groundwater storage levels in the Shallow HRU does not differ a lot between the measures, ranging from an increase in storage from 7.8 to 10 mm. The most suitable measure for this area becomes clear when looking at the discharges. The transformation of conventional drainage into controlled drainage does increase the discharge during the dry summer months and makes for a significant decrease in winter discharges. Next to that, a combination with improving the soil structure can further increase the discharges in spring, while it also contributes to decreasing winter peaks. The change of land-use only worsened the situation, this measure will not contribute to decreasing discharge peaks nor will it contribute to increasing the base discharge.

The removal of drainage does deliver significant results in the Brook Valley HRU, in which it can increase groundwater storages during summer by 50 mm. Especially combining the removal of drainage with raising weir levels, the storage can be increased by even 26 mm more. In Brook Valley, no measures would contribute significantly to the discharging problems, according to the results. The results of the Podzol HRU are more straight forward, as the numbers indicate that overall, the transformation of drainage is the most promising measure, it makes for an increased groundwater storage of 15 mm and the base discharge gets larger, while the peaks will get delayed. Again, the combination with improving the soil structure does deliver better results during the spring season.

In the Geest HRU, there are no significant changes in discharges after implementing the measures, the main results of this analysis show that the raising of the riverbeds will contribute the most to increasing groundwater levels. In the other HRU with a large aquifer, the Outwash Plain, a combination of two measures, controlled drainage and increasing weir levels will not only increase discharges during drier seasons and decrease discharges during the winter season, but it will also increase groundwater levels by a significant amount. The statement in *4.1.2 Surface water system* that there is capacity to store excess amounts of precipitation in the sand channel turns out to be true. Lastly, the percolation trenches, although the effects of these trenches on the discharges in the Human HRU may be a rough estimation, the measure does turn out to be effective at increasing groundwater storages.

The results indicate a distinction in which areas which measures can be effective. Figure 11 indicates in which areas which problems can be decreased. The areas with a larger aquifer in the area have more potential to increase the groundwater storage (the areas with vertical blue lines in Figure 11), while areas with a shallower aquifer can be used to decrease the discharging problems in the area (the areas with horizontal red lines in Figure 11). In some areas, all three problems can be decreased.

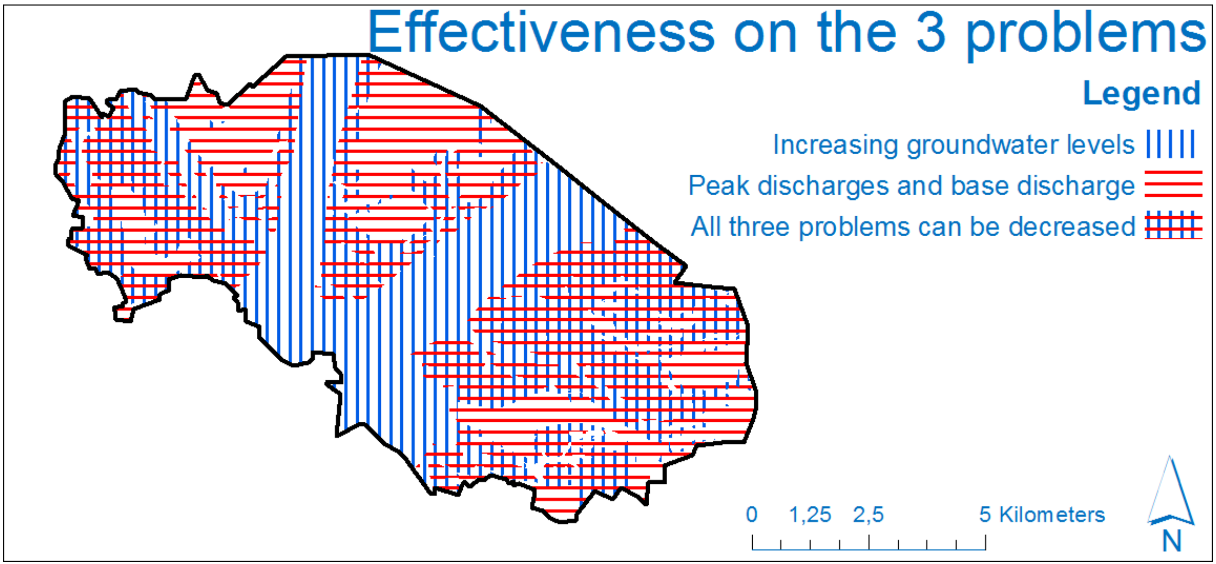


Figure 11 - Locations at which the three main problems can be decreased, vertical lines indicate the possible increase in groundwater tables, horizontal lines indicate locations in which the discharging problems can be tackled.

Combining all the effective measures in the different hydrological response units, several things can be noted. First, the discharges in the Groenlose Slinge could be lowered by 6% during the winter season. Next to that, the spring and summer discharges can be increased by 6 and 5%, resulting in a larger base discharge during the drier months of the year. The combination of measures does not significantly change the discharges during the autumn.

The expected increases in groundwater tables can significantly decrease the groundwater problems in the project area. As stated in *1.1 Research motivation*, the groundwater levels declined by as much as 10 centimetres more during the summer of 2018 and 2019 than during average years. For the project area, with its average loamy sand soil (Onderstal, 2009), the saturated zone of the soil consists roughly of 50% soil solids (a combination of sand, silt, and clay) and 50% pore spaces and water (Vittum, 2009). The decrease in groundwater tables of 10 centimetres is therefore equal to a decrease in groundwater storage of 5 centimetres (or 50 mm). In the Brook Valley HRU and the Outwash Plain, the problem of these declining groundwater tables of 10cm during the very dry years can be resolved completely, as the measures in these areas can increase groundwater storages in the area by more than 50 mm. In the other sub-areas within the project area, the measures do not eradicate the problem completely, but can decrease the problem by at least 30%.

5. Discussion

The results provide a basis to determine whether measures will be effective. However, during the research, several choices have been made to obtain results. These choices must be considered to value the results. This chapter will provide an overview of the choices that have been made and how that affected the results of the research.

In the definition of hydrological response units, the choice was made to define 6 HRUs. The reasoning was that the areas were different, but homogeneous enough to determine the effects. Due to a schedule, no more areas could be defined. However, with more (smaller) hydrological response units, the effects of measures could be mapped more specifically, to obtain a clearer image of effects on groundwater tables. With smaller HRUs, the specified areas will be even more homogeneous, which makes for less variation in effects over the whole HRU.

After that, for every predefined measure, it is determined in which of the hydrological response units the measure could decrease at least one of the three problems. This analysis includes only the areas in which the measures seem most promising. It is not the case that the measures that were deemed "not-promising" are in fact worsening the situation. It may well be that the measures could have a positive effect on the three problems, however their contribution to decreasing the problems will be smaller. Every retained drop of water counts, so these measures are not ruled to be ineffective, but the research only suggests that the effects on the problems will be smaller.

Now, the quantification. First, the effects on groundwater storages. The effects of measures on the groundwater storages can be exaggerated, as the quantification of effects often included an extreme implementation of the measure. For example, for the measure of increasing weir-levels, all weirs within an area would be raised, which may be unfeasible. This research only discusses the potential profit for groundwater storages. However, as all measures are implemented in this way, the differences in effects between the different measures still indicate the suitability of a measure in an HRU. The other major factor in this analysis is that at the end, the effects of measures on groundwater storages are added, to obtain the effects if both measures are implemented. Again, this indicates the potential of the measures, but it is not known what the effects of measures would be when working together. It is possible that a measure works great in combination with another measure, but the opposite can also be true, in which case the effects cannot be added.

Second, the effects on the discharge of the Groenlose Slinge. The model used for the quantification is based on several assumptions, which should be considered when addressing the results of the model. For the calibration, a portion of the project area was chosen that discharged through a measurement point. However, the calibration catchment was smaller than the total area that flows into that measurement point and there is a fish-ladder around the measurement point. The assumption is that the flow from the catchment that is not considered is roughly equal to the flow through the fish-ladder. Also, the flow from the sewage plant is not considered, as this is not area-specific water. This resulted in the model getting smaller peak discharges than the peak discharges that are measured at Jonkersbrug.

The next assumption is about the step from the calibration area to the 6 hydrological response units. It is assumed that the calibration catchment has an average rainfall-discharging behaviour, and that based on this area, the other areas can be modelled as well. This conversion of calibrated parameters to the HRU specific models is based on literature, which leads to more uncertainties. The last point of the effects on discharges comes from the implementation of the three measures; raising weir-levels, raising riverbeds and the implementation of percolation trenches. The implementation in the conceptual-hydrological model is based on decreasing the runoff-coefficients. The exact number could not be obtained from literature, so this value is estimated based on expert judgement. The results of the analysis of these three measures should therefore be considered with this knowledge, that expert judgement is used, in mind.

The last discussion point is that the research does only consider the numerical effects on the groundwater and on the discharges. This report does not include other factors that may be important for the implementation of measures. Retaining water for longer can result in a change in water quality and gives a larger potential of flooding, as the water cannot discharge as quickly. This is not considered in this paper. That said, the research does have potential for generalizations. The differences in effects give insights into what measures are effective in which locations. The research has shown that removing drainage/converting drainage into controlled drainage will contribute to the three problems, no matter what circumstances. Next to that, the research indicated that thicker aquifers have a large potential to retain more water in the soil.

6. Conclusion

The system analysis provided several characteristics that define distinct areas within the project area. A feature that became apparent at several aspects of the analysis, was the existence of the natural course of the surface water system. This area was distinctly different from the rest of the project area, and therefore could be defined as the first hydrological response unit. The second characteristic that became apparent in the system analysis, was the variation in thickness of the aquifer above an impermeable layer in the subsurface. The thickness of the aquifer has such an influence on the hydrological functioning of the project area, that this was the basis for defining the next HRUs. Throughout the project area, there was a large area that had an aquifer thickness of less than 1 meter, which resulted in the second HRU, as the groundwater levels are significantly different from the other areas.

The third HRU has a maximum aquifer thickness of 10 meters. This area generally has a homogeneous hydrological system. Next to these aquifer thicknesses, there are two deep sand channels in the area, which allow for an aquifer thickness of more than 10 meters. Within the area with a thick aquifer, there are two clear separate areas, one with a small average slope and a small freeboard, and the other one with almost twice the average slope and a larger freeboard. These two areas make up two separate areas. The last HRU consists of human made areas, the built-up area of Winterswijk and several other structures that are distinctly different from the other areas due to paved surface and sewage systems.

Within each HRU, several measures were determined to be able to contribute to solving the three problems in the project area. The removal or transformation of conventional drainage would be most effective in the areas with the largest amount of drainage, an improvement of soil structures is determined to be effective in areas with the lowest amount of organic matter content and a large amount of compacted area. Lastly, the raising of riverbeds or weir levels would be most effective in areas with a larger medium to infiltrate (a thick aquifer).

The results of the third research question, or the quantification of effects of the measures, indicated that there is a distinction in which areas the problems can be decreased. In the areas with a shallower aquifer (<10-meter thickness aquifer), the two discharging problems can be reduced by the water-retaining measures. The transformation of conventional drainage into controlled drainage in these areas can increase the summer and autumn discharge by as much as 11%, while decreasing the winter discharge by 8% in the shallow aquifer-area. The transformation of drainage works best in the areas with an aquifer thickness smaller than 10 meters. Especially in combination with an improved soil structure, the winter discharges in these areas can decrease by 12%, while increasing the discharges during drier times of the year by 11%. The other measures have a larger influence on the groundwater storages.

The problem of declining groundwater tables can mainly be reduced in areas with a thicker aquifer. In these areas, the groundwater storage during the driest time of the year (at the 31st of July) could be enlarged by 30 to 76 mm. At several locations, implementing measures can overcome a decline in groundwater levels experienced during the dry years of 2018 and 2019. During these years, the decline in groundwater storage was 50 mm larger than the usual yearly decline of the storage during summer. Removing drainage and raising weir-levels contributed to an increase in groundwater storage of more than 50 mm during the driest part of the summer.

7. Recommendations

The recommendations of this research are twofold. The research itself can be improved, and the knowledge that is obtained in this research can be extended by researching several other points of interest, that could not be researched in this paper.

First, the recommendations to improve the research itself. As stated in *5. Discussion*, it is possible to define smaller, more specific hydrological response units in the area, which are more homogeneous than the 6 areas that are defined in this paper. With smaller areas, the specific effects for smaller plots of land can be determined, which can give more specific results on what the effects of the measures will be. For the quantification of effects on the groundwater storages, most effects were calculated based on a complete implementation of the measure, for example all the weirs in the area would be raised. This can be costly and time-consuming and could therefore not be done all at once. For a gradual introduction of the measures, it would be advised to first determine what the effects of one increased weir would be in an area.

For the discharging model, there are a lot of assumptions. Not all these assumptions could be conclusively be backed up by literature and/or calibration. In order to make sure that the model is correct, either the assumptions should be proven accurate, or more discharging data should be collected in the area, such that the model can be calibrated better. This increase in measuring and data gathering is also included in the recommendations for further research.

