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UNIVERSITY OF TWENTE.

Drought and groundwater

How the dry year 2018 affected the groundwater levels in the east of the Netherlands

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Responsibility

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Preface

This document is the final element of my bachelor Civil Engineering at the University of Twente. This research is carried out from April 2020 to June 2020 at consulting and engineering company Tauw in Deventer.

Prior to the research I did not know a lot about drought or groundwater but the topic intrigued me because of its lack of direct visibility. When rivers have a water shortage it can be seen directly by the eye, but for groundwater this is not the case. So when the time came to finish my bachelor, I looked for a company which is familiar with the topic. This company came in the form of Tauw.

During the research I have only been twice at the office in Deventer due to the COVID-19 outbreak. The first time at the office in Deventer, I collected my laptop. The second time I handed it back in. The period in between the research took place in my student room. Nevertheless, the contact with employees of Tauw was a fun experience through the meetings over Microsoft Teams and Skype and I found very welcome there.

I want to thank Tauw for providing room and guidance for my bachelor thesis. This goes with the gratitude for the interest and help in my research from the employees of Tauw. In particular I want to thank Rob Ligtenberg, Willem Capel and Ed Beije. Rob, as main mentor at Tauw, for helping me with getting to know Tauw, for answering all the questions I had on the topic and for guiding me in the right direction. Willem for his critical look at all my results and opening new directions to look into for the research. Ed for his help with processing data and his patience during that time when everything did not seem to work. Last but not least I want to thank dr. Ir. E.M. Horstman, also known as Erik, for his help as my UT supervisor. With his help this report became a scientific report I can be proud of.

Enschede, June 2020

Rob van Zee

Abstract

Water has always been a hot topic in the Netherlands. Historically the battle against water was mostly because of the excess of water. In the last few years the opposite is happening, there is a shortage of water. Consequences of this hydrological drought are for instance falling groundwater levels, damage to nature, and economic losses for agriculture. The goal of this research is to find out what the effects of the hydrological drought are on groundwater levels in the east of the Netherlands where the drought had major consequences.

The summer of 2018 was very dry, the precipitation deficit of that summer is estimated to occur only once every 30 years. This research focuses on the groundwater levels during that summer in three areas in the Netherlands with different soil compositions: a sand, peat and river area. The goal is to find out how dry the summer of 2018 was in terms of the lowering of the groundwater level. To do this the average of the three lowest groundwater levels of 2018 (LG3) is compared with the Mean Lowest Groundwater Level (MLGL) of the period 2010-2017. For each area, the LG3 of 2018 is found to be significantly lower than the MLGL of 2010-2017. The averages of the groundwater level lowering in 2018 compared to 2010-2017 are: -35 cm for the sand area, -22 cm for the peat area and -26 cm for the river area. The sand area shows large groundwater level drops that do not seem to be linked to the soil characteristics. The peat area contains a very dense peat colony and there the local groundwater level drop is on average 15 cm. In the river area, the groundwater level drops are relatively small, (except for in Nijmegen and the high sand grounds in the area) likely caused by groundwater level policies. The results show that other factors than precipitation and evaporation play a big role in the observed changes of the groundwater levels in the respective areas. Overall, the groundwater levels in the peat area are relatively stable due to the water retaining capacity of peat and the possible groundwater level policies in the area. A small peat colony next to Nijverdal (Wierdense Veld) has a significant groundwater drop in 2018 of more than 50 cm. This is alarming because peat needs high, stable groundwater levels to flourish.

For the sandy area, a relationship is found between the difference in groundwater level and the recurrence time of the observed groundwater level in 2018. The greater the groundwater level drop compared to the period 2010-2017, the longer the recurrence time. This pattern cannot be found in the peat area. There is not sufficient data available for the river area to draw conclusions about recurrence times in relation to the groundwater levels. The 2018 groundwater levels in the sand area have a recurrence time of on average 51 years and a median of 47 years. For the peat area, these recurrence times are respectively 91 and 48 years. This shows that the hydrological drought in 2018 has been more extreme for the groundwater levels in the sand and peat area than it was for the precipitation and evaporation (which had a recurrence time of 30 years).

The future will see more extreme weather. More rain in shorter periods of time with longer lasting droughts in between. The groundwater levels are expected to drop even further because of the longer lasting droughts while the water demand keeps rising. The computed recurrence time of the groundwater level of 2018 from this research will drop because the extremely low groundwater levels will be reached more often. The people of the Netherlands will have to adapt their water systems and water use to deal with the increasing problem of hydrological drought.

Samenvatting

Water is altijd een veelbesproken onderwerp in Nederland. Onze historie met water gaat meestal over een overschot van de vloeistof. De afgelopen jaren is juist het tegenovergestelde aan de hand, er is een tekort aan water. De gevolgen van deze hydrologische droogte zijn schade aan de natuur, dalende grondwaterstanden, economische verliezen, enzovoort. Het doel van dit onderzoek is erachter te komen wat de effecten van de hydrologische droogte zijn op de grondwaterstanden in het oosten van Nederland. In deze regio heeft de droogte grote consequenties gehad.

Volgens experts was de zomer van 2018 extreem droog. Het neerslagtekort wat die zomer is opgetreden komt naar schatting slechts één keer in de 30 jaar voor. Dit onderzoek focust zich op de grondwaterstanden van drie gebieden binnen Nederland: een zand-, veen- en rivier gebied. Het doel van dit onderzoek is om erachter te komen hoe droog de zomer van 2018 is met betrekking tot grondwater. Dit wordt gedaan door het gemiddelde van de drie laagste grondwaterstanden van 2018 (GL3) te vergelijken met de Gemiddeld Laagste Grondwaterstand (GLG) van de periode 2010-2017. Bij ieder gebied is gevonden dat de GL3 van 2018 significant lager is dan de GLG van de periode 2010-2017. De gemiddelde dalingen zijn -35 cm voor het zandgebied, -22 cm voor het veen gebied en -26 cm voor het riviergebied. In het zandgebied zijn grote dalingen te vinden die niet gekoppeld lijken te zijn aan de grondsamenstelling. In het veengebied zit een gebiedje met een zeer hoge veenconcentratie waar de grondwaterdaling gemiddeld -15 cm is. In het riviergebied zijn de grondwaterdalingen relatief klein (behalve bij Nijmegen en de aanliggende hoge zandgrond) en waarschijnlijk veroorzaakt door plaatselijk peilbeheer. De resultaten laten zien dat er meer factoren meespelen voor het geobserveerde grondwaterpeil dan alleen de neerslag en verdamping. Voor het veengebied kan gezegd worden dat de grondwaterstanden relatief stabiel zijn door het water vasthoudende veen. Een kleine veenkolonie naast Nijverdal (Wierdense Veld) heeft een significante grondwater daling in 2018 van maar liefst ruim 50 cm. Dit is alarmerend want veen heeft hoog, stabiel grondwater nodig om zich te ontwikkelen.

In het zandgebied is een verband zichtbaar tussen het verschil in de geobserveerde grondwaterstand en de herhalingstijd van 2018. Hoe groter het verschil in grondwaterstand, hoe groter de herhalingstijd. Dit verband is niet zichtbaar in het veengebied. Het riviergebied heeft niet genoeg data om daarover conclusies te kunnen trekken. Het zandgebied heeft een gemiddelde herhalingstijd van 51 jaar en een mediaan van 47 jaar. Voor het veengebied zijn deze getallen respectievelijk 91 en 48 jaar. Hieruit kan geconcludeerd worden dat de droogte in 2018 extremer was voor het grondwaterstand in het zand- en veengebied dan het neerslagtekort was (die een herhalingstijd heeft van 30 jaar.

In de toekomst zullen we te maken krijgen met meer extreme weersomstandigheden. Meer regen in kortere tijdsperiodes en langer durende droogte tussen deze regenbuien. De grondwaterstanden zullen naar verwachten nog verder wegzakken door deze langdurige droogte terwijl de vraag naar water toeneemt. De berekende grondwaterstand herhalingstijd van 2018 zal kleiner worden omdat extreme grondwaterstanden steeds vaker voor zullen komen. De Nederlands zullen hun watersysteem en hun watergebruik moeten aanpassen om deze hydrologische droogte het hoofd te kunnen bieden

1 Introduction

1.1 Context

Dry, drier, driest! Instead of the never-ending battle to keep the water out, the Dutch now must deal with a new water-related problem: the shortage of water. Summers in the Netherlands are becoming increasingly drier due to climate change (Pfleiderer et al., 2019). It comes with many consequences: falling groundwater levels, reducing agricultural yields, damage to nature, rotting of wooden pile foundations, acidification of the groundwater, loss in biodiversity, etc. The economic loss to the Dutch agricultural sector due to drought is expected to be enormous, from 700 million euros in a 'dry year' (with a frequency of occurrence of 1:10 years) to 1800 million euros in an 'extremely dry year' (a frequency of occurrence of 1:100 years) (OECD, 2014).

Drought is very often defined as precipitation deficit, which is the time accumulated difference between precipitation and evaporation. But this is only one of four categories of drought, namely, the meteorological drought. The other three categories are: agricultural drought, hydrological drought and socioeconomic drought (Wolchover, 2018). Agricultural drought occurs when crops do not get enough water for optimal growth. Hydrological drought refers to a lack of water in the hydrological systems which can be seen in low water levels in streams, rivers, groundwater and reservoirs (WIREs Water, 2015). Socioeconomic drought occurs when the demand of water exceeds the supply. The last one is becoming an increasing problem as the human population and its demands grow. For example, Melbourne has been captivated in socioeconomic drought for the past few decades (Mehran et al., 2015). When drought is mentioned in this research, it refers to hydrological drought because this research focusses on the lack of water below the surface. The effects of this can be seen in low groundwater levels.