Second, the recommendations for further research, based on the results of this thesis. During this study, several features in the project area turned out to have an influence on the water system, but these features could not be defined as a separate HRU. The natural course of the Ratumsebeek runs through the Koppelleiding. The reroute towards the Willinkbeek turns out to have an impact on the loss of water in the area. It is recommended to research the effects of restoring the natural course on the losses of water.

Other areas that can be used for gaining water for the discharging streams during the summer, but that are not further researched, are the deeper permeable layers in the subsurface, which reach the aquifer at several locations in the project area. The hydrological effects of these connections to deeper groundwater storages are not fully understood now. In order to understand and maybe even use the hydrological effects on discharges of these deeper layers, it is recommended to deepen the knowledge of these areas. This can be done by measuring discharges at various locations along the upper reaches of the Groenlose Slinge throughout the year, to determine the locations where water is gained and where water is lost to the subsurface. This field research can be extended to examining the exact depth of the aquifer, to improve the knowledge of the subsurface structures.

Next to that, before the measures are implemented, the effects of water retention on water quality and on the increased risk of water nuisance at some locations should be determined. With a larger groundwater storage, the soil does have less space for a large precipitation event, which can result in water nuisance at those locations. These risks for water quality and water nuisance are not considered in this thesis, but it would be important to know before implementation of the measures.

The last recommendation for further research is to research the possibilities of retaining water in the German part of the catchment, as this area does also deliver peak discharges during precipitation events. There is some cooperation between Waterschap Rijn en IJssel and Germany, but this connection can be improved by for example more data sharing and working on the same catchment area simultaneously, to find solutions that can benefit both sides of the border.

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Appendices

Appendix A – Figures system analysis

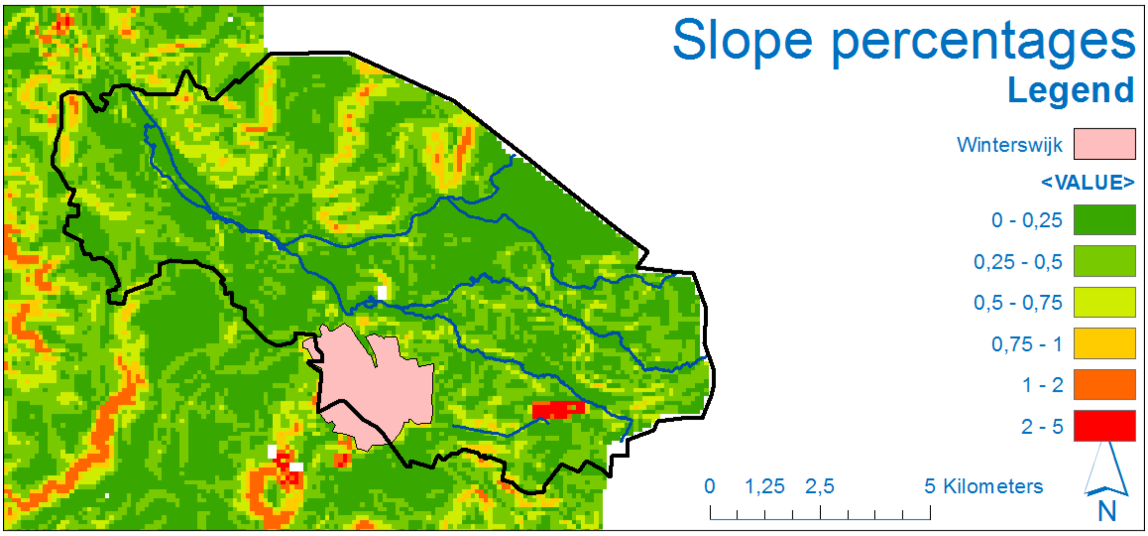

Figure 12 - Slope area (calculated with Slope-tool in ArcMap, based on AHN grid 100x100m)

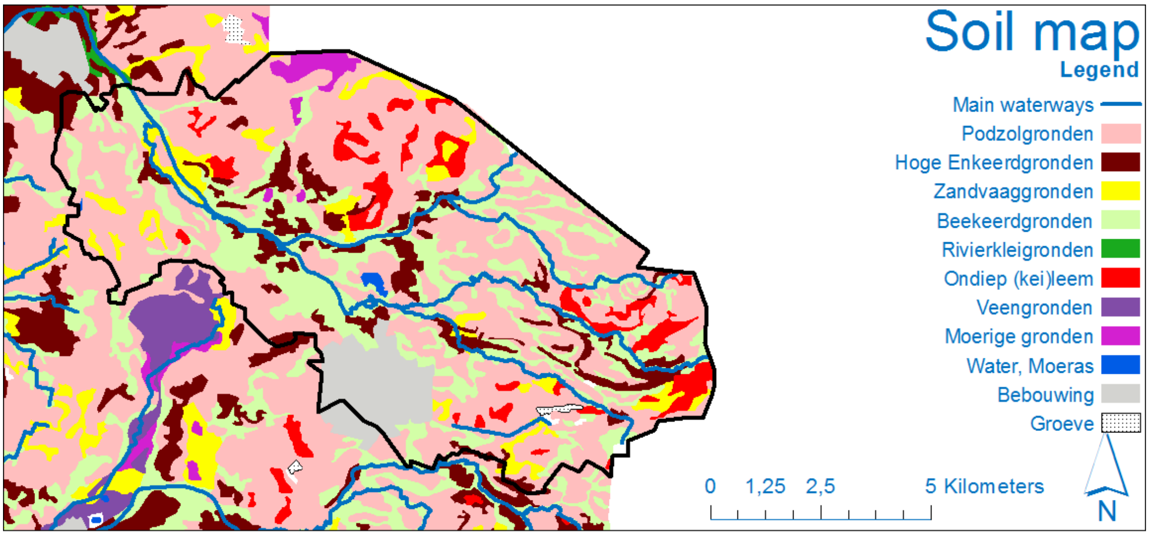

Figure 13 - Soil map (Onderstal, 2009)

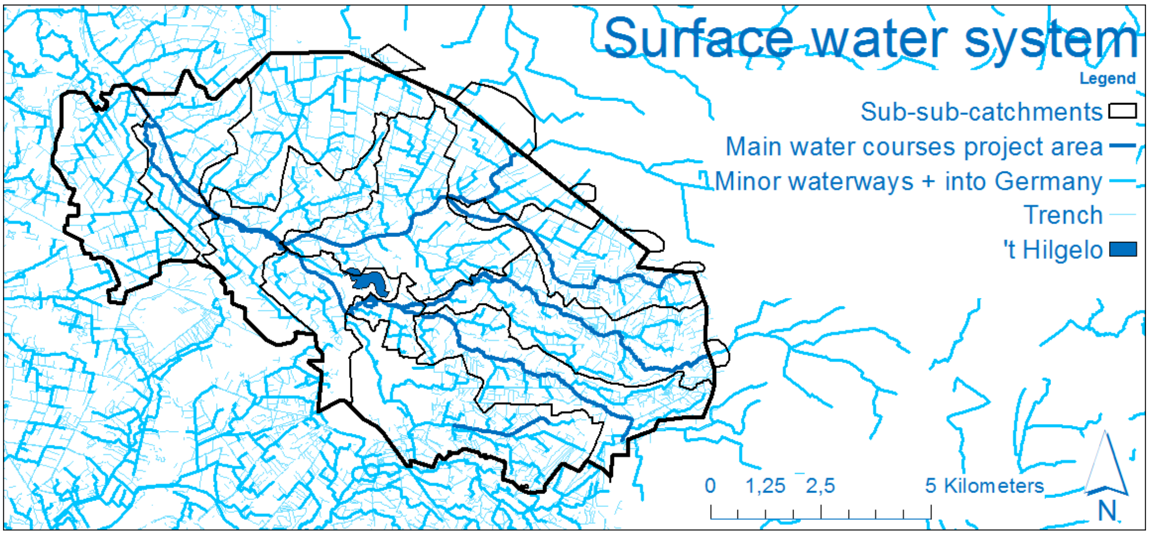

Figure 14 - Surface water system

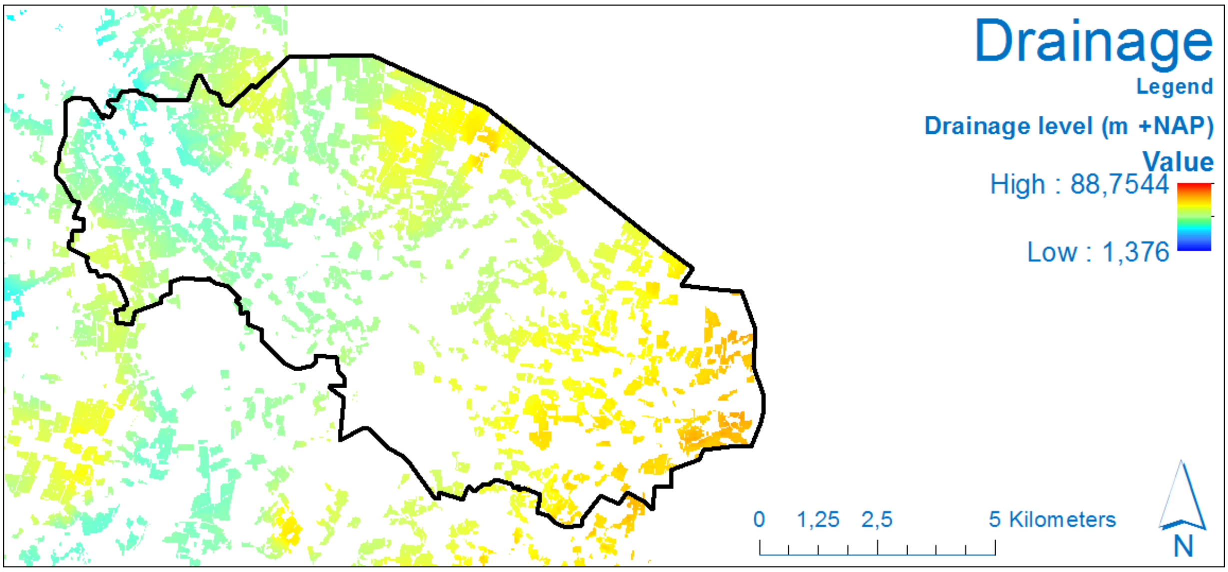

Figure 15 - Drainage (levels)

Appendix B – Locations several groundwater and surface water measurement points

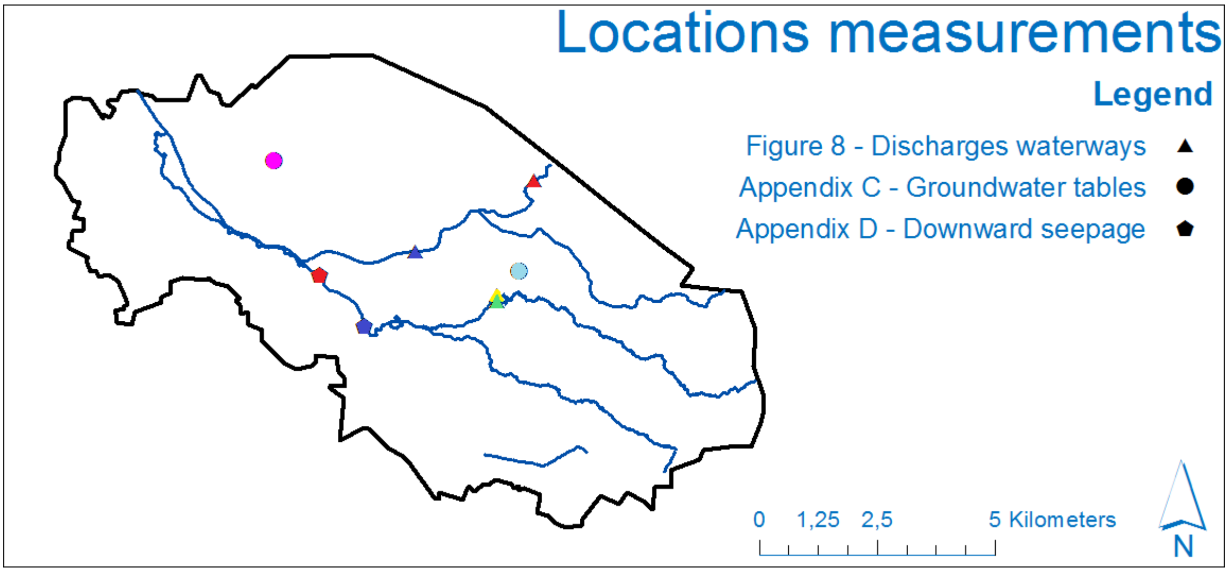

Figure 16 - Locations of measurements (colour of graphs corresponds to location in map, shape corresponds to legend)