Hydrological drought is highly visible in surface water such as reservoirs, rivers and lakes but is less visible in groundwater. Therefore, groundwater monitoring is in place to track ground water levels. This is important because groundwater is a major water resource in the Netherlands, 55% of the drinking water supply stems from groundwater. Agriculture and nature are heavily depending on groundwater too and if groundwater levels drop, foundations will be damaged and salination of the groundwater will occur in low-lying coastal areas (Centre for Climate Adaptation, 2020). High grounds without major surface water reservoirs are most at risk because in a longer period of drought, the water will flow to the lower laying areas and then there is no natural water supply to keep high groundwater levels (Centre for Climate Adaptation, 2020).

In recent years, a great deal of research has been conducted into the impact of climate change on our water system (Lenderink et al., 2011; Pfleiderer et al., 2019; Van den Hurk et al., 2014). The 4 different scenarios displayed in Figure 1 are pathways for development of the climate in the Netherlands until the year 2100. To date, most of these studies have been using model predictions. But the dry summers of 2018 and 2019 have provided us with valuable measurement data of potentially increasing effects of droughts on our water system. It is time to further analyse the measurement data from these summers and to use these observations to obtain a better understanding of the potential effects of future climate changes on our groundwater levels. To measure is to know!

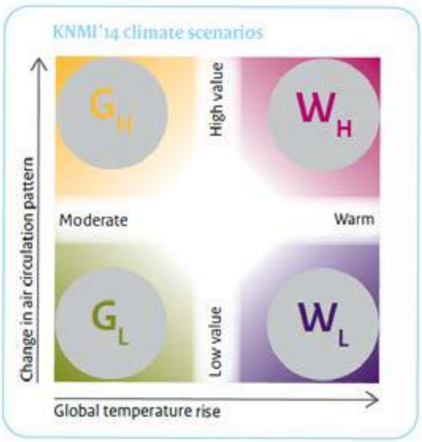

Figure 1, Climate scenarios for the Netherlands for 2100 (Van den Hurk, et al., 2014)

1.2 Problem definition

The droughts in the summers of 2018 and 2019 gave an example of what is to come under the increasingly extreme weather conditions due to climate change (Sluijter et al., 2018). Due to these droughts the Achterhoek and Liemers, areas in the east of the Netherlands, were experiencing severe drought and dropping groundwater levels. In fact, groundwater levels in these areas are still recovering of the shortage incurred in these summers (Waterschap Rijn en IJssel, 2020). At the time this research paper is written the precipitation deficit has already been higher than it ever has been (Figure 2). The drought helps wildfires spread and arise faster (NU.nl (a), 2020) and the KNMI has found a connection between the drought and climate change (NU.nl (b), 2020).

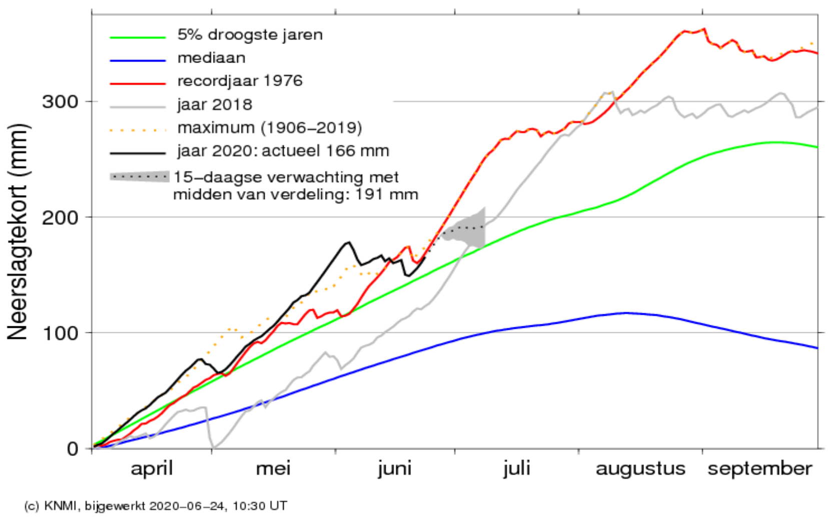

Figure 2: The precipitation deficit of the Netherlands averaged over seven station (the black line is the precipitation deficit of the year 2020, the grey line is the precipitation deficit of the year 2018) (KNMI (a), 2020)

Low groundwater levels have a large impact on the agricultural sector, the housing sector, nature and our everyday water use. If severe droughts hit us again, it will have large financial consequences on the agricultural sector and it will hit the nature around us by not having enough water to stay alive. These effects could possibly (partially) be mitigated if we do anticipate (OECD, 2014). Therefore, it is important to know the impacts of the climate on the groundwater levels and how often these low groundwater levels can be expected in the future. The question at hand is also whether the summers of 2018 and 2019 are representative of the dry summers from the Wh climate scenario for 2100, or whether things will be getting worse.

The repetition time of the drought of the year 2018 based on precipitation and evaporation data has already been determined by the KNMI. It has been calculated to have a repetition time of 30 years (Sluijter et al., 2018). This calculation uses weather stations from all over the Netherlands, so the 30 years is considered to be representative for the Netherlands. The repetition times of the associated groundwater levels might be different. Groundwater levels are more dependent on the local hydrological systems. For example, in a river system there is constant supply of water, while high sand grounds are depending on precipitation for their water supply. To date, it is not known what the effects of the drought of 2018 were on the groundwater level in different areas. To be prepared for droughts we need to know the intensity and scale of these effects.

1.3 Research aim and questions

The main aim of this research is to investigate the following question:

To what extent did the groundwater levels in sandy areas, peat colonies and river areas in the Netherlands change as a result of the dry summer in 2018 in comparison to the period 2010-2017?

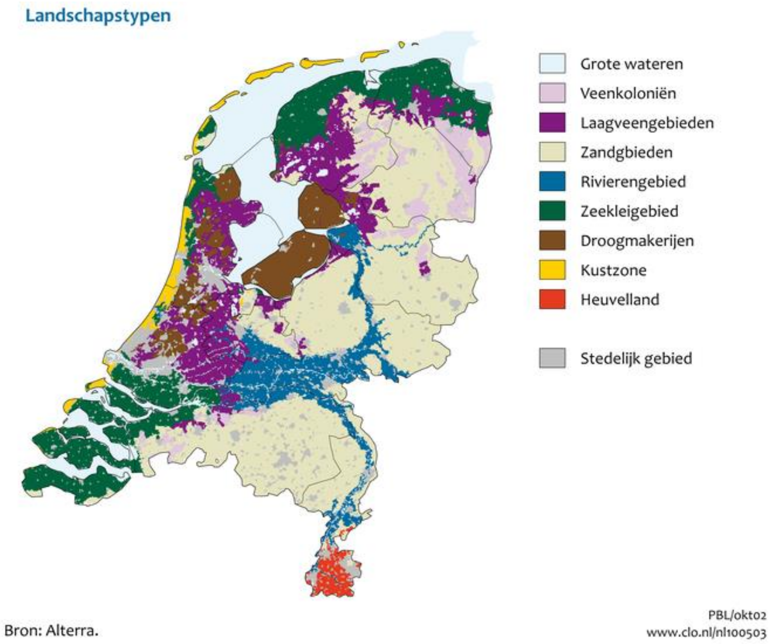

Figure 3, Landscape types in the Netherlands (Rijksoverheid, 2013)

From the research aim the following research (sub-)questions are constructed:

- *1: To what extent are the lowest measured groundwater levels in areas with different soil types for 2018 deviating from the period between 2010 and 2017?*
  - Is there a trend in observed groundwater levels over the period between the reference period 2010-2017 and the extremely dry year 2018?
  - Are there differences in the observed changes of the groundwater levels between the different soil types?
  - Can these deviating groundwater levels be linked to other properties of or policies in each of these areas?

- *2: What are the recurrence times of the measured groundwater levels in 2018 for the studied areas and what is the relation with the groundwater level difference between 2018 and the period 2010-2017?*
  - What is the current recurrence time for the precipitation and evaporation for the year 2018 based on data from the KNMI?
  - What is the current recurrence time of the observed groundwater levels for the years 2018 for each area?
  - What is the connection between the recurrence time of the precipitation and evaporation from the KNMI and the recurrence times of the observed groundwater levels?
  - What is the connection between the recurrence times of groundwater levels and the groundwater level difference between 2018 and the period 2010-2017?

1.4 Scope

The term groundwater refers to the water within the pore spaces in the ground. This is not all the water which is in the ground, but specifically the water in the unconfined aquifer: this is the uppermost permeable layer of the ground (Figure 4). For its water supply, this unconfined aquifer is dependent of rivers, lakes and precipitation which recharge the groundwater in the soil. This layer is often positioned on top of an impermeable layer that does not let water through. Beneath this for water impermeable layer a confined aquifer is found. Water in this zone is trapped and water movements in this layer are often very slow. This research does not focus on these confined aquifers because these are hardly affected by the seasonal variations that are under consideration.