Appendix C – Groundwater tables

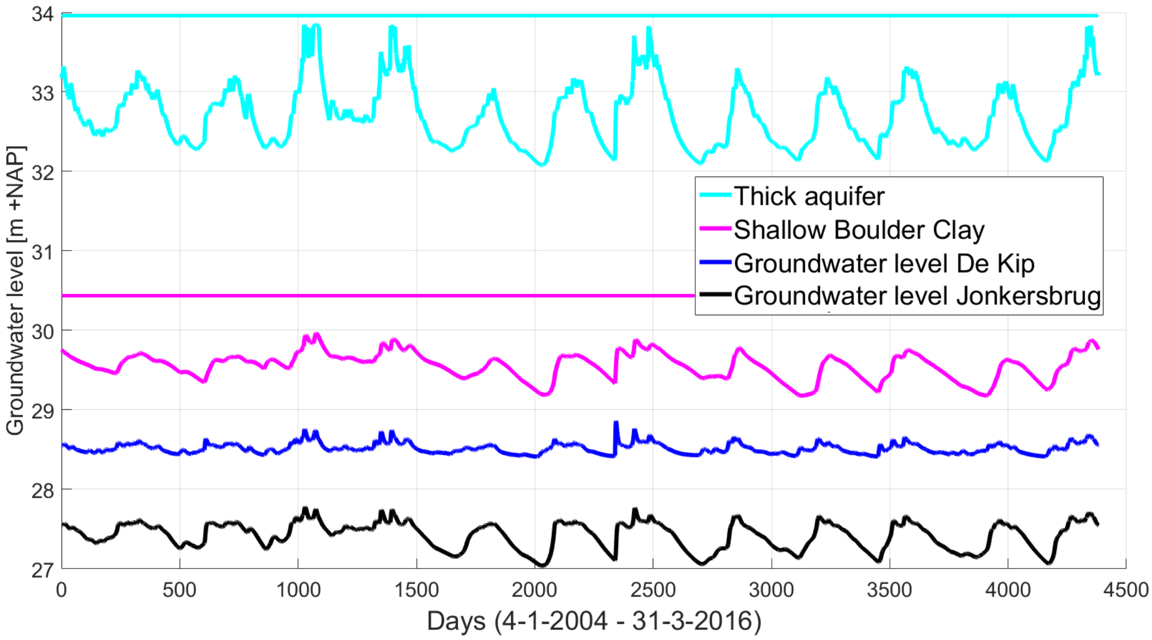

Figure 17 - Groundwater tables in shallow and deep aquifer, with their ground levels (locations are indicated in Appendix B)

Appendix D – Downward seepage

In order to check whether downward seepage takes place above the deep sand channel, the discharge passing measurement location Jonkersbrug will be analysed (see location in Appendix B). The smallest discharge of each year has been determined and visualized in Figure 18. In order to see whether downward seepage takes place, the data from an upstream measurement point must be used. The sewage plant of Winterswijk is upstream of the measurement point at Jonkersbrug, see Appendix B. Figure 18 also indicates what the minimum discharge of the year was, minus the discharge that is released by the sewage plant at the day the minimum discharge at Jonkersbrug was measured.

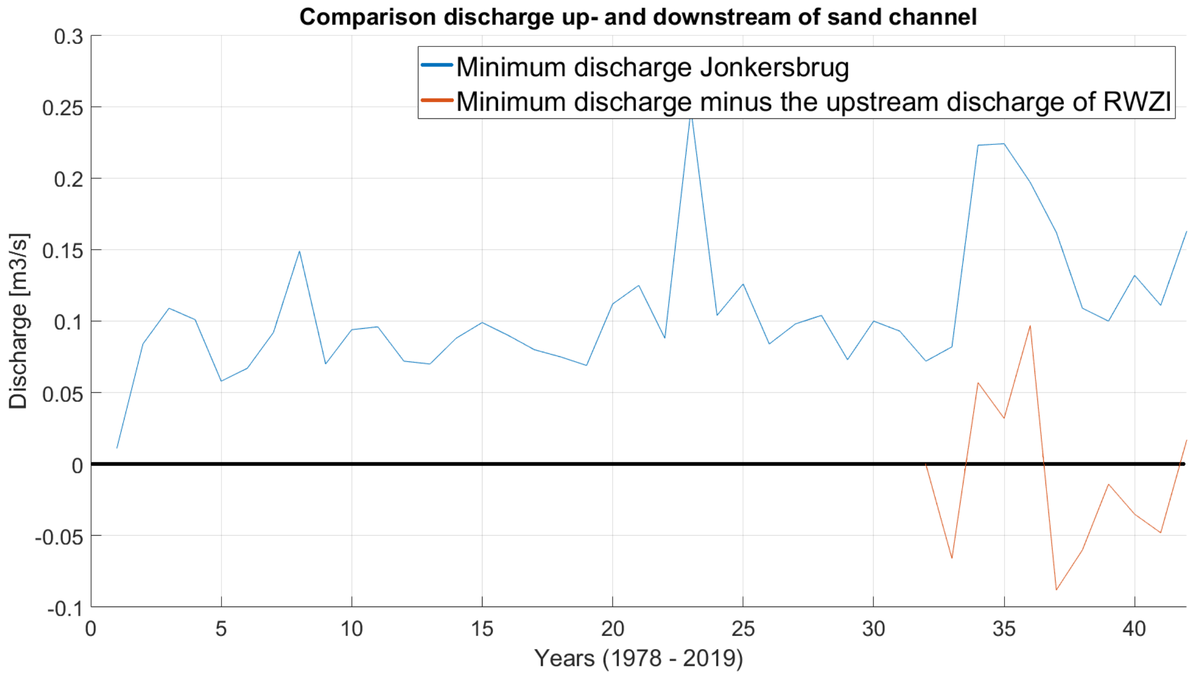

Figure 18 - Minimum discharges Jonkersbrug over the years

As can be seen, the discharge of the sewage plant RWZI sometimes can be larger than the discharge that is measured at Jonkersbrug. Water will be lost somewhere in between. Bear in mind that one factor is not considered, which is the fish-passage at Jonkersbrug. The discharge through this passage around the Jonkersbrug is not measured and therefore not included in the graph in Figure 18. It might seem that the conclusions drawn should be abolished. However, the discharges of the Ratumsebeek, the Willinkbeek and the Wehmerbeek are also not taken into the calculation. It is assumed that the discharges of these three sources will be larger than the discharge through the fish-passage and therefore it is strongly suspected that water percolates from the Groenlose Slinge into the sand channels during drier times.

Appendix E – Characteristics Hydrological Response Units

Table 9 - Characteristics HRUs (1) The groundwater levels in the Shallow unit are difficult to model, hence the remarkable values, 2) No data

Hydrological Response Unit	Average organic matter content (%)	Main GW-ladders (with low, spring and high groundwater tables in m below ground level)
Shallow	5.1	V, VI (2.00, 1.25, 0.99)[1)]
Brook Valley	4.2	III*, VI (1.59, 1.15, 0.96)
Podzol	5.2	III, V, VI, VIII (1.97, 1.37, 1.15)
Geest	5.1	III*, VI, VII (2.12, 1.59, 1.39)
Outwash Plain	6.7	III*, VI (1.62, 1.10, 0.88)
Human	-[2)]	-[2)] (2.18, 1.69, 1.54)

Appendix F – Technical implementation increasing organic matter

The current amount of organic matter content is listed in Table 9 above. As it takes a while for organic matter levels to rise in an area, a decision will be made on what the exact implementation of this measure will be. The options of using slurry and the option of not working the land will be considered. The implementation of slurry is a fast way of raising organic matter contents, it takes a lot of cow manure to do this, while not working on the land has the ability to raise the amount of organic matter content by 1.54% in 10 years (Eekeren, Deru, Hoekstra, & Wit, 2018). As this is a long time, a distinction will be made on how the organic matter content will be raised. The choices that were made are based on expert judgement on what would work best for each area, the choices are given in Table 10.

Table 10 - Increase of organic matter content per HRU

Hydrological Response Unit	Increase by slurry [%]	Increase by not working the land [%]	Explanation
Shallow	2	0	Lots of agriculture, no time to use the second option
Brook Valley	1	1.54	Less agriculture in the area, more areas to naturally develop more OGC
Podzol	1	0	Only fast increase needed, problem mainly arises from compaction
Geest	2	0	Lots of agriculture, no time to use the second option

Appendix G – Effects on groundwater storage

Transforming conventional drainage into controlled drainage

The location of the drainage beneath ground level has been determined by comparing the elevation map in Figure 3 and the drainage level +NAP in Appendix A. For every hydrological response unit, a random plot of land was chosen to compare the elevation level and drainage level in m +NAP, the results are listed in Table 11.

Table 11 - Drainage level compared to ground level

HRU	Drainage level (m +NAP)	Elevation level AHN (m +NAP)	Distance between elevation level and drainage level (m)
Shallow	38.42	39.21	0.79
Brook Valley	23.36	24.24	0.88
Podzol	28.60	29.45	0.85
Outwash Plain	34.37	35.19	0.82

It is concluded that the drainage level beneath ground level was around the usual drainage level, which is between 80 and 100 cm beneath ground level. Therefore, the effect on groundwater levels due to the transformation to controlled drainage can be obtained from the results Landbouw op Peil (2014). This paper provides insights into the effects of this transformation under usual circumstances (at drainage level 80-100 beneath ground level). Landbouw op Peil (2014) states that this measure is most effective in areas with a continuing water supply over the year. This supply can be precipitation, upward seepage or surface water supply. In areas without a large supply of water, the increase in groundwater levels over the year will be just 10 mm, while areas with a larger supply of water can eventually get an increase in groundwater storage of 20 mm. Based on the characteristics of the HRUs, the increase in groundwater storage is determined and stated in Table 12.

Table 12 - Increase in groundwater storage due to transformation to controlled drainage

HRU	Increase in groundwater storage	Explanation
Shallow	10 mm	Little to no supply, only precipitation.
Podzol	15 mm	Average supply.
Outwash Plain	20 mm	Large supply from surface water.

These results also correspond to the estimated effects of Phernambucq, et al. (2019) for the project area.

Removal of drainage

The effects of this measure are also discussed in Landbouw op Peil (2014). In the paper it is stated that this measure can increase the groundwater level up to 40 cm in wet times and 10 cm in dry times. Vittum (2009) states that an average loamy sand soil consists roughly of 50% soil solids (a combination of sand, silt, and clay) and 50% pore spaces and water. Based on this conclusion, it is determined that the difference in groundwater storage is half (or 50%) of the difference in groundwater tables, which translates to an increase of 5 cm in groundwater storage, or 50 mm.

Increasing weir levels

KnowH2O, et al. (2019) have done research into the effects of increasing weir levels and raising riverbeds. The results of that analysis will be used for this study. The study from KnowH2O, et al. (2019) used the Nationwide Hydrological Model (in Dutch: Landelijke Hydrologisch Model) with a grid of 250x250m. The study calculated the effects of several measures on the groundwater levels in an area, by comparing the groundwater levels in the dry year of 2018 after implementing the measures to the reference situation, which were the average groundwater levels during the period from 1981 to 2018. Please note that these results are therefore short term (one year), as the measures are implemented at the 1st of January and run until the end of 2018, the effects could be smaller or larger over a larger time-span. For the calculations on daily-basis, the other inputs have been kept constant, hence no land-use changes since 2010 have been taken into account in the calculations of the year 2018.

The research conducted focussed on the effects of measures on groundwater levels, seepage, soil moisture, evaporation and surface water discharges in the dry year of 2018. The measures have been implemented in an extreme way, to test the sensitivity of the area to such a measure, but therefore the results may not be completely realistic. For the increase of weir levels, this meant that every single weir in the area would be raised by 30 cm (in all secondary and primary waterways), which may not be realistic. That said, the results give an indication of how and how much the measures can affect the water system in the area.

Scenario 4 in this study is the increase of weir levels in the main waterways (in Dutch: leggerwaterlopen), by 30 centimetres. For the purpose of this study, only the model-output of the groundwater table will be discussed. The model output gives the difference in groundwater level compared to the ususal groundwater level at that day for three days of the year and plots the results for each grid cell in a map. The three days that are plotted, are the 1st of April (during spring), the 31st of July (driest time of the year) and the 1st of October, which is in the Autumn. For every date, a map is obtained as depicted in Figure 19.