The unconfined aquifer has an unsaturated and a saturated zone. The pore space in the unsaturated zone is mostly filled with air with only a few traces of water. In the saturated zone the pore spaces are completely filled with water (8). In between these layers is a transition zone from saturated to unsaturated and exactly that transition marks the groundwater level that is of interest in this research (Vonk, 2020).

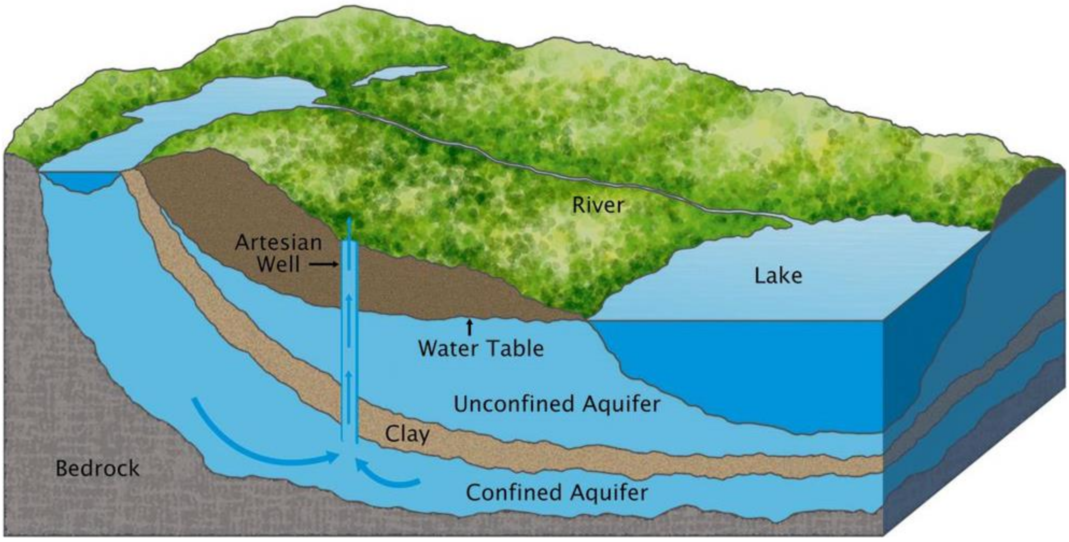

Figure 4: Confined and Unconfined Aquifers (Gunther, 2011)

In this research three pilot areas of approximately 15x15-kilometers (differs per area) with each a different hydrological system will be examined. These pilot areas will be a sandy area, a peat area and a river area. Each of these pilot areas will be selected to be a good representation of the general properties of that area type. The pilot areas are all situated in the east of the Netherlands. This area is selected because the drought has had the most impact in this area compared to the rest of the Netherlands.

For **sandy areas** with some height differences, the area around Denekamp is studied (Figure 5). This area is selected because the ground contains one of the largest sandy brook valley grounds of the Netherlands. Twenthe airport is included in this area because of the long historical data which might come in useful later in the research. The total study area for sandy ground is almost 20 x 30 km in extent. The large size of the area is due to the inclusion of Twenthe airport.

For the **peat area** the area north of Almelo is selected. This area is selected because there are a lot of peat colonies and there are multiple studies from Tauw going on in this area. Tauw also has close connections to local municipalities in this area and extra knowledge about it will help Tauw with giving advice in the future

The area selected for the **river type area** is mainly located along the rivers Meuse and Waal. This area is selected because of the availability of groundwater data in that area. It is also one of the most eastern river areas in the Netherlands which connects best with areas that suffered greatly from the drought. More information about the areas can be found in Appendix 2.

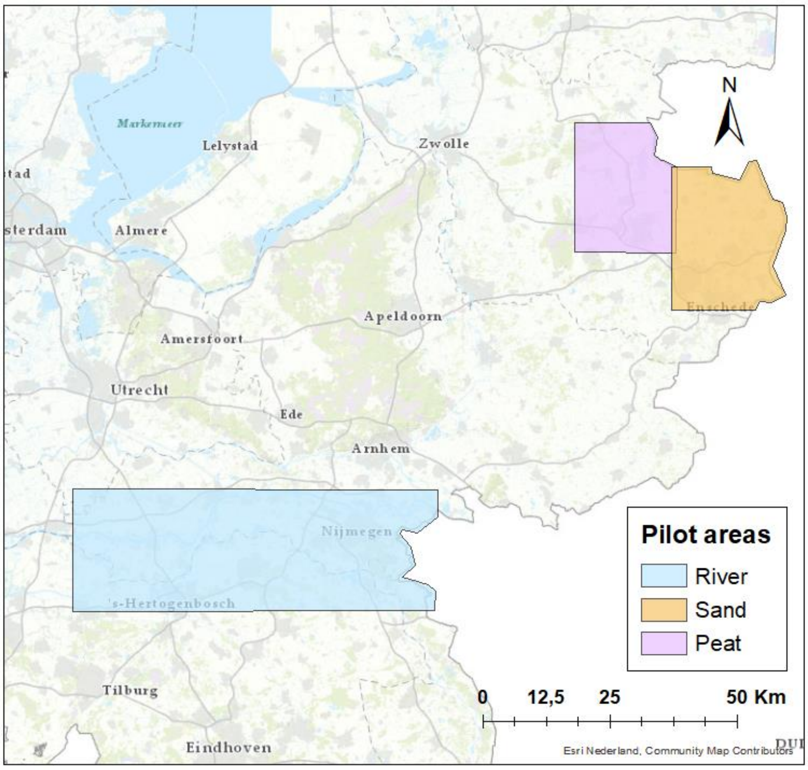

Figure 5: Research areas

This study is limited to a statistical analysis based on measurement data of groundwater levels retrieved from www.dinoloket.nl. This will be done to study the effects of the subsequent droughts on the groundwater levels in these areas. The data will cover the timespan of the period 2010 – 2018 for the analysis of the areas. A selection of measurement wells with long data series within the study areas will be used for defining recurrence times. The results of the research will be compared to data of the KNMI relating to drought and climate change with respect to the climate scenarios for the Netherlands.

2 Methodology

2.1 Analysing low groundwater levels

In order to quantify the changes of the (lowest) groundwater levels over time, measurement data of the groundwater levels in these areas is needed. From DINOloket.nl all available groundwater level data from 2010 to 2019 for the three study areas is requested. A method is selected to analyse the retrieved groundwater level data and data unusable for this research is excluded. The analysed groundwater level data contains coordinates to give a spatial overview of the data of groundwater levels.

2.1.1 Groundwater level data from DINOloket

DINOloket is a database that collects data of groundwater levels in the Netherlands. A lot of its data is coming from companies, governments agencies and citizens (TNO (a), 2020). Measurement wells within the three study sites were selected and data was obtained for the time period 2010-2019. An example of such a selection can be seen in Figure 6. The selected area covers the sand area and has a time span of 2010 to 2019.

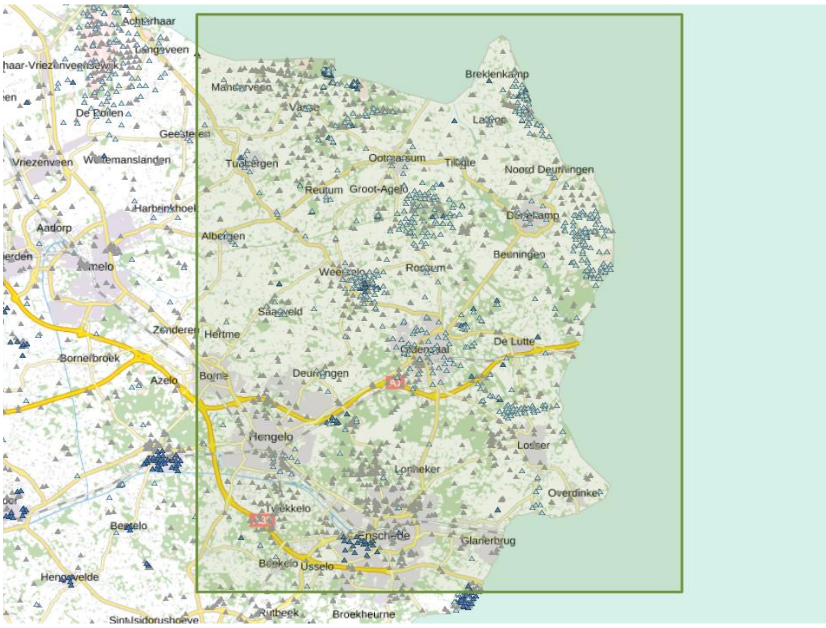

Figure 6: Selection in DINOloket of groundwater well data for the period 2010-2019

2.1.2 Selecting a method for the analysis of groundwater levels

In order to quantify the changes of the (lowest) groundwater levels over time a method must be applied to quantify the lowest groundwater levels in the study areas. The two methods considered are both incorporated in a tool created by geohydrologists working for Tauw. The first method is the calculation of the GxGL, the second method computes percentiles of the groundwater level occurrence. Both methods for the computation of groundwater level statistics use the time span of a hydrological year which year lasts from April 1st till March 31st.