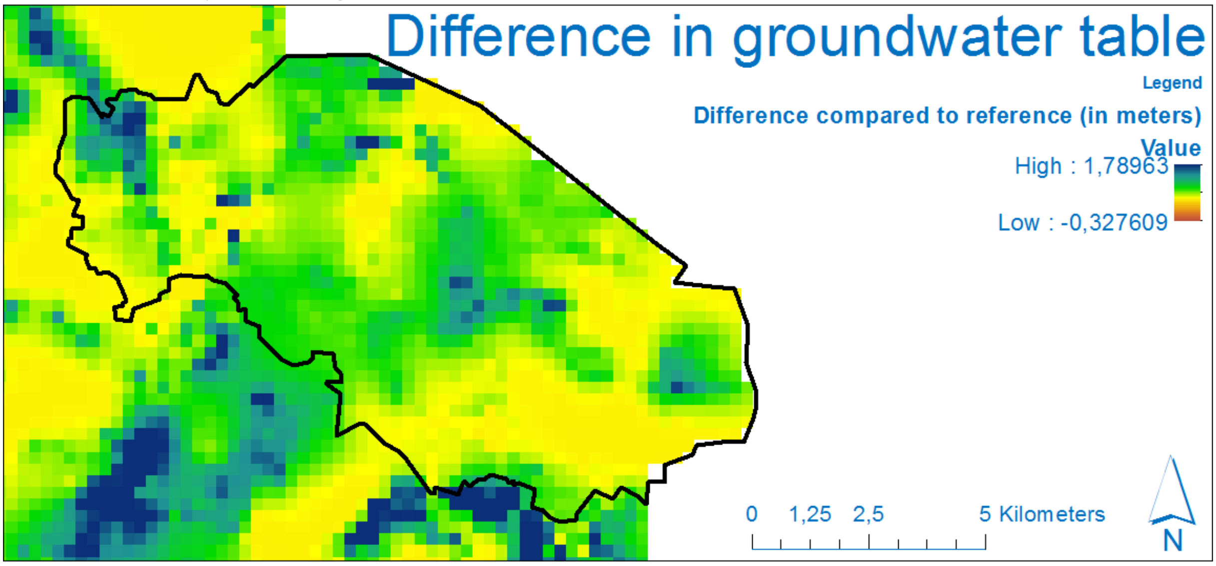

Figure 19 - Increasing weir levels: difference in groundwater table 1 April

The figure seems to show main increases in groundwater tables in the deep sand channels and around the brooks. Using the ArcMap tool ZonalStatistics, the average increase in waterlevels due to raising of weirs could be determined for each of the three dates in the HRUs that are expected to benefit the most from this measure. The results are shown in Table 13.

Table 13 - Increase in groundwater tables due to raising weir levels

HRU	Difference groundwater table - 1 April	Difference groundwater table - 31 July	Difference groundwater table - 1 October
Brook Valley	+63 mm	+52 mm	+58 mm
Outwash Plain	+73 mm	+64 mm	+71 mm

This must be translated into an amount of water (the storage). Using the same conclusion of Vittum (2009) as in *Removal of drainage*, with an average loamy sand soil there is 50% water in the saturated zone, the difference in groundwater storage is half of the difference in groundwater tables. The increase in groundwater storages is given in Table 14.

Table 14 - Increase in groundwater storages due to raising weir levels

HRU	Difference groundwater storage - 1 April	Difference groundwater storage - 31 July	Difference groundwater storage - 1 October
Brook Valley	+31.5 mm	+26 mm	+29 mm
Outwash Plain	+36.5 mm	+32 mm	+35.5 mm

The effect on groundwater tables that is most important for this research, is the effect on summer groundwater tables, in order to overcome the droughts in the area. Hence, the value in the third column will be shown in the Results paragraph for the third research question.

Raising riverbeds

This measure is also included in the analysis from KnowH2O, although this needs more computation. The way this measure has been calculated in the analysis, is by combining the increase of weir-levels and the raising of riverbeds by 30 centimetres. Therefore, the effects of raising riverbeds are only known in combination with the other measure. In order to determine the results that can directly be attributed to the raising of the riverbeds, the effects of raising weir levels will be subtracted from the effects of the combined measures. It is possible that the true effect of the raising of riverbeds is larger than the values that will be obtained with this method, as there can be overlap between the effects of the two measures, but this cannot be conclusively backed up.

Again, this scenario has been implemented in an extreme way, by modelling an increase in riverbeds in all waterways smaller than 3 meters. This is again a hypothetical situation, as in reality not all these waterways can be adjusted at once, but it shows the sensitivity of the area for such a measure. The ArcMap tool is used to obtain the increased groundwater levels, after subtracting the groundwater levels that can be attributed to the increased weir levels, Table 15 is obtained.

Table 15 - Increase in groundwater tables due to raising riverbeds

HRU	Difference groundwater table - 1 April	Difference groundwater table - 31 July	Difference groundwater table – 1 October
Brook Valley	+20 mm	+6 mm	+6 mm
Podzol	+20 mm	+8 mm	+7 mm
Geest	+19 mm	+7 mm	+4 mm

Again, this will be translated into the increase in groundwater storages. The results are given in Table 16.

Table 16 - Increase in groundwater storages due to raising riverbeds

HRU	Difference groundwater storage - 1 April	Difference groundwater storage - 31 July	Difference groundwater storage – 1 October
Brook Valley	+10 mm	+3 mm	+3 mm
Podzol	+10 mm	+4 mm	+3.5 mm
Geest	+9.5 mm	+3.5 mm	+2 mm

The increase of groundwater levels after implementing the raised riverbeds tend to decrease during the summer period. Later during summer, some streams were already running dry during the reference years, hence a smaller difference with the new situation, in which the brooks also run dry, as the bed is simply much higher above the groundwater table. The effects on the driest date will be included in the Results paragraph of the main report.

Improving soil structure

First, the compaction in the areas. For the calculation of water in the subsurface, a calculation from Sietzema (2016) will be used. This paper provides a formula to calculate the moisture retaining capacity of compacted and non-compacted soils in the topsoil and subsoil. The data that the paper provides has been obtained in the project area and can therefore be used for this calculation as well. The data collected only gives information on podzol soils. Therefore, the Shallow HRU, with its large amount of podzol soils, and the Podzol HRU will be calculated.

The moisture retaining capacity (in Dutch: vochtbergend vermogen) of the podzol soils. The retaining capacity of a soil in its unsaturated zone can be calculated with Equation 1.

$$M = T_t * M_t + T_s * M_s \qquad \textit{Equation 1}$$

M = Moisture retaining capacity [mm]
T_t = Thickness topsoil [dm]
M_t = Moisture retaining capacity topsoil [mm/dm]
T_s = Thickness subsoil [dm]
M_s = Moisture retaining capacity subsoil [mm/dm]

Table 17 - Moisture retaining capacities compacted and non-compacted podzol soil (Data retrieved from Sietzema (2016))

Compaction	T_t podzol soil [dm]	M_t podzol soil [mm/dm]	T_s podzol soil [dm]	M_s podzol soil [mm/dm]
Not compacted	3	22.4	1.5	22.2
Compacted	3	15.6	1.5	10.2

With the data that is obtained from Sietzema and Equation 1, a difference of 38.4 mm in retention capacity is obtained between the compacted and the non-compacted soil. Not only does the removal of compaction on a plot of land have an impact on the amount of moisture that can be retained in the unsaturated zone, the removal also results in an increase in groundwater levels. With Equation 2, this increase in groundwater storage in podzol soils is determined.

$$S = T_t * S_t + T_s * S_s \qquad \textit{Equation 2}$$

S = Specific retaining capacity [mm] (in Dutch: specifiek bergingsvermogen)
S_t = Specific retaining capacity topsoil [mm/dm]
S_s = Specific retaining capacity subsoil [mm/dm]

Table 18 - Specific retaining capacities compacted and non-compacted podzol soil (Data retrieved from Sietzema (2016))

Compaction	T_t podzol soil [dm]	S_t podzol soil [mm/dm]	T_s podzol soil [dm]	S_s podzol soil [mm/dm]
Not compacted	3	19.6	1.5	10.9
Compacted	3	13.4	1.5	18.1

With Equation 2, a difference of 7.8 mm in retention capacity is found between the compacted and the non-compacted soil. Therefore, the groundwater table will increase 7.8 mm due to the removal of compaction. With these calculations, the results for the Shallow and the Podzol HRU are determined. There is not enough data to calculate the exact increase in retention capacity and in groundwater tables, therefore these will be determined using expert judgement.

The document from Sietzema (2016) indicates that soils that do not consist of podzol soils are compacted less than the podzol soils that have been calculated. However, the subsoils of the Brook Valley HRU and the Geest HRU are trice or even four times as thick as the subsoil in podzol (0.5m and 0.65 m respectively). Balancing the factors, the conclusion was that the groundwater storage in the Geest HRU would increase with a half of the result of the Podzol area, and the effects in Brook Valley would be a third.

Table 19 - Increase groundwater storage and retaining capacity due to removing compaction

HRU	Increase in groundwater storage due to removing compaction	Increase in retaining capacity unsaturated zone soil due to removing compaction
Shallow	7.8 mm	38.4 mm
Brook Valley	2.6 mm	11.0 mm
Podzol	7.8 mm	38.4 mm
Geest	3.9 mm	12.8 mm

Only the second column will be shown in the main report, the retaining capacity for the unsaturated zone is only an intermediate result that will be used in the calculation of discharges. The other factor in improving the soil structure, is the increase in organic matter content. The amount of increased organic matter content has been determined in Research Question 2. Gerner (2020) provides a basis on how to calculate the increase in water retaining capacity based on the amount of increased organic matter content.

Figure 20 gives an indication on how effective each percentage increase in organic matter content will be at increasing the amount of volume of water in the soil for different amounts of loam. The HRUs in which this will be applied have different loam contents, the Shallow HRU has a large loam content and will therefore use the red line and the other three HRUs have a smaller loam content and will be applied to the black line.

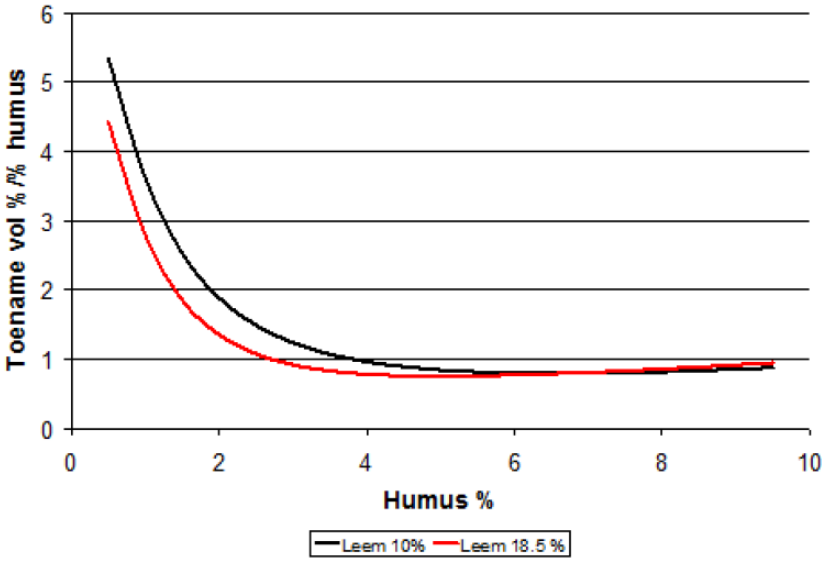

Figure 20 - Relation increase organic matter content and volume of water per volume of soil (Wösten, Eekeren, & Gerner, 2016)

Using the current organic matter content and the increase of content that is strived for with this analysis (from Appendix F) to determine the resulting volume-increase per decimetre in Figure 20, the fourth column in Table 20 is obtained. Multiplying this volume-increase per decimetre with the thickness of this topsoil results in the increase in retaining capacity in the unsaturated zone of the topsoil.

Table 20 - Calculation retaining capacity

HRU	Current organic matter content [%]	Target increase [%]	Resulting volume-increase per dm [%/dm]	Thickness topsoil [dm]	Increase in retaining capacity unsaturated zone
Shallow	5.133	2	1.6	3	4.8 mm
Brook Valley	4.166	2.54	1.9	3.2	6.1 mm
Podzol	5.222	1	0.8	3	2.4 mm
Geest	5.136	2	1.6	3.5	5.6 mm

The results of this analysis will also not be shown in the main report but is an intermediate step to determine the effects on discharges.

Changing land-use

This measure is discussed in the paper Landbouw op Peil (2014) as well. By implementing crops that thrive a little earlier in the year, the less water will be evaporated during the dry time. This can, according to Landbouw op Peil, result in an increase of 10 mm of groundwater storage during the drier times of the year in the Shallow area.

Percolation trenches

In order to quantify the results of percolation trenches, an analysis of weirs in farmers trenches will be used. According to Landbouw op Peil (2014), the effects of these two measures are roughly the same. Both measures prevent surface discharge from occurring. Landbouw op Peil (2014) gives a bandwidth of an increase in groundwater tables of 10 to 20 mm. It indicates that the measure will be most effective in areas with a larger supply of water (precipitation, upward seepage or surface water supply). As the Geest HRU has a relatively large supply of water and the Human HRU has an average supply compared to an area with a small supply such as the Shallow HRU. Therefore, the extra amount of groundwater storage due to the percolation over the year will be as in Table 21.

Table 21 - Increase groundwater storage due to percolation trenches

Hydrological Response Unit	Increase in groundwater storage
Geest	+20 mm
Human	+15 mm

Appendix H – Effects measures on discharges

In order to determine the effects of different measures on the discharge of the different hydrological response units, the conceptual-hydrological 'bucket' model depicted in Figure 21 will be used. This model will be implemented in MATLAB.