The GxGL is a collective name for the Mean Highest Groundwater Level (MHGL), the Mean Lowest Groundwater Level (MLGL) and the Mean Spring Groundwater Level (MSGL). The method is developed in the 50s and 60s of the last century (Averink, 2013). At that time the groundwater levels were measured two times a month: on the 14th and 28th day of the month. It uses the data of these days for its calculations. To say compute the GxGL, measurements of the groundwater level are needed, preferably two times a month, from at least eight consecutive hydrological years (preferably up to 30 years).

The second method to quantify groundwater levels is based on exceedance frequency percentiles. It needs high-frequency measurements to be applicable, preferably once every hour. Taking the 90th percentile and the 10th percentile of the observed groundwater levels is a good approximation for the MHGL and the MLGL (Averink, 2013). One must be careful using percentiles because if the time-interval of the data varies, the percentiles will be biased towards the higher-frequency observations. The default MLGL procedure does deal with this problem by only using two measurements of each month, even when more measurements are available. The advantage of this method based on exceedance frequency percentiles is that it gives a good representation of the highest and lowest groundwater levels without requiring eight consecutive years of data. Very extreme incorrect data point are also less likely to influence the outcome because they will be in the top and bottom percentiles. This is useful because sometimes groundwater well data accidentally gives incorrect extreme values.

The longer time series and the variable frequency of the groundwater measurements in the period 2010-2018 make it inconvenient to apply percentiles in this research to give an approximation of the MLGL. Therefore, the GxGL method is used. The tool created by Tauw provides several options to determine the type of output, these settings can be found in section 2.1.3. The output must be studied and filtered according to the criteria described in section 2.1.4. After the filtering, the resulting groundwater level data is displayed in ArcGIS.

2.1.3 GxGL

Groundwater levels vary in time. To know how groundwater levels are changing over time groundwater time series are studied. From those measurements the GxGL can be calculated. The average of the three highest groundwater levels (HG3) and the average of the three lowest groundwater levels (LG3) in a year is computed and are used to calculate the MHGL (1) and MLGL (2), respectively (Sluijs, 1982). These ground water levels are typically provided with respect to the NAP (Amsterdam Ordnance Datum) reference level. So, the outcome is in meters above/below NAP if the number is positive/negative.

$$MHGL = \frac{1}{n}\sum_{1}^{n} HG3 \tag{1}$$

$$MLGL = \frac{1}{n}\sum_{1}^{n} LG3 \tag{2}$$

In order to obtain these GxGL values, processing of the available groundwater data requires a few steps that are programmed in a Python tool. These processing steps are summarized in the next sections.

2.1.3.1 Data selection

The tool makes use of the formulas (1) and (2). It uses the data measured on every 14th and 28th of the month. To decrease the chance that good data is discarded because it misses data on one of these days the tool is allowed deviate from these dates by a maximum of two days. So it has the ability to grab data from the 12-16th and 26-30th of every month.

2.1.3.2 Minimum data points per year

For the calculation of the GxGL there is looked at 24 groundwater level observations per year (two observations per month). To get the most reliable result only measurement series with all those 24 observations are included. But very often some points are missing in a year and then the HG3 and LG3 are not calculated. Because of this a lot of wells were discarded and a lot of data was not taken into account. When the minimum required number of observations per year is lowered to 20, it increases the amount of data points with almost 50% (from 1200 to 1766). When taken down to a threshold of 15 observations it increases the amount of data points with another 30% (from 1766 to 2330). After consultation with an expert at Tauw, a minimum threshold of 20 observations per year is deemed reasonable. In this way the number of data points is significantly increased and the chance of missing important points is low. When only considering 15 observations per year, it is possible to miss out on an entire season, rendering this threshold too low.

2.1.3.3 Differences

The last operation of the tool is the comparison of the LG3 of 2018 with the MLGL of the period 2010-2017. This will eventually show if the groundwater levels are higher or lower in 2018 in comparison to the period before. The MLGL for 2010-2017 is subtracted from the LG3's for 2018. This means that a negative number of the output indicates the groundwater level has gone down and vice versa. This will be called the 2018 difference.

2.1.4 Data filtering

Filtering of data is an important step to eliminate bad data from the analysis presented in the previous section. In addition to the filtering on the minimum threshold for the number of observations in the computation of the GxGL, a few more filters have to be applied to ensure the quality of the obtained results. The data is not filtered prior to the processing of the data because of the amount of time that would go into early filtering. Factors like missing data from a crucial summer month or limits in measurement depth of the wells are only visible when the groundwater level is plotted against time. All the factors taken into account for filtering are described in the section below. The timeseries will be displayed in Menyanthes, a program which displays the spatial layout and the measured groundwater levels of the measurement wells, and the following criteria will be used to manually assess whether the data will be rejected or included.

2.1.4.1 Start, end and minimum number of data years for MLGL

One of the weak points of the tool is that it computes a MLGL regardless of the number LG3's available. So it is possible it does calculations without data being available for all 8 hydrological years. Therefore the option is built in to look at the number of years taken into account to calculate a certain MLGL. When LG3's are available for less than 5 years, the data of the measurement well will not be used for further analyses.

All the measuring wells where the last data point is before 1 October 2018 will be rejected. This is done so the summer season of 2018 is included in the calculations of the LG3. Without the summer of 2018 there is no comparison possible and the data is not useful. The summer is very often the driest season and is therefore most important to include for the calculations of the LG3. Because there is no possibility of less than 5 consecutive LG3's the included measurement series must at least have started by 1 October 2013.

2.1.4.2 Limits of filters

The observed groundwater time series sometimes show an upper or lower limit; a groundwater level that it does not exceed. This shows limits of the filter of the groundwater well and therefore gives incorrect information about the groundwater level (Appendix 3). Figure 7 shows that the observed groundwater levels reached a limit in 2016. Such a (sudden) limitation is incorrect when determining the LG3 and therefore this data series is rejected. Such limits of the groundwater levels are often observed at wells with multiple filters. Sometimes there are up to five filters which have different measurement ranges. Some of these filters are positioned in the same well to measure different aquifers in the ground, but only one of them is needed for this study, the filter in the unconfined aquifer. More information on filters can be found inAppendix 3c. Including multiple filters for the measurement same well will disturb further analysis. Therefore the filter which displays data without any irregularities is selected and the others are discarded. Groundwater well filters that are beneath the unconfined aquifer are excluded from this research. This exclusion can be done with the help of the cross sections found in Appendix 2 by determining the depth of the unconfined aquifer. If it is not clear if the groundwater level filters are in the unconfined aquifer the filter closest to the ground level is selected because that is most likely the filter monitoring the unconfined aquifer layer.

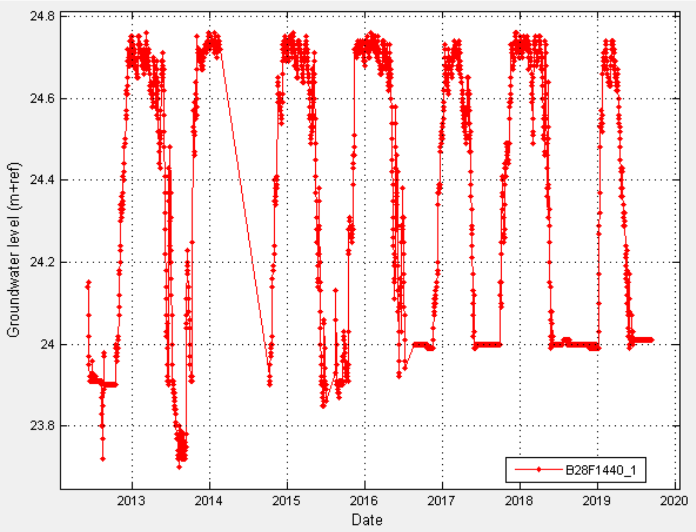

Figure 7: Boundary in groundwater level data (near +24.0 m NAP)

2.1.4.3 Lacking data continuity

When the groundwater time series is not continuous it cannot give a good representation of the MLGL because points are missing. An extreme example of this can be seen in Figure 8. This lack of data continuity will be largely filtered by the python tool but a second look is good in case it misses something. For example when the tool misses data of the month July or August. This is not filtered out because the groundwater level data misses only four LG3's which is not filtered by the tool (described in section 2.1.3.2). July and August are very important months for the calculation of the LG3 and without data of those month the lowest groundwater levels are very likely to not be part of the measurement data. In a case like that the groundwater well is rejected.

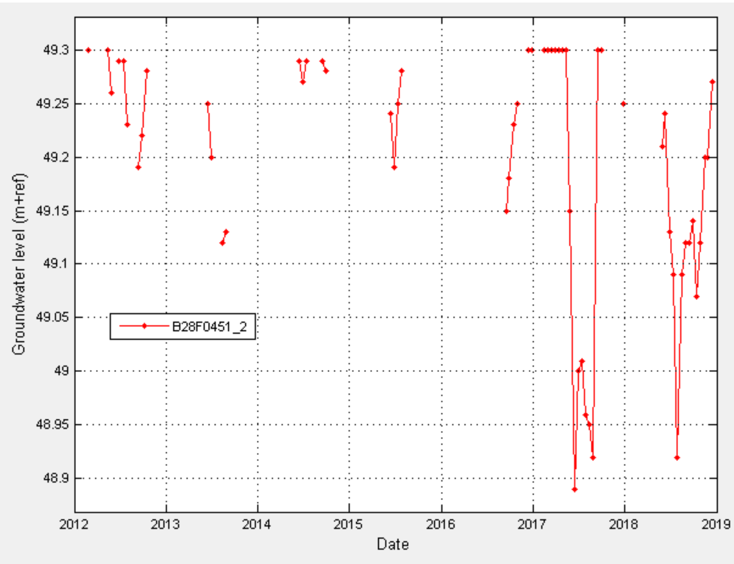

Figure 8: Non-continuous data of a groundwater measurement well

2.2 Recurrence time of drought

The drought of 2018 caused severe lowering of groundwater levels. To quantify how extreme these groundwater levels are, a time series analysis will be carried out to estimate the recurrence times. The data retrieved to compute the recurrence times is the same as described in section 2.1.1 except for the time span, which is now set at 1901-2020. When the groundwater level data is retrieved the irrelevant data must be discarded. The groundwater level datasets that are relevant are compared to historical precipitation and evaporation data with the help of the program Menyanthes. This program estimates how well the datasets correspond. If this correlation below a certain threshold the datasets will be rejected. The groundwater level data sets left will be used for a time series analysis with the precipitation and evaporation data from the nearest meteorological station. The output of this time series analysis then provides continuous groundwater level data (a combination of observations and reconstructions) from 1957 to present and is fit for calculations to determine the recurrence times. Figure 9 shows that the LG3 of the groundwater levels typically has a normal distribution. Because of this the cumulative distribution function can be used to determine the recurrence times of the obtained lowest groundwater levels.

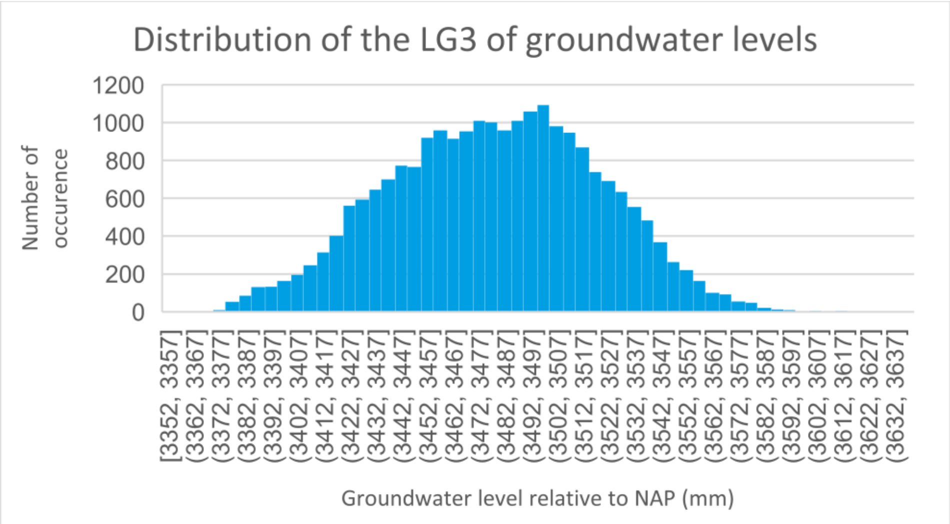

Figure 9: Distribution of the LG3 of groundwater levels for the period 1957-2018

2.2.1 Selection of measurement wells

In section 2.1 the data used focused on the period between 2010 and 2019. To say something about recurrence times a longer time span of groundwater data is more accurate. The longer the time span, the fewer groundwater levels have to be generated by Menyanthes. The minimum time scale of data used for the computation of recurrence times is 30 years. In DINOloket the maximum time span is used to get the maximum amount of data (1901-2020). Furthermore, these measurement wells must have:

- A continuous data set (no gaps larger than two years)
- A very long history (at least 30 years)
- No signs of deviating groundwater levels
- No direct link to one of the other selected measurement wells like filters on top of each other

If they do not meet these requirements the data will be rejected. All of this is done based on the visual representation of the groundwater level data. Because of this the filtering of the groundwater level data will, to a certain extent, be subjective.

2.2.2 Precipitation and evaporation series

The evaporation and precipitation data can be retrieved from multiple KNMI weather stations in the area. For example, in the sand area there are five stations that recorded precipitation. However, some of the data does not go back to the earliest measurements in the Netherlands or misses some data from the precipitation or evaporation on certain days. Both are compensated with data from the nearest station with available data. All the precipitation data is supplemented till 1951 because that is the most common data available of precipitation in the weather stations. It does not have to go further back because there is no data of evaporation available for before 1957. Therefore, this will be the maximum length of the time series models. So all models will have a range of 62 years.

Because not all precipitation and evaporation series are complete, Menyanthes cannot predict the groundwater levels for the full period. Therefore the incomplete series were combined with complete series from nearby weather stations. Table 1 shows which series downloaded from KNMI are used. If there is a blank in the column ‘Completed with…’ the dataset has no added data. When it is not blank the original data set has incomplete data and is completed with data of the nearest station. The name of the nearest station can be found in the third column.

Table 1: Overview of the used precipitation and evaporation series for the time series analyses

Area	Original dataset	Completed with…	Precipitation (P) or evaporations (E)
Sand	Weerselo	Denekamp	P
	Denekamp	Weerselo	P
	Enschede	-	P
	Hengelo	-	P
	Tubbergen	Weerselo	P
	Twenthe	Enschede	P
	Almelo	-	P
	Twenthe	De Bilt	E
Peat	Vroomshoop	-	P
	Almelo	-	P
	Hellendoorn	-	P
	Tubbergen	Vroomshoop	P
	Rheezerveen	-	P
	Holten	Hellendoorn	P
	Heino	De Bilt	E
River	Zaltbommel	Nuland	P
	Megen	Nuland	P
	Oss	Nuland	P
	Capelle (Nb)	-	P
	Andel	-	P
	Heumen	Nuland	P
	Tiel	-	P
	Geldermalsen	-	P
	Nuland	-	P
	Herwijnen	De Bilt	E
	Volkel	De Bilt	E

2.2.3 Similarity between groundwater levels and precipitation & evaporation

After the precipitation and evaporation datasets are completed, a model is fitted reconstructing the groundwater levels from the measurement wells based on the precipitation and evaporation data. The more the model reconstructions agree with the observed groundwater levels the higher the Explained Variance Percentage (EVP) of the model. So when a low EVP shows up, there are other factors outside the precipitation and evaporation series that cause the groundwater levels to deviate. An EVP above 70% is considered sufficient by the experts of Tauw. When the EVP is below 70%, the model will be rejected. A high EVP is needed because the precipitation and evaporation series will be used to reconstruct groundwater levels for in the period before groundwater data was available. If the model reconstructions for the groundwater levels do not fit the available data very well, the model also will not be very good at reconstructing the groundwater levels for the period before groundwater level data were available. Figure 10 shows the groundwater level data of measurement well B34F1314. It uses the precipitation and evaporation series of Twenthe. The precipitation and evaporation data have a fit of 89,2% with the groundwater observations and therefore the model this measurement well is fit for the groundwater time series reconstruction.

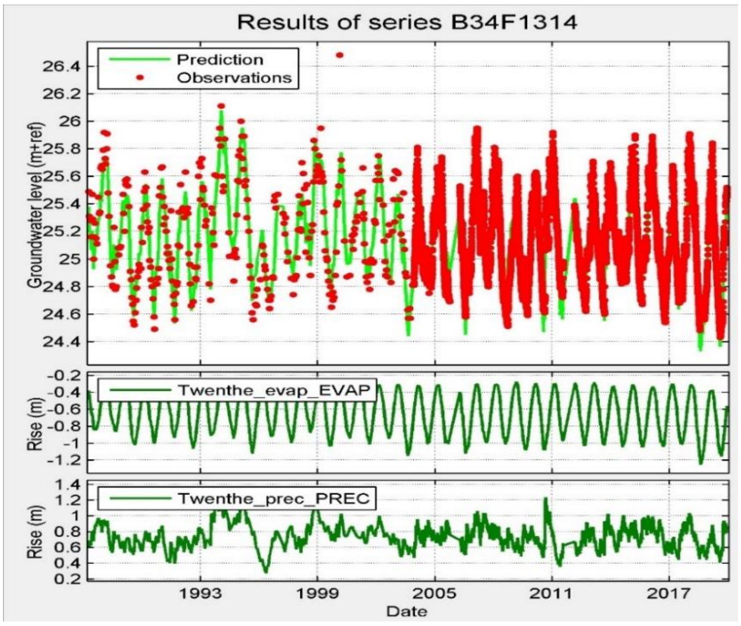

Figure 10: Groundwater level data with the predicted groundwater levels from precipitation and evaporation

To provide an estimate of how good the evaporation data fits the observations, an evaporation factor is generated by Menyanthes. This factor the evaporation data gets multiplied by this evaporation factor. Menyanthes estimates what the evaporation factor must be to give the best reconstruction of the observed groundwater levels. This factor varies because of the different evaporation rates of areas. For example, the evaporation factor is smaller in urban areas less than in areas with a lot of green due to the smaller evaporation possibilities. If this factor is below 0.5 or above 2 the data is not considered reliable by experts at Tauw. The same holds for a standard deviation greater than half the value of the parameter. In both cases the time series model of that particular well will be rejected. The evaporation factor of measurement well in Figure 10 is 1,22.