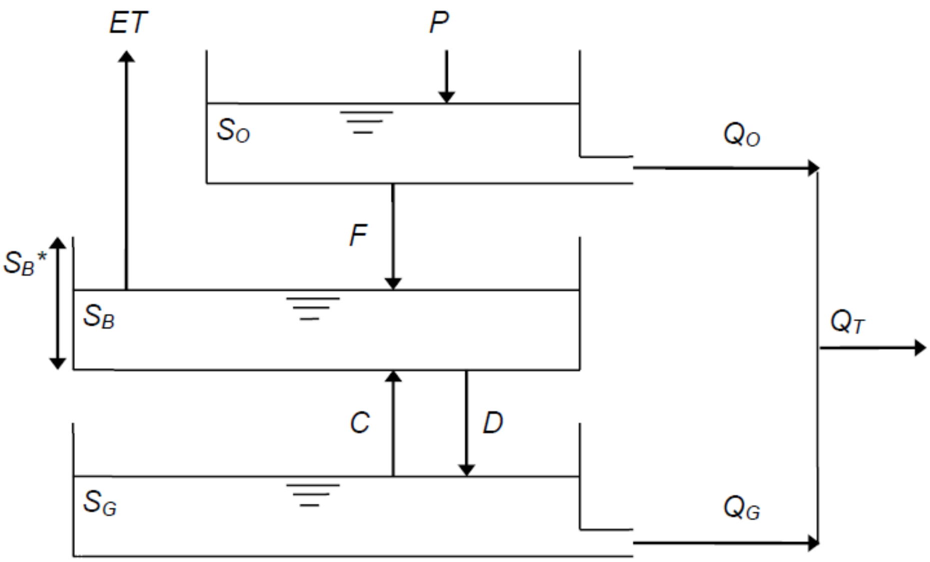

Figure 21 – Conceptual hydrological model (Booij, 2019)

Table 22 - Elaboration parameters Figure 21

Unit of measurement	Elaboration	Unit
ET	Evapotranspiration from soil (with parameter α [-])	[mm/d]
P	Precipitation	[mm/d]
F	Infiltration (with parameter F*)	[mm/d]
D	Percolation (with parameter D*)	[mm/d]
C	Capillary rise (with parameter C*)	[mm/d]
Q	Discharge (Q_O: surface (with parameter k_O [1/d] and n_O [-]), Q_G: groundwater (with parameter k_G [1/d]), Q_T: total)	[m^3/s] (after Equation 9)
S	Storage (S_O: surface, S_B: soil, S_G: groundwater)	[mm]
S_B*	Maximum soil moisture storage	[mm]

The model runs on a daily basis, for every time step (so every day), the model calculates the fluxes, storages and discharges. These values are calculated with formulas 3 to 12.

$$ET_a = ET_p \cdot \frac{S_B}{\alpha \cdot S_B^*} \qquad if\ S_B < \alpha S_B^*$$
$$ET_a = ET_p \qquad if\ S_B \geq \alpha S_B^*$$
Equation 3

ET_a is the actual evapotranspiration [mm/d]
ET_p is the potential evapotranspiration [mm/d]
α is the percentage of the maximum amount of soil moisture above which potential evapotranspiration takes place [-]

The ET_p-time range will be input for this model. The actual evapotranspiration in the project area is not known. The average monthly evaporation in De Bilt will be obtained from KNMI (2017&2018), the data only shows the total evapotranspiration per month, during the whole run-time of the model. Therefore, the total evaporation per month is assumed to be uniform, every day during the month has the same potential evapotranspiration, adding up these values gives the right total evaporation during that month. The actual transpiration in the project area will be determined by multiplying the measured (potential) evaporation in De Bilt with project area-specific parameters. These parameters will be determined in the calibration of the model.

The first flux within the model that will be calculated, is the infiltration. This infiltration is dependent on the amount of precipitation, the maximum infiltration and the saturation rate of the unsaturated zone of the soil, as can be seen in Equation 4.

$$F = P \cdot \left(\frac{S_B^* - S_B}{S_B^*}\right) \qquad if\ P < F^*$$
$$F = F^* \cdot \left(\frac{S_B^* - S_B}{S_B^*}\right) \qquad if\ P \geq F^*$$
Equation 4

F is the maximum infiltration parameter [mm/d]*

The maximum infiltration capacity can be determined based on the amount of loam in the soil (Berhanu, Melesse, & Seleshi, 2012). The article from Berhanu, et al. (2012) provides the values for the infiltration capacities of the different HRUs. The infiltration capacity depends on more than just the loam content, but the defined HRUs have quite significant differences in loam content, hence the model will be based on only the loam content. This infiltration can be implemented in the next flux, the percolation in the soil, which is calculated with Equation 5.

$$D = 0 \qquad if\ F + S_B - ET_a < D^*$$
$$D = D^* \qquad if\ F + S_B - ET_a \geq D^*$$
Equation 5

D is the maximum amount of percolation [mm/d]*

The value of the maximum amount of percolation will be determined in the calibration of the model. The third flux in the model is the capillary rise. This capillary rise is solely dependent on the groundwater storage S_G.

$$C = 0 \qquad if\ S_G \leq C^*$$
$$C = C^* \cdot \left(\frac{S_B^* - S_B}{S_B^*}\right) \qquad if\ S_G > C^*$$
Equation 6

C is the maximum amount of capillary rise [mm/d]*

The internal fluxes of the system can be calculated with the equations discussed till now. The system also has three fluxes out of the system. The first outflux is the actual evapotranspiration ET_a, which has been calculated in Equation 3. The other two outfluxes will be calculated with Equation 7 and 8.

$$Q_O = k_O S_O^{n_O} \qquad \textit{Equation 7}$$

$$Q_G = k_G S_G \qquad \textit{Equation 8}$$

k_O is the reservoir constant for the surface water [1/d]
n_O is a coefficient that indicates the degree of non-linearity of the surface water runoff [-]
k_G is the reservoir constant for the groundwater [1/d]

The total discharge out of the system is the sum of the two discharges. The unit of this total discharge is still in mm/d, in order to compare this discharge to discharges in m^3/s, the average discharge per day can be calculated with Equation 9.

$$Q_T = \frac{(Q_O + Q_G) \cdot A}{1000 \cdot 3600 \cdot 24} \qquad \textit{Equation 9}$$

A is the surface area of the area that is in question [m^2]

In order to continue to the next day, the storage in the surface water, unsaturated zone and in the groundwater must be updated. This will be done with Equation 10, 11 and 12.

$$\frac{S_O(t + \Delta t) - S_O(t)}{\Delta t} = P(t) - F(t) - Q_O(t) \qquad \textit{Equation 10}$$

$$\frac{S_B(t + \Delta t) - S_B(t)}{\Delta t} = F(t) + C(t) - ET_a(t) - D(t) \qquad \textit{Equation 11}$$

$$\frac{S_G(t + \Delta t) - S_G(t)}{\Delta t} = D(t) - C(t) - Q_G(t) \qquad \textit{Equation 12}$$

The discharging data in the project area is not enough to calibrate the model. In order to get a model that represents the area, the results of one area will only be visually compared to measured discharge data and groundwater data. There are a lot of factors that are not considered, only the Dutch part of the Willinkbeek territory is considered for the calibration (exact catchment used for the calibration is shown in Figure 22). The discharge of the German area and the Ratumsebeek that end up at the measurement location at Jonkersbrug are included in the measured data, but not in the calculated discharges. The measured data at Jonkersbrug is also not complete, as the discharge through the fish ladder around the weir is not measured, but it indicates the general discharging pattern of the area. Therefore, the model cannot be calibrated on the data, as there is too much uncertainties in the data, only a visual inspection will be done.

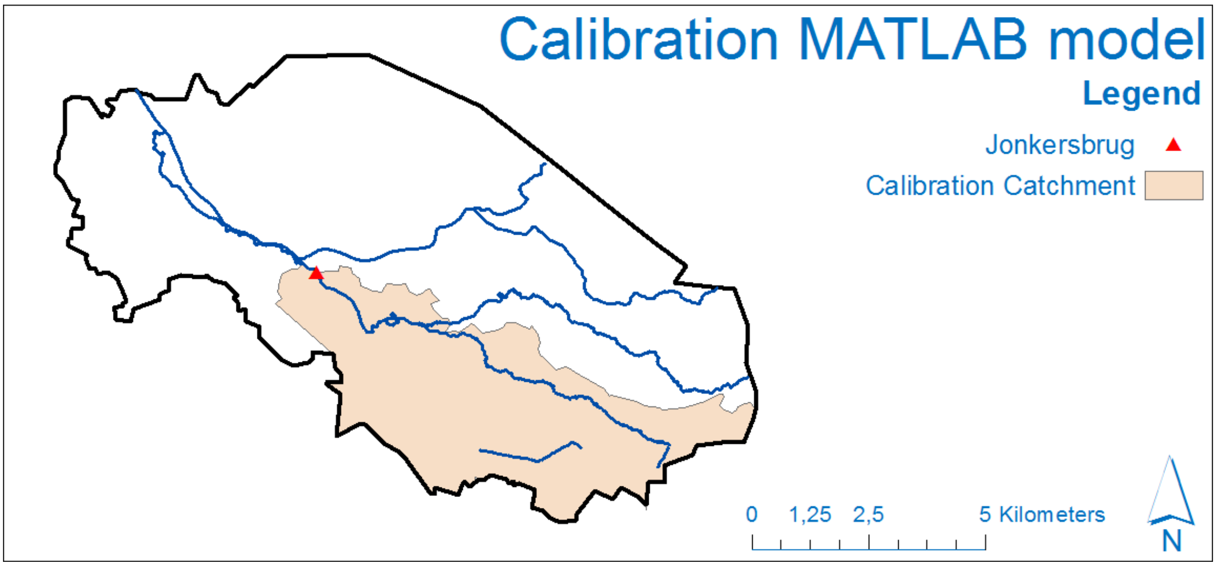

Figure 22 - Locations that have been used to calibrate the discharge model

This catchment is chosen, as a) there is a measurement point (Jonkersbrug) at the most downstream location, which can be used for calibration, b) all different HRUs have an overlap with this area, to obtain an average idea of the discharging behaviours of the different HRUs, c) the catchment of the Ratumsebeek is not included, as water from this catchment can also flow into the Koppelleiding, and lastly, d) the discharge through the fish ladder is not included in the measurement data, which is assumed to be equal to the discharge from the Ratumsebeek. The RWZI is also included in this catchment, the discharge from this location is subtracted from the measurement data, to obtain the most natural discharge pattern that can possibly be used in this project area.

The surface discharge in the area is not the complete story of the hydrological model, the groundwater storage must also be calibrated. The discharges and groundwater storage in the model after tweaking the parameters compared to the measured discharges and groundwater tables are visualized in Figure 23 and 24.

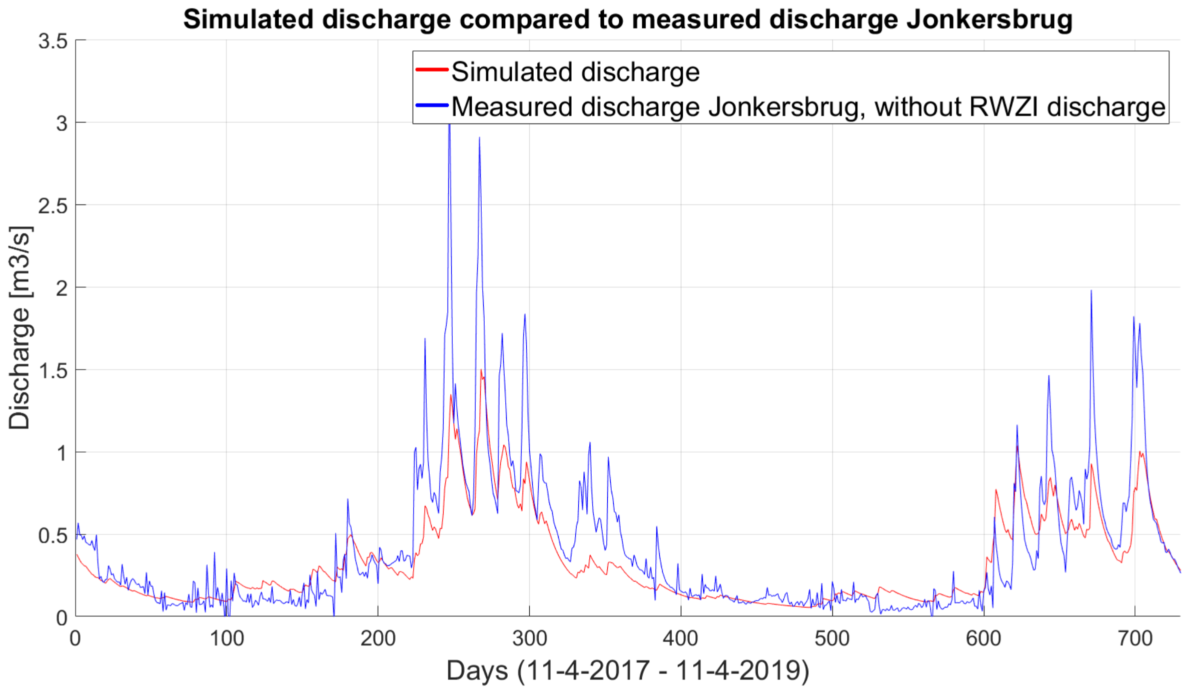

Figure 23 - Simulated discharge compared to measured discharge Jonkersbrug

There is a trade-off between optimizing the discharge and optimizing the groundwater storage, it was an arbitrary decision with which parameters both discharges, and groundwater storages were represented in a realistic manner compared to the measured values. With the found parameters, the simulated discharges seem to represent the measured discharges in Figure 23 quite well. The discharging peaks of the measured data is much larger, mainly because not the complete catchment that flows through the measurement point has been simulated. The groundwater tables in Figure 24 also represent reality well. Note that the units of the measured groundwater table and the calculated groundwater storage differ, hence these cannot directly be compared. However, the general trend can be compared. The small in- and decreases in the measured data come back in the calculated data, for example the relatively small increase around day 200. Next to that, general winter peaks and summer valleys clearly come back.

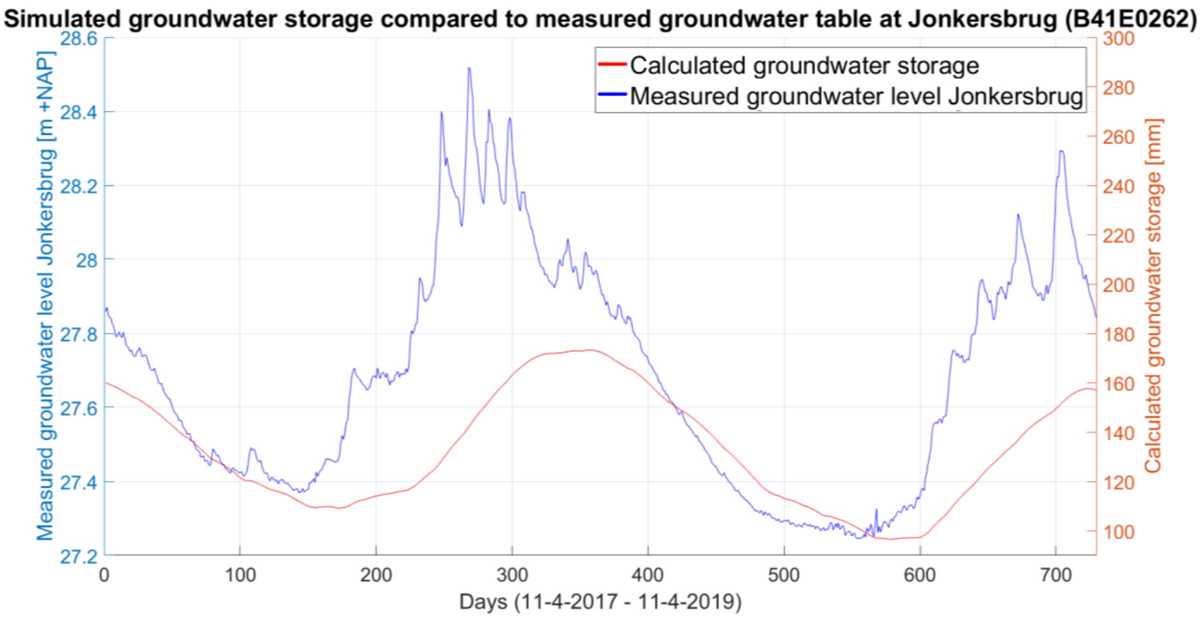

Figure 24 – Simulated groundwater storage compared to measured groundwater table at Jonkersbrug

The parameters for the calibrated area are determined. These are depicted in the 2nd row in Table 23, called the "Base". The catchment that has been calibrated overlaps various HRUs, therefore, it is assumed that this catchment represents the average natural discharge of the six HRUs. For every HRU, it is determined whether the parameter in question is smaller or larger than in the average scenario. This resulted in Table 23 for each of the parameters in each HRU.

Table 23 - Final parameters base model and models each HRU

HRU	F* [mm/d]	D* [mm/d]	C* [mm/d]	S_B* [mm]	K_O [1/d]	K_G [1/d]	S_G [mm]	Total area [m²]	Drained area [m²]
Base	103.2	1.36	2.0	100	0.005	6.2^{E}-4	160	33,973,992	-
Shallow	55.2	1.42	2.2	100	0.006	6.2^{E}-4	60	22,575,199	13,129,375
Brook Valley	103.2	1.37	2.0	95	0.007	7.0^{E}-4	160	7,434,901	2,215,000
Podzol	71.4	1.37	2.0	90	0.006	6.2^{E}-4	160	33,928,257	12,575,625
Geest	103.2	1.23	1.8	100	0.006	6.2^{E}-4	160	8,410,991	-
Outwash Plain	103.2	1.23	1.8	110	0.005	6.2^{E}-4	160	7,657,354	2,273,750
Human	24	1.365	2.0	100	0.007	6.2^{E}-4	160	5,776,271	-

The infiltration capacity F* has been obtained from Berhanu, Melesse, & Seleshi (2012), based on the loam content and then tweaked a little by lowering the capacity in areas with a large compaction. The maximum capillary rise per day is obtained from research from Brady & Weil (2008) and is compared to the sand, loam and clay content of each HRU. The values maximum soil moisture content S_B* have been determined based on a base scenario of 100 mm and adding or subtracting storage capacity based on compaction levels and organic matter contents. The last main point of Table 23 is the groundwater storage. The Shallow HRU has a small storage, relative to the variation differences in Appendix D (only 60 centimetres variation). The remaining parameters have been used to fit the model to the measured data. The values that do not differ in each HRU are $\alpha = 0.4$ [-], $n_0 = 1.6$ [-], $S_B = 30$ [mm] and $S_O = 25$ [mm].

The last of the column of Table 23 already indicates the existence of drainage in several HRUs. The base situation on which the model is calibrated does not contain much drained area, hence it was not incorporated in the base model. However, the amount of drainage in some of the areas is that large

(>30% of the total area, see Table 4) that this factor may not be neglected in modelling the areas, as this draining of plots of land has a large impact on the discharges of a system. Therefore, for the four areas with a larger amount of drainage than 30% of the total area, drainage will be included in the current situation of the hydrological system of the area. This is done by setting a limit on the maximum amount of groundwater storage. An example is given in Figure 25. This example shows the groundwater storage before and after implementing drainage in Brook Valley. The drainage level has been determined to be 147 mm, every drop of water above this groundwater storage level immediately gets discharged to the total discharge.

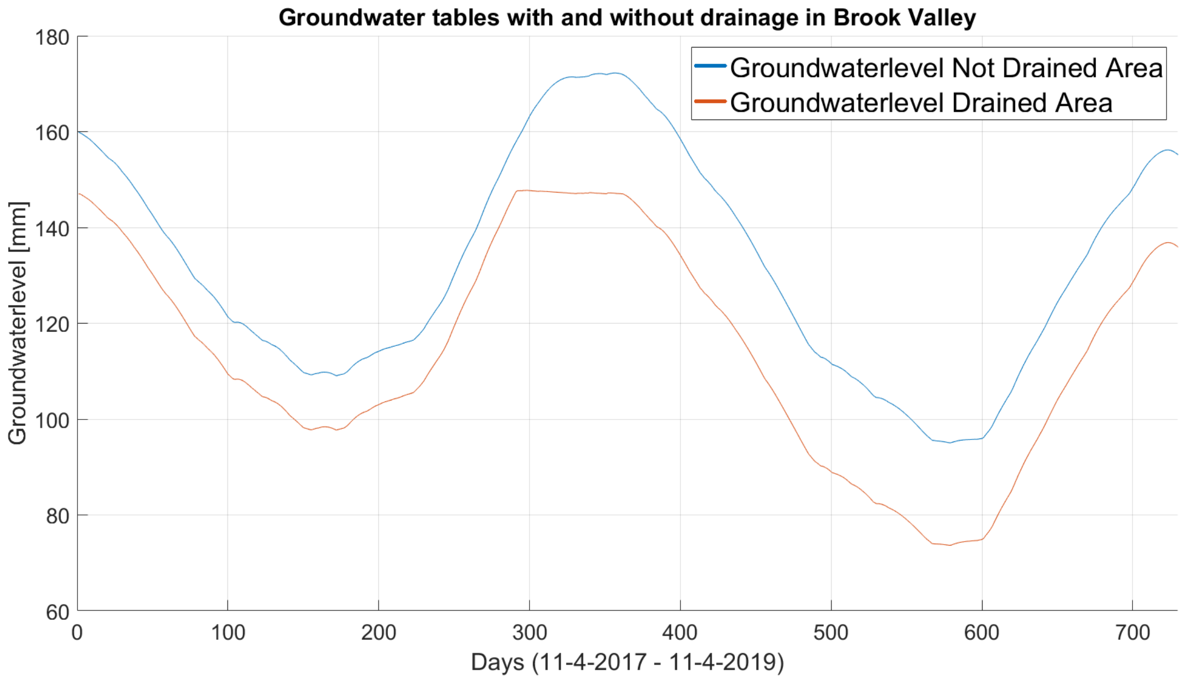

Figure 25 - Groundwater tables with and without drainage in Brook Valley

The drainage level for each of the HRUs has been determined to be located around 2/3rd of the storage peak, as this is the usual level of the groundwater fluctuation at which drainage is located in the area (Vitens, 2020b). The drainage level in this location is visible as around 2/3 of the natural curve, the groundwater levels tend to go straight. Note that the summer of 2018 was so dry, that the drainage level was not even reached in the winter of 2019, in this area. It is assumed that this resembles reality, as the precipitation deficit was that large during 2019, that this could be true. In other areas, the drainage level was reached, this one stood out. The exact drainage level for each HRU is given in Table 24.

Table 24 - Drainage level for the HRUs in which drainage will be modelled

HRU	Drainage level [mm]
Shallow	47.75
Brook Valley	147
Podzol	145
Geest	-
Outwash Plain	145
Human	-

The Geest HRU and the Human HRU have too little drained area to completely take this into account, also do these two areas not have measures that affect drainage in the area, hence it not being beneficial to implement drainage in the models of these areas. This drainage is implemented in the area that is known to be drained, so only in the amount of drained area from Table 23, the rest of each HRU will be considered as a natural acting system.

Now onto the measures. For each HRU, the model changes for each measure will be elaborated. First, the Shallow area. In the drained area of this HRU, controlled drainage must be implemented in the model. As the effects of controlled drainage are like removing drainage, as the water does not get discharged as fast, this measure is implemented as removing the drainage in the drained area and therefore creating an area that has the size of the total area HRU, without any drainage. The next measure was improving the soil structure. The infiltration factor F* has increased one factor, to a maximum infiltration capacity 103.2 mm/d, to account for the removal of compaction. The improved organic matter content of the soil is accounted for by adding the increase in retention capacity in the unsaturated zone that is calculated in Appendix G. The last measure for the Shallow HRU is implemented by changing the evapotranspiration factors. It is assumed that a quarter of the complete area could be transformed from a vegetation that evaporates earlier in the year. The decision was made to make the transition from corn to grain. The evaporation factors for half of the area changed as in Table 25.

Table 25 - Evaporation factors corn and grains (Hydromedah, 2020)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Corn	0	0	0	0	0.5	0.9	1.2	1.2	1.2	0	0	0
Grain	0	0	0	0.7	1	1.2	1.3	0.6	0	0	0	0

First, the part of the evaporation data in De Bilt that can attributed to the quarter of the area that is assumed to be corn (denominator in Equation 13). After that, this quarter is replaced by the amount of evaporation that grain would have on that day. The potential evaporation after implementing new crops is calculated with Equation 13.

$$E_{landuse} = \frac{E_{currently} \cdot (\frac{3}{4} \cdot T_{factorgrass} + \frac{1}{4} \cdot T_{factorgrain})}{\frac{3}{4} \cdot T_{factorgrass} + \frac{1}{4} \cdot T_{factorcorn}}$$

Equation 13

$E_{landuse}$ is the amount of evaporation after changing the land-use in ¼ of the project area [mm/d]
$E_{currently}$ is the amount of evaporation as measured in De Bilt (the base scenario in the model) [mm/d]
$T_{factorgrass}$ is the transpiration factor of grass (always 1) [-]
$T_{factorcorn}$ is the transpiration factor of corn [-]
$T_{factorgrain}$ is the transpiration factor of grain [-]

For every day of the year, this transition into a new amount of potential evaporation is calculated. This new potential evaporation is implemented in the model. The results are shown in Figure 26, the discharge in the current situation in the Shallow HRU is shown and the discharges after implementing controlled drainage, improving soil structure and the change of land-use.