2.2.4 Groundwater time series reconstruction

In a time series analysis a long historical dataset of precipitation and evaporation will reconstruct groundwater level data with the help of models. Menyanthes will be used for the time series reconstruction of groundwater levels. Menyanthes uses the precipitation and evaporation data to reconstruct groundwater levels with a stochastic simulation. The groundwater level data from the groundwater well is used as main data and if in between the data is missing Menyanthes reconstructs the data points with a stochastic simulation. When using the stochastic simulation the original data will be used for the output and the missing data will be reconstructed. Menyanthes also has the built-in function to use the average of all the stochastic simulations. When the average of all stochastic simulations is used the original data gets overwritten. In this research the stochastic simulation is chosen because of the preservation of the original data, but because of the randomness of a stochastic simulation this part of the research cannot precisely be repeated. The stochasticity of the model will stay within certain limits so it will give similar results, but not the exactly the same.

If a groundwater well did not have data before a certain point in time, it will also reconstruct all the groundwater levels based on available precipitation and evaporation data. Figure 11 shows how this works. The red dots are original groundwater level data of measurement well B34F1314 and the green line is the reconstructed groundwater, based on the precipitation and evaporation data. The grey dotted lines show the 95% confidence interval of the reconstructed groundwater levels. When the reconstructed groundwater level (the green line) approaches a red dot the span of the confidence interval shrinks. In between the red dots the reconstructed groundwater level is based on information of precipitation and evaporation. Before 1987 there are no measurement data available and therefore the green line is based on precipitation and evaporation data only. The confidence interval gets much larger because for this period the model lacks the information of the regularly measured groundwater levels.

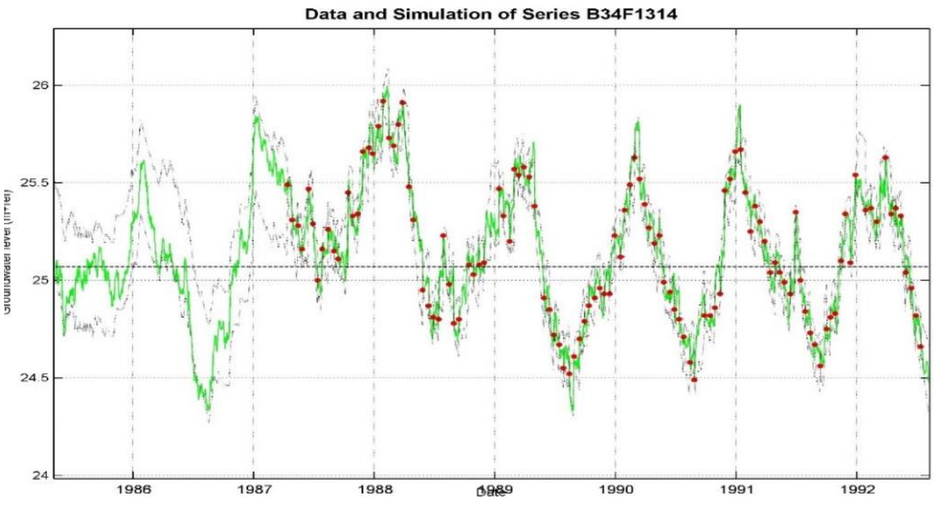

Figure 11: Time series model of measurement well B34F1314

Data that has an EVP above 70% and is inside the limits of the evaporation factor will be used (section 2.2.3). Because the precipitation and evaporation data have a good fit with the original groundwater well, reconstructions can be made of groundwater levels. The obtained groundwater level models are used to generate groundwater timeseries for every measurement well for the full period from 1957 to 2019 based on the available precipitation and evaporation data. The model simulates an expected groundwater level for each day. Because all simulations that are used for the reconstruction of the groundwater levels are random stochastic simulations this part of the experiment cannot be exactly repeated.

2.2.5 Computing recurrence times

To obtain recurrence times the LG3 of each year is needed for all reconstructed groundwater level timeseries. This can be done with the same method described in section 2.1.3. After the calculation of the LG3 for a monitoring well for each year, the recurrence times for the droughts of 2018 and 2019 can be computed. There are several methods to compute recurrence times which are described in Appendix 4. The method that is selected is for determining exceedance frequencies is based on the Cumulative Distribution Function (CDF). This method is chosen because of the normal distribution of the LG3's of groundwater level measurements (Figure 9). When the data set has a normal distribution the CDF can be used to obtain exceedance frequencies. This CDF is given by:

$$F(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} \exp\left(-\frac{(t-\mu)^2}{2\sigma^2}\right)dt \tag{3}$$

Where x is the stochastic variable, the groundwater level in this case, μ is the mean of the distribution and σ is the standard deviation (Matlab, 2020). This CDF uses the groundwater level data of a measurement well and returns the chance groundwater level is lower than a certain value.

The method describes the chance of a certain groundwater level being exceeded. To compute the recurrence time of the LG3 of 2018 the following formula can be used:

$$recurrence\ time = \frac{1}{F(x)} \tag{4}$$

The distribution of the data will look like displayed in Figure 12. The blue line shows the connection between the recurrence time and groundwater level. The LG3 of 2018 is represented by the dotted horizontal line. From the intersection of the two lines the recurrence time of the LG3 of the year 2018 can be derived (see the red dotted line in Figure 12). The recurrence time of the measurement well shown in Figure 12 is 5,7 years.

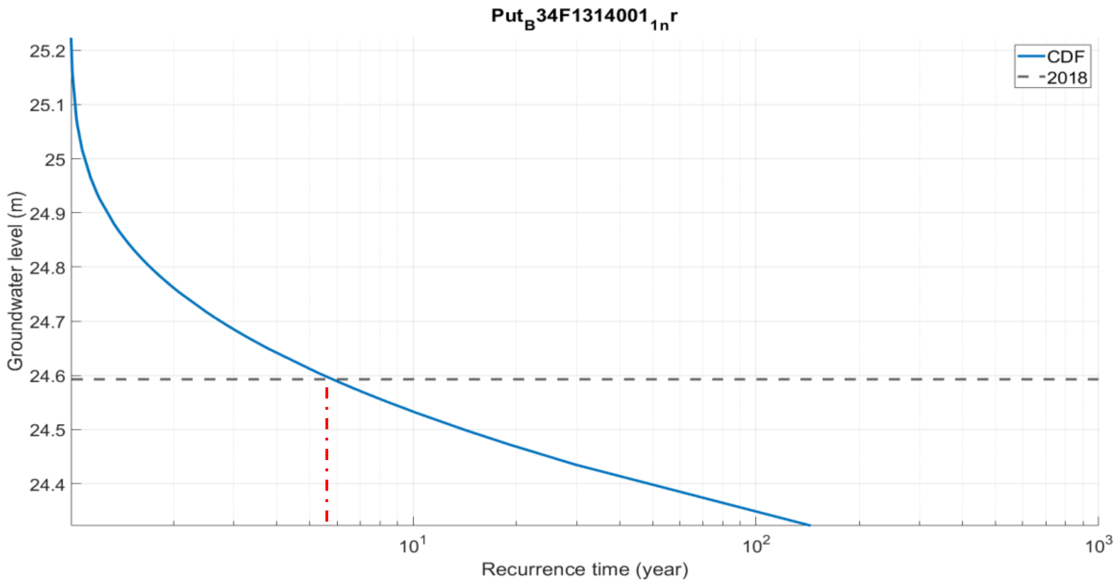

Figure 12: Visualisation of the recurrence times plotted against the groundwater level of measurement well B34F1314 with the use of the CDF

3 Results

3.1 Analysis of low groundwater levels

After processing the groundwater level data available in each of the study areas, the changes in groundwater level are displayed in the figures below. The difference between the LG3 of 2018 and the MLGL of the period 2010-2017 is compared. Groundwater level differences between -0,05 m and 0,05 m are deemed not significant differences by experts of Tauw and are therefore displayed white.

3.1.1 Drought in the sand area

Overall almost the entire area has significant lower groundwater levels in 2018 compared to the 8 years before. Figure 13 shows that the groundwater level changes range from a drop of 1,7 m to an increase just above 0 m. The distribution of dropping groundwater levels seem to be quite evenly spread throughout the area; there are no particular areas that show a substantial greater decline in groundwater level than others. The maximum 1,7 m drop of the groundwater level is located southeast of Oldenzaal. Other big groundwater level drop is 1,1 m.