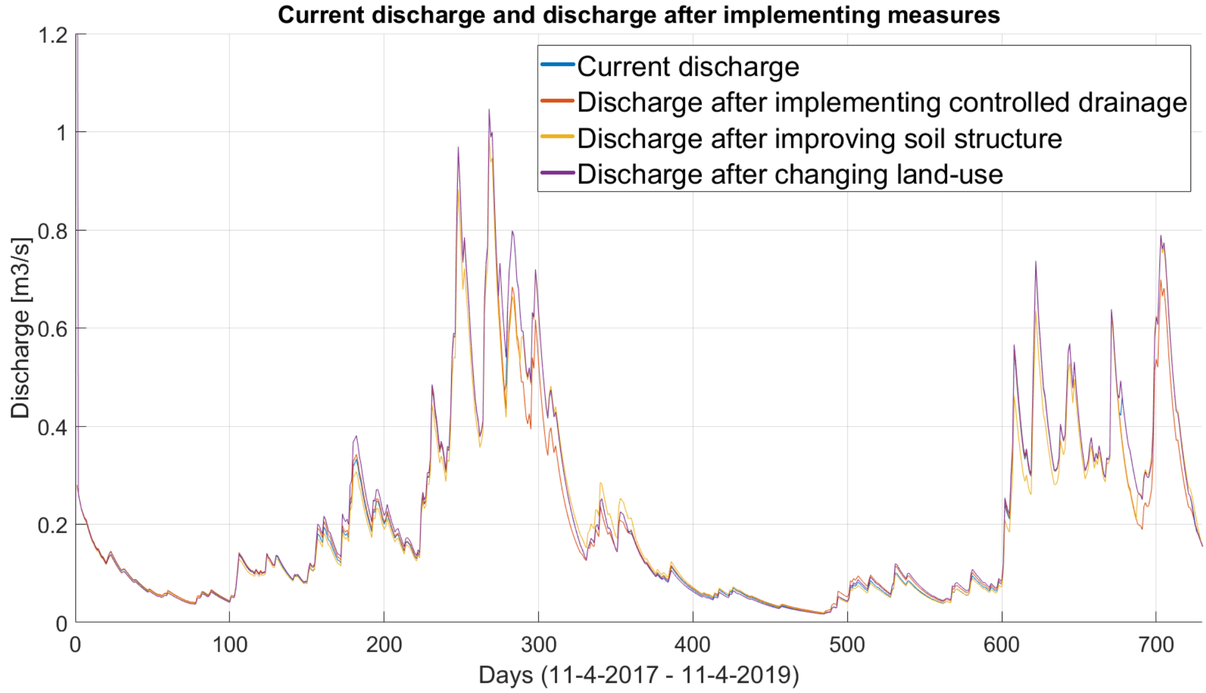

Figure 26 - Current discharge and discharge after implementing discharge in Shallow HRU

This way of visualizing can be confusing. Therefore, Figure 27 is created, which shows the absolute difference between the current situation (y=0) and after implementing measures.

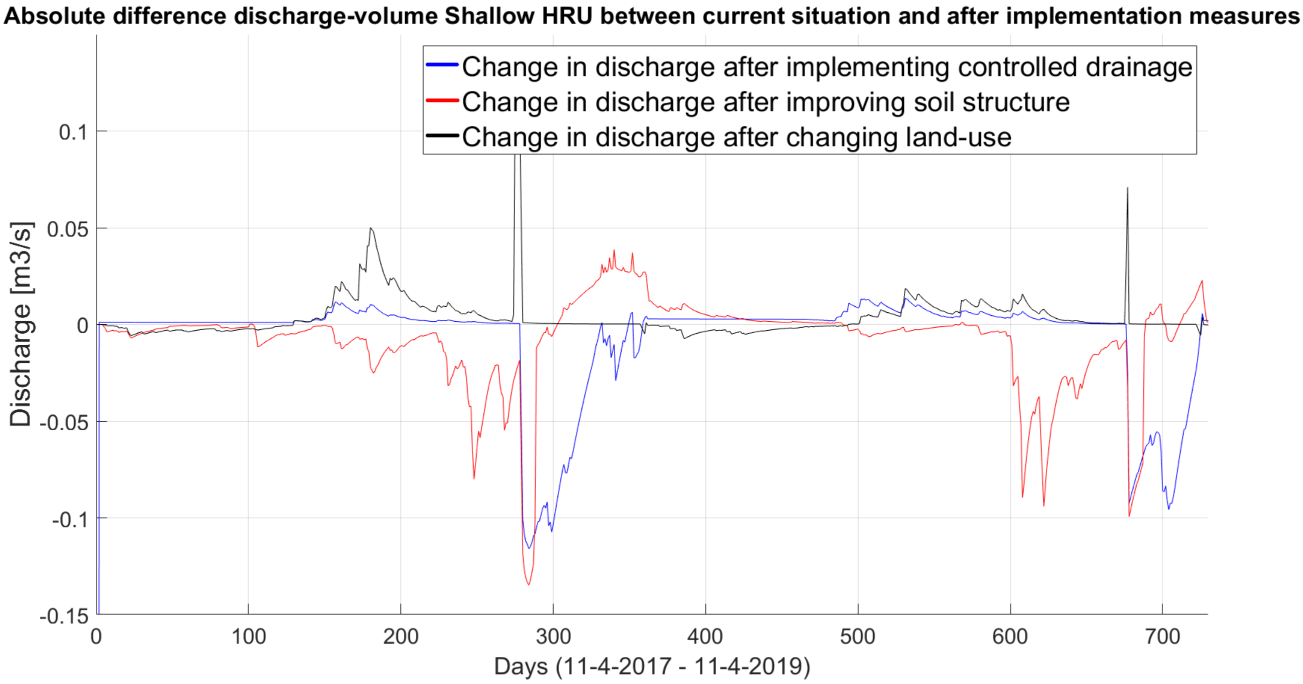

Figure 27 - Absolute difference discharge-volume Shallow HRU between current situation and after implementation measures

This figure gives a little more insight, but in order to visualize the results in a coherent way, the change in discharges will be given in percentages of the current discharge in Figure 28.

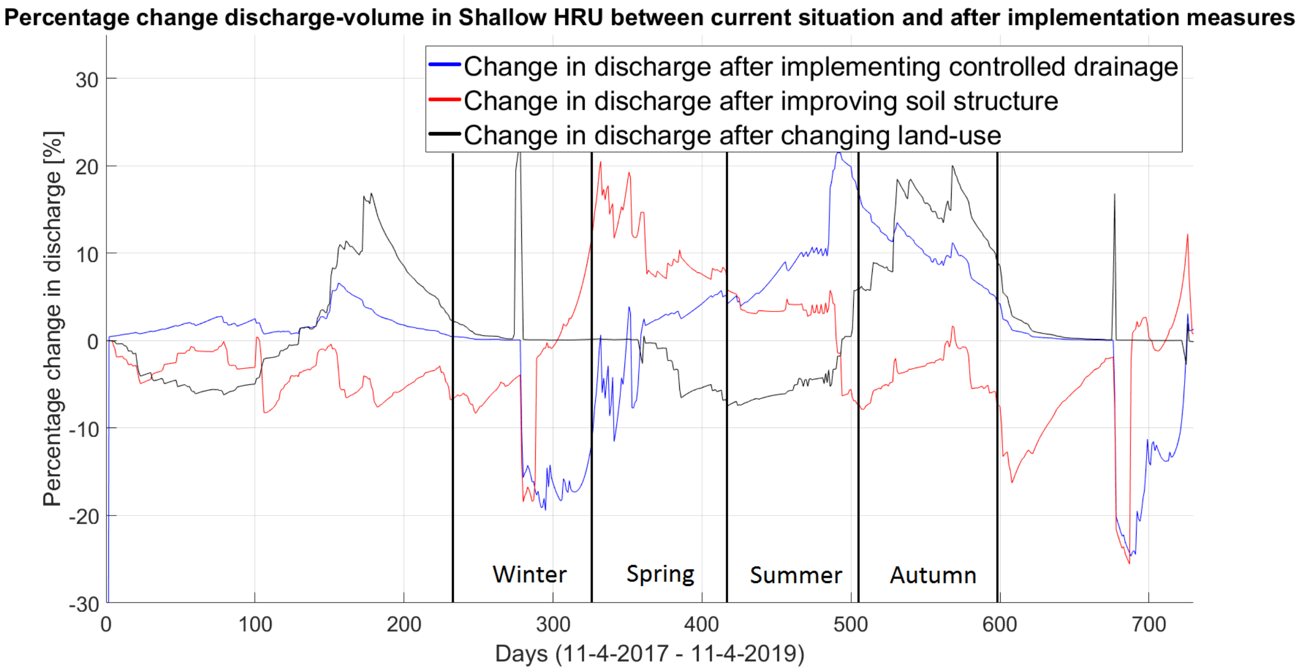

Figure 28 - Percentage change discharge-volume in Shallow HRU between current situation and after implementation measures

Although the absolute increases in discharges during the summer months may be small, the discharge may increase by quite a large margin compared to the situation before any measures were implemented. In order to make the results comparable, the average increase/decrease in percentages will be given for each measure for each HRU per season of 2018, the exact dates that will demarcate the boundaries of the seasons that are shown in Figure 28 are listed in Table 26.

Table 26 - Exact dates seasons

	Winter discharge	Spring discharge	Summer discharge	Autumn discharge
Dates	1 December 2017 – 28 February 2018 (Days in graph: 235-324)	1 March 2018 – 31 May 2018 (Days in graph: 325 – 416)	1 June 2018 – 31 August 2018 (Days in graph: 417 – 507)	1 September 2018 – 30 November 2018 (Days in graph: 508 – 597)

For each measure, the bandwidth of the results will also be given minimum and/or maximum increase/decrease will also be given in the results. The bandwidths will be given per season, to get an idea of the effects over the year. The results for the Shallow HRU are given in Table 27.

Table 27 - Effects measures on discharge Shallow HRU (average and between brackets are the bandwidths)

	Winter discharge	Spring discharge	Summer discharge	Autumn discharge
Controlled drainage	-8% (0% | -19%)	0% (+6% | -14%)	+10% (+22% | +4%)	+10% (+16% | +5%)
Soil structure	-4% (+9% | -18%)	+11% (+21% | +7%)	+2% (+8% | -8%)	-4% (+2% | -8%)
Changing land-use	+2% (+23% | 0%)	-2% (+1% | -7%)	-4% (+6% | -7%)	+13% (+20% | +6%)

The results in the main report only show the average increases/decreases. The second HRU, Brook Valley, has four measures. As in the Shallow HRU, the effects of removing drainage can be calculated by creating a situation without drainage and comparing that to the current situation. The second measure for this HRU is also the improvement of soil structure, in this area this will be completely rely on the improvement of the organic matter content. The calculated values for the increase of retention capacity in the unsaturated zone of the soil will be used from Appendix G and added to the maximum soil moisture S_B*. Next to that, the effects of the increase in riverbeds and the increase of weir levels will be determined by adjusting the reservoir constant k_O, as the measures affect the speed at which water gets discharged. In Appendix G, it became clear that weirs have a larger effect, this will also be used in this part of the analysis, hence the k_O value for the weirs will change by a larger factor (k_O = 0.006) than this factor for the raise of riverbeds (k_O = 0.0065). The results of the measures are shown in Table 28.

Table 28 - Effects measures on discharge Brook Valley (average and between brackets are the bandwidths)

	Winter discharge	Spring discharge	Summer discharge	Autumn discharge
Removal of drainage	-3% (0% | -10%)	0% (+4% | -5%)	+2% (+4% | +1%)	+1% (+2% | +1%)
Soil structure	-2% (3% | -10%)	+3% (+6% | -1%)	0% (+2% | -4%)	-1% (0% | -3%)
Riverbed	0% (+3% | -3%)	+2% (+8% | -1%)	+1% (+2% | -2%)	0% (+2% | -2%)
Weirs	+1% (+7% | -6%)	+3% (+8% | -1%)	+2% (+4% | -5%)	0% (+4% | -5%)

The Podzol HRU also has the measures controlled drainage and the improved soil structure. These two are implemented in the model in the same way as the Shallow and the Brook Valley HRU. Just as in the Brook Valley, the raise of riverbeds will be calculated in this HRU. This time, the k_O value shifts to 0.0055. The results are given in Table 29.

Table 29 - Effects measures on discharge Podzol (average and between brackets are the bandwidths)

	Winter discharge	Spring discharge	Summer discharge	Autumn discharge
Controlled drainage	-4% (0% | -12%)	+1% (+5% | -7%)	+3% (+5% | +2%)	+2% (+3% | +1%)
Soil structure	-4% (+6% | -13%)	+8% (+15% | +3%)	0% (+5% | -8%)	-3% (+1% | -8%)
Riverbed	0% (+4% | -4%)	+2% (+5% | 0%)	+1% (+3% | -3%)	0% (+2% | -3%)

The implementation of improving soil structure in the Geest HRU is equal to the implementation in the other HRUs. The raising of riverbeds is modelled as a decrease in k_O value of 0.0005 to a value of 0.0055. The implementation of percolation trenches is expected to increase the retention time of surface water even larger, so the k_O value is decreased to 0.005 for the calculations of the effects of percolation trenches.