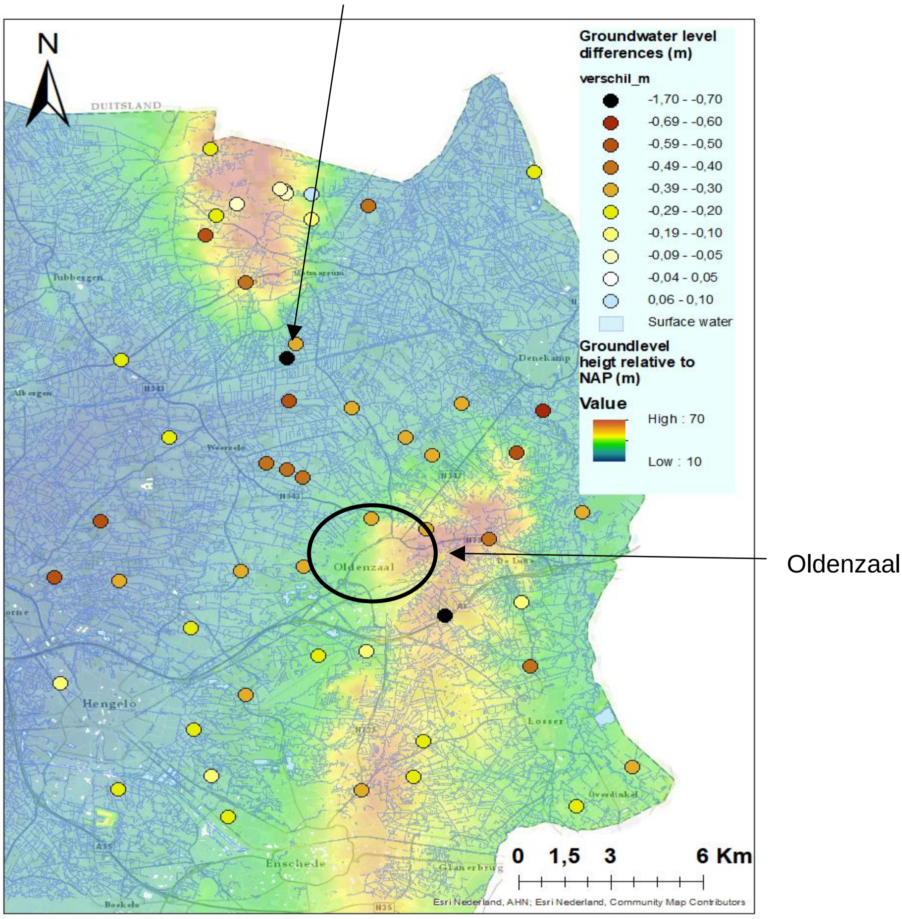

Figure 13: Groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 of the sand area on a height map

The soil map in Figure 14 (TNO (c), 2020) shows that podzol soils (light purple), loamy sand (brown) and brook valley grounds (green and light grey) are the most common soil types in the sand area. Multiple groundwater wells are placed in one of those three soil types. Figure 14 shows that there is no visible relation between the soil composition and the groundwater level differences. For example, the measurement wells in podzol soils show a groundwater level drop between 0,0 m to 0,6 m. The (Dutch) legend about the soil composition of Figure 14 can be found in Appendix 5.

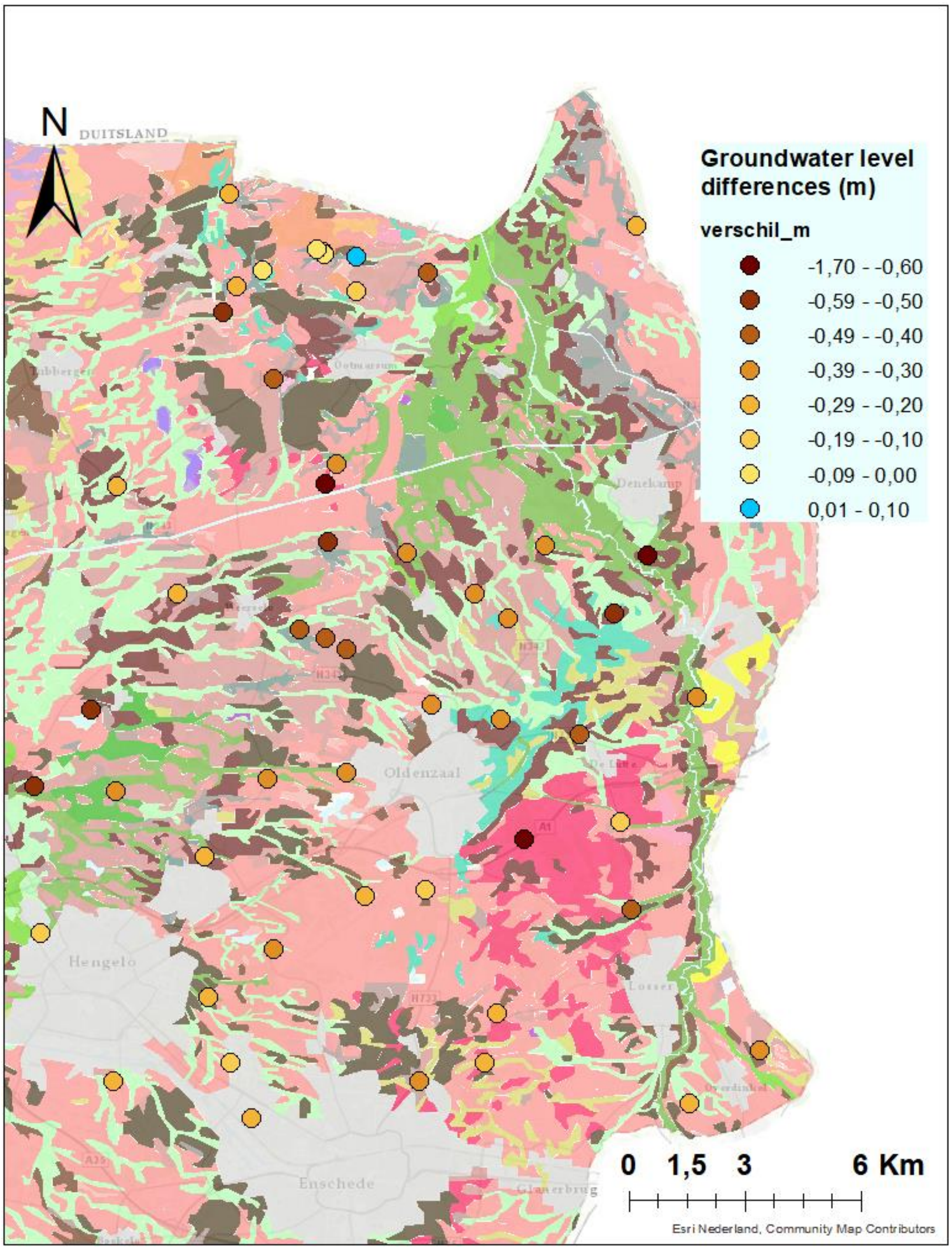

Figure 14: Groundwater level difference between the MLGL of the period 2010-2017 and the LG3 of the year 2018 of the sand area on a soil map

3.1.2 Drought in the peat area

Figure 15 shows that the entire area has lower groundwater levels in 2018 compared to the time period 2010-2017. The legend displays a range from -0,55 m to 0,00 m, which indicates that no increase in groundwater levels was observed. If zoomed in it can be seen that the areas around Bergentheim and Langeveen all have more or less the same decrease in water levels. This is due the presence of peat colonies which hold a lot of water and therefore retain a more stable, higher groundwater level. Another explanation of the stable groundwater levels in the peat area could be groundwater level policies to preserve the peat.

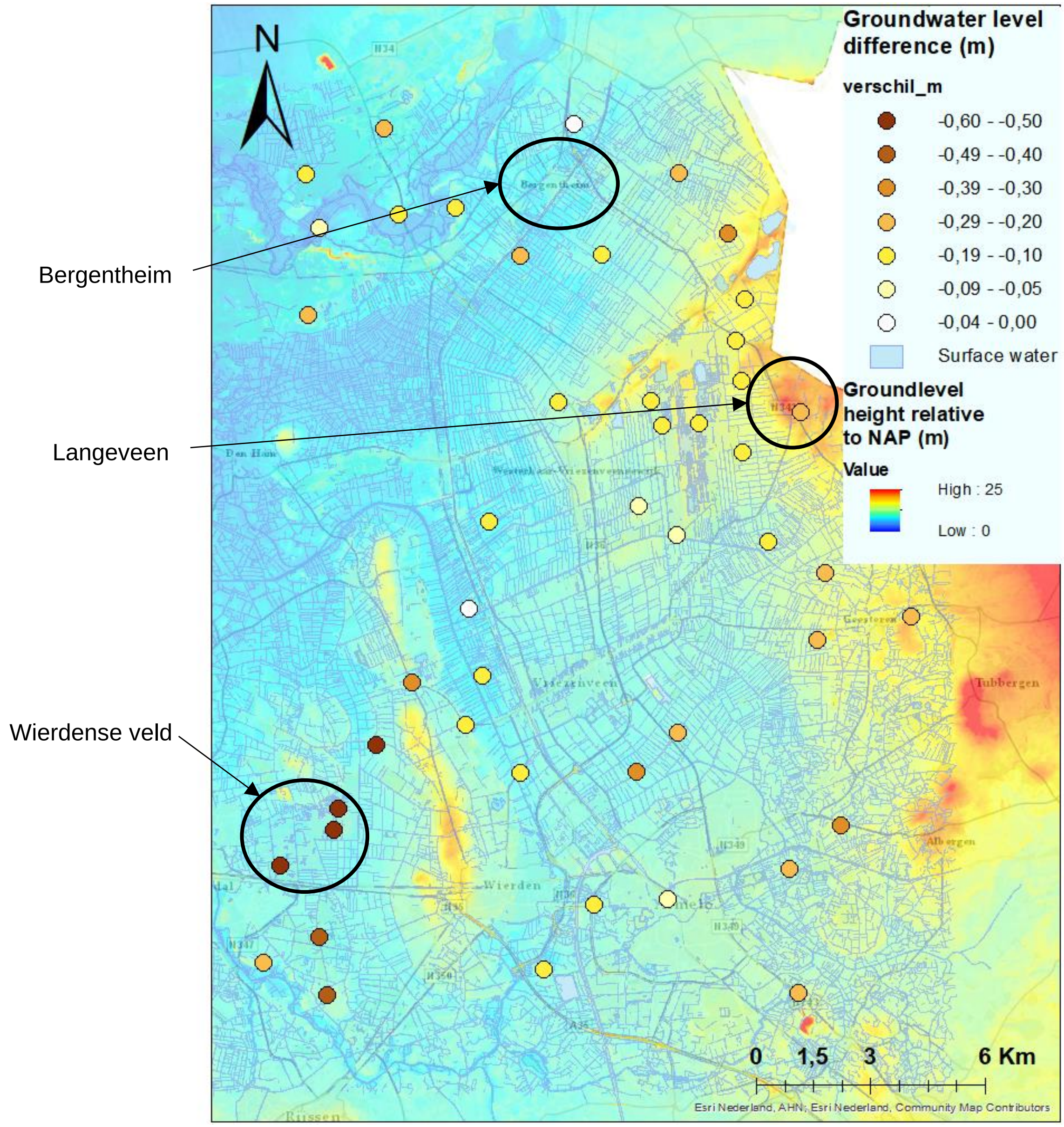

Figure 15: Groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 of the peat area on a height map