Table 30 - Effects measures on discharge Geest (average and between brackets are the bandwidths)

	Winter discharge	Spring discharge	Summer discharge	Autumn discharge
Soil structure	-2% (0% | -4%)	+3% (+5% | 0%)	0% (+3% | -4%)	-2% (0% | -4%)
Riverbed	0% (+4% | -4%)	+2% (+5% | 0%)	+1% (+2% | -3%)	0% (+2% | -2%)
Percolation trenches	+1% (+9% | -7%)	+5% (+10% | 0%)	+3% (+5% | -5%)	-1% (+4% | -5%)

The effects on the Outwash Plain are given in Table 31. The calculation of the effects of controlled drainage is again done by creating a new HRU with the same characteristics, but without the drainage. The implementation of weirs is done by decreasing the value of k_O by 0.001.

Table 31 - Effects measures on discharge Outwash Plain (average and between brackets are the bandwidths)

	Winter discharge	Spring discharge	Summer discharge	Autumn discharge
Controlled drainage	-2% (0% | -8%)	0% (+4% | -7%)	+2% (+3% | +1%)	+1% (+2% | +1%)
Weirs	0% (+10% | -9%)	+6% (+12% | +1%)	+4% (+7% | -5%)	-1% (+4% | -5%)

In the Human HRU, only the effects of percolation trenches must be calculated. Not only does the k_O value decrease in this area (k_O = 0.005), but the infiltration rate does also increase dramatically. Once (a part of) the paved area makes way for percolation, the maximum infiltration capacity of the area will increase from F*=24 mm/d to F*=103.2 mm/d.

Table 32 - Effects percolation trenches on discharge Human (average and between brackets are the bandwidths)

	Winter discharge	Spring discharge	Summer discharge	Autumn discharge
Percolation trenches	+2% (+17% | -13%)	+8% (+20% | -1%)	+5% (+10% | -10%)	-1% (+8% | -9%)

Appendix I – Discharges combination measures each HRU

The measures that are either deemed effective at battling discharge problems or the groundwater problems are listed for every HRU in Table 33. The effects of a combination of the measures will now be determined. This Appendix shows the effects of the combinations per HRU, Appendix J shows the effects for the complete project area.

Table 33 - Effective measures for each HRU

Shallow	Brook Valley	Podzol	Geest	Outwash Plain	Human
Controlled drainage Improved soil structure	Raising weir levels	Controlled drainage Improved soil structure	Raising riverbeds	Controlled drainage Raising weir levels	Percolation trenches

The effects of the combinations on the discharge of the different HRUs is calculated per day and shown in Figure 29. The results indicate the effects of the measures in a percentage difference compared to the current discharge of each HRU.

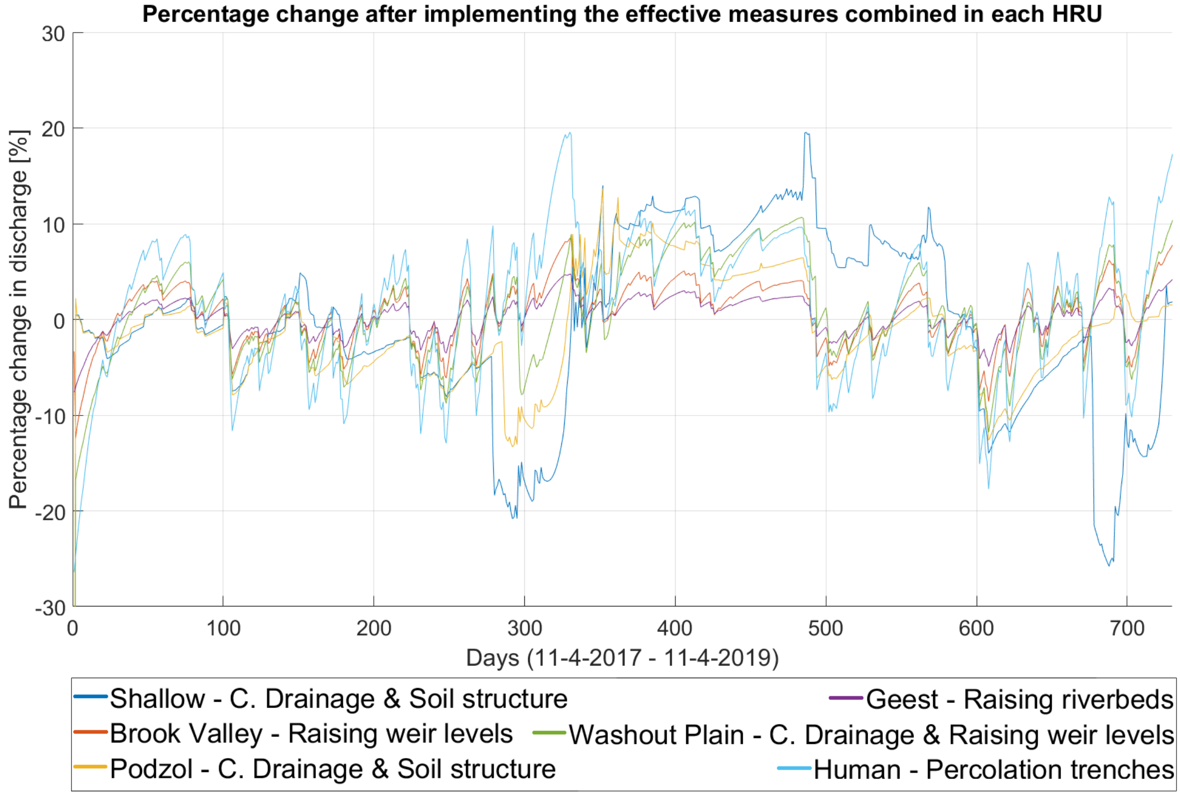

Figure 29 - Percentage change after implementing the effective measures in each HRU

Based on the results, the average seasonal effects on the discharges can be determined. The same dates for the seasons are used as in Appendix H, see Table 34.

Table 34 - Exact dates seasons

	Winter discharge	Spring discharge	Summer discharge	Autumn discharge
Dates	1 December 2017 – 28 February 2018 (Days in graph: 235-324)	1 March 2018 – 31 May 2018 (Days in graph: 325 – 416)	1 June 2018 – 31 August 2018 (Days in graph: 417 – 507)	1 September 2018 – 30 November 2018 (Days in graph: 508 – 597)

The average, maximum and minimum effects of the combination of effective measures per season per HRU are given in Table 35.

Table 35 - Effects combination of effective measures per HRU per season (average and between brackets are the bandwidths)

	Winter discharge	Spring discharge	Summer discharge	Autumn discharge
Shallow HRU [CoDr&SoSt]	-12% (-4% | -21%)	+7% (+14% | -14%)	+6% (+12% | -1%)	+6% (+12% | -1%)
Brook Valley [RaWe]	+1% (+7% | -6%)	+3% (+8% | -1%)	+2% (+4% | -5%)	0% (+4% | -5%)
Podzol [CoDr&SoSt]	-7% (-2% | -13%)	+7% (+14% | -5%)	+3% (+8% | -5%)	-1% (+2% | -6%)
Geest [RaRi]	0% (+4% | -4%)	+2% (+5% | 0%)	+1% (+2% | -3%)	0% (+2% | -2%)
Outwash Plain [CoDr&RaWe]	-2% (+5% | -9%)	+6% (+10% | -3%)	0% (+6% | -4%)	-2% (+5% | -9%)
Human [PeTr]	+2% (+17% | -13%)	+8% (+20% | -1%)	+5% (+10% | -10%)	-1% (+8% | -9%)

Appendix J – Total discharges after implementing measures

With all measures that turned out effective (listed in Table 33, Appendix I), the total difference in discharges after implementing measures could be determined. The discharges before and after implementing these measures are shown in Figure 30. The discharges of the current HRUs are added to obtain the current discharge in the project area, the total discharge after implementing measures is also added up by adding all discharges from the HRUs, after implementing the effective measures.

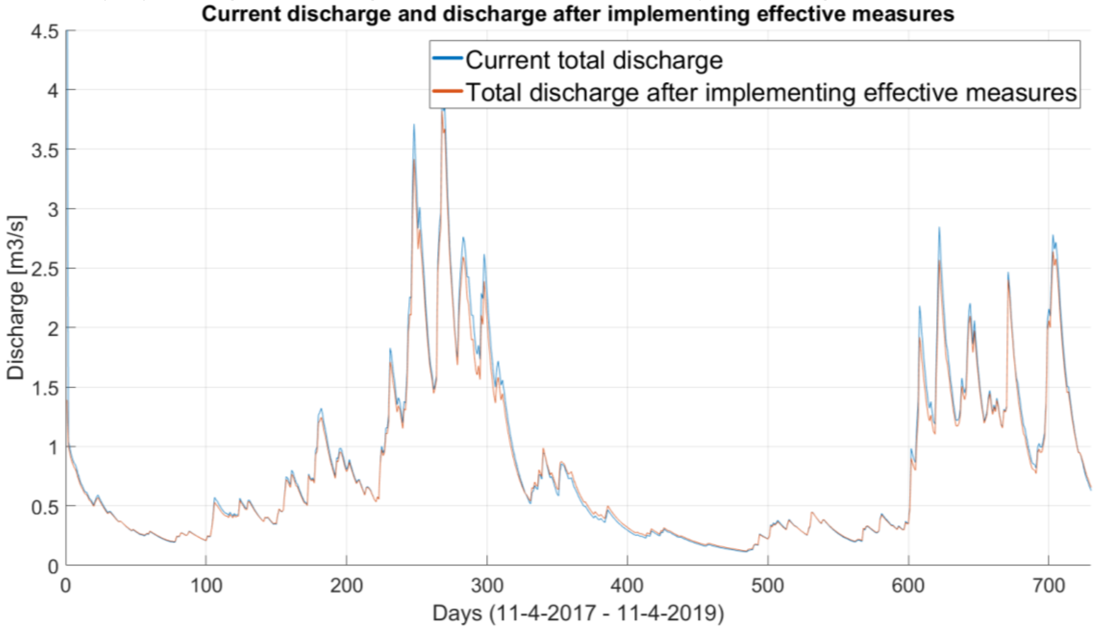

Figure 30 - Current discharge and discharge after implementing effective measures

The differences between both curves in Figure 31 are given in percentages in Figure 31.

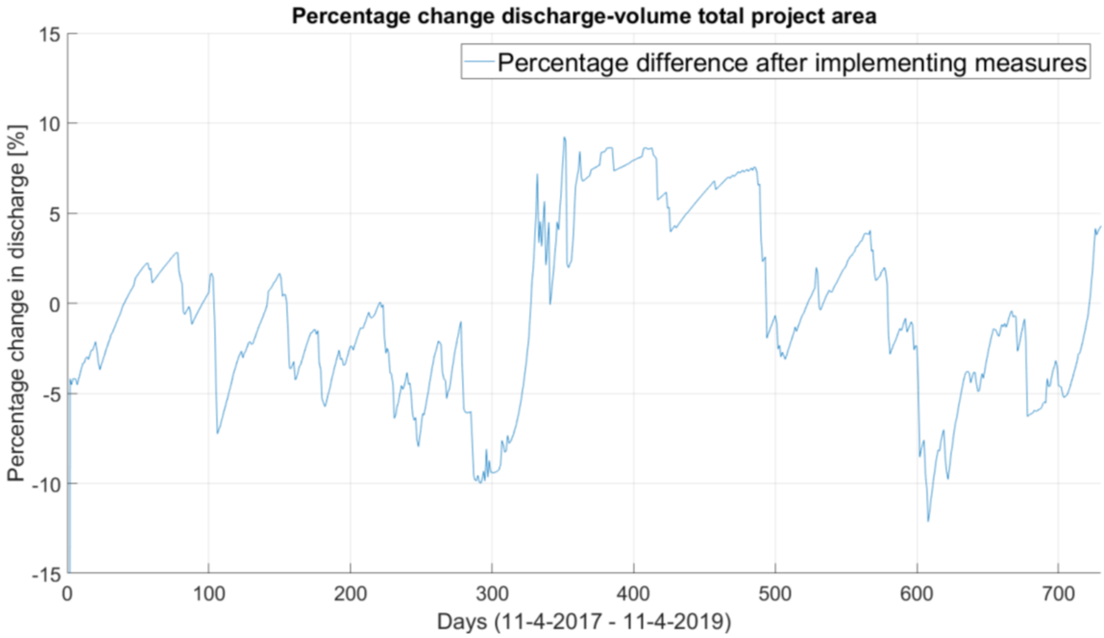

Figure 31 - Percentage change discharge-volume total project area

The averages per season are calculated and shown in Table 36.

Table 36 - Percentage changes discharge total project area, by implementing all effective measures in their suitable HRUs

	Winter discharge	Spring discharge	Summer discharge	Autumn discharge
All effective measures	-6% (-1% | -10%)	+6% (+9% | -3%)	+5% (+8% | -3%)	+1% (+4% | -3%)