The largest declines in groundwater level in this study area is in Wierdense Veld (Figure 16). This Natura 2000-area contains a lot of peat and therefore needs large quantities of water to flourish (Provincie Overijssel (a), 2020). A decline in groundwater levels of 50 cm is remarkable and alarming for a peat area. The white/purple is a Natura 2000-ara and is called Engbertsdijksvenen (Provincie Overijssel (b), 2020). This area contains relatively a lot of peat. In Engbertsdijksvenen the groundwater levels have gone down less than in the surrounding area with a groundwater level drop of on average 15 cm. In the northwest of this study area, the area around the river Vecht, groundwater levels are also quite stable. In the area where sandy soils dominate the groundwater levels dropped somewhat more than in the peat area, by around 30 cm. This area contains mainly 'field podzol soils'. The (Dutch) legend about the soil composition of Figure 16 can be found in Appendix 5.

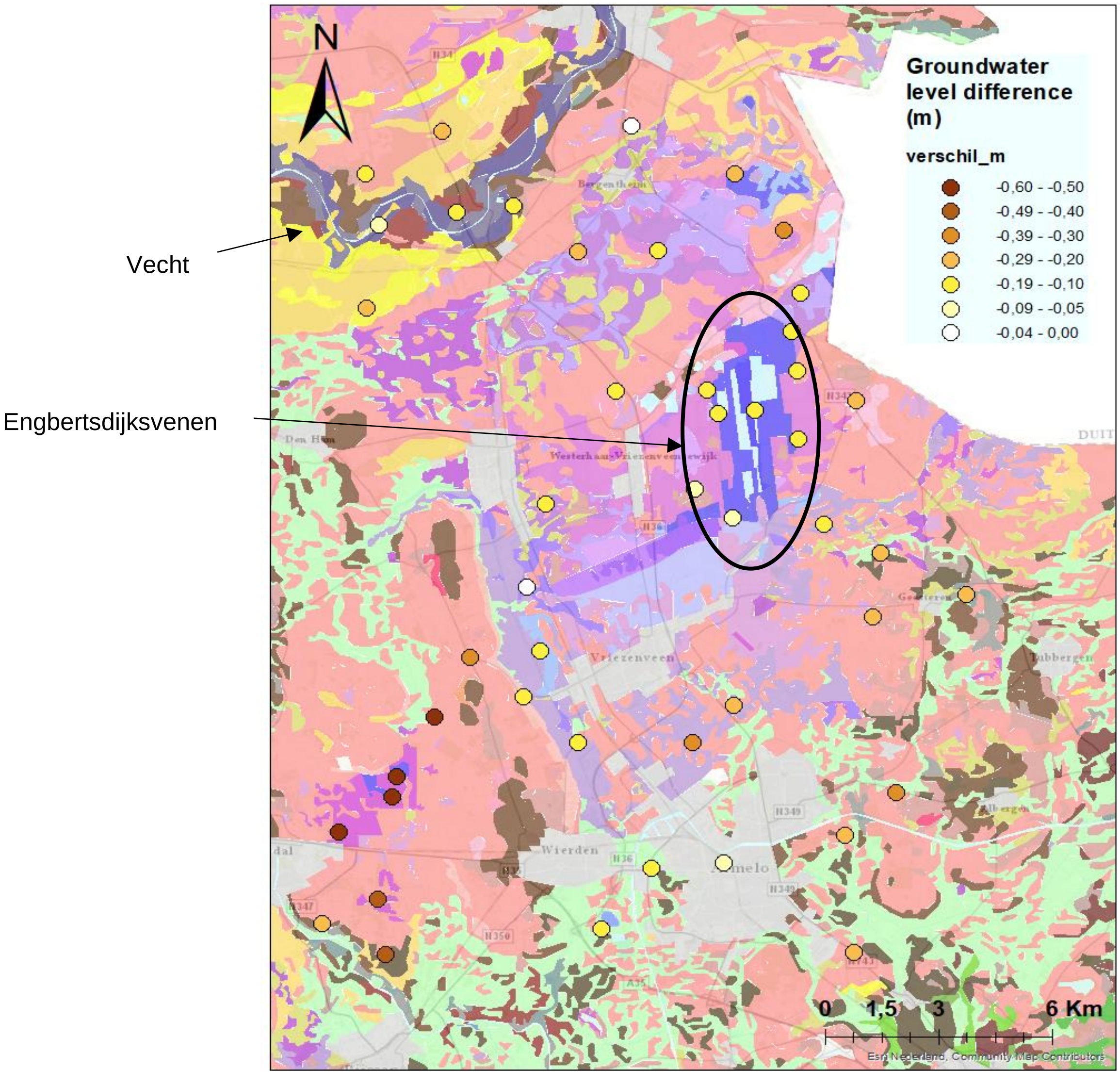

Figure 16: Groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 of the peat area on a soil map

3.1.3 Drought in the river area

In contrast to the other study areas, Figure 17 and Figure 18 show that in the river area the groundwater level has gone up in 2018 in some measurement wells compared to the eight years before. The observed groundwater level changes within this area are rather counterintuitive because locations close to the river seem to have a greater groundwater level drop than locations further away, for example in Nijmegen. The areas with an increasing groundwater level, the area above Oss and the areas around Cuijk, have local groundwater level policies to keep the groundwater levels high (Advies Waterbeheer, 2014) (Foolen, 2019). The rest of the study shows a decrease in groundwater levels. The average drop of the groundwater level is 25 cm. The area that shows a positive groundwater level difference has the same soil composition as most of the river area where the groundwater levels have declined (Figure 17). The more severe groundwater level declines are observed around the higher laying areas which are accompanied with sandy soil compositions in the east of this study area. The (Dutch) legend about the soil composition of Figure 17 can be found in Appendix 5.

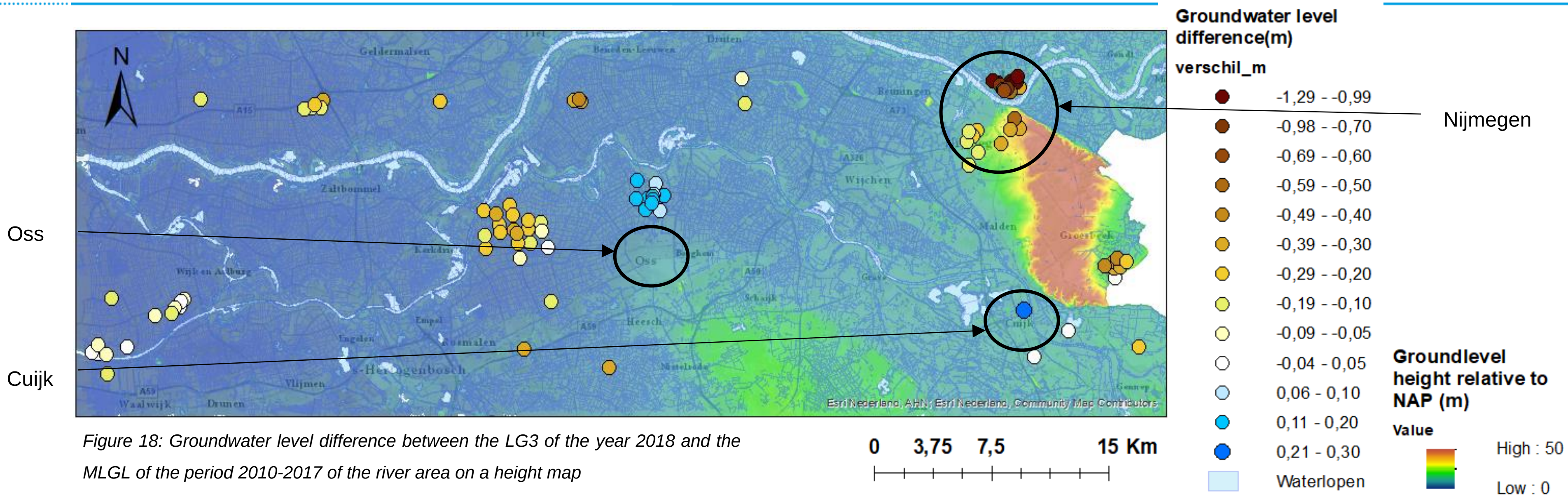

Figure 18: Groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 of the river area on a height map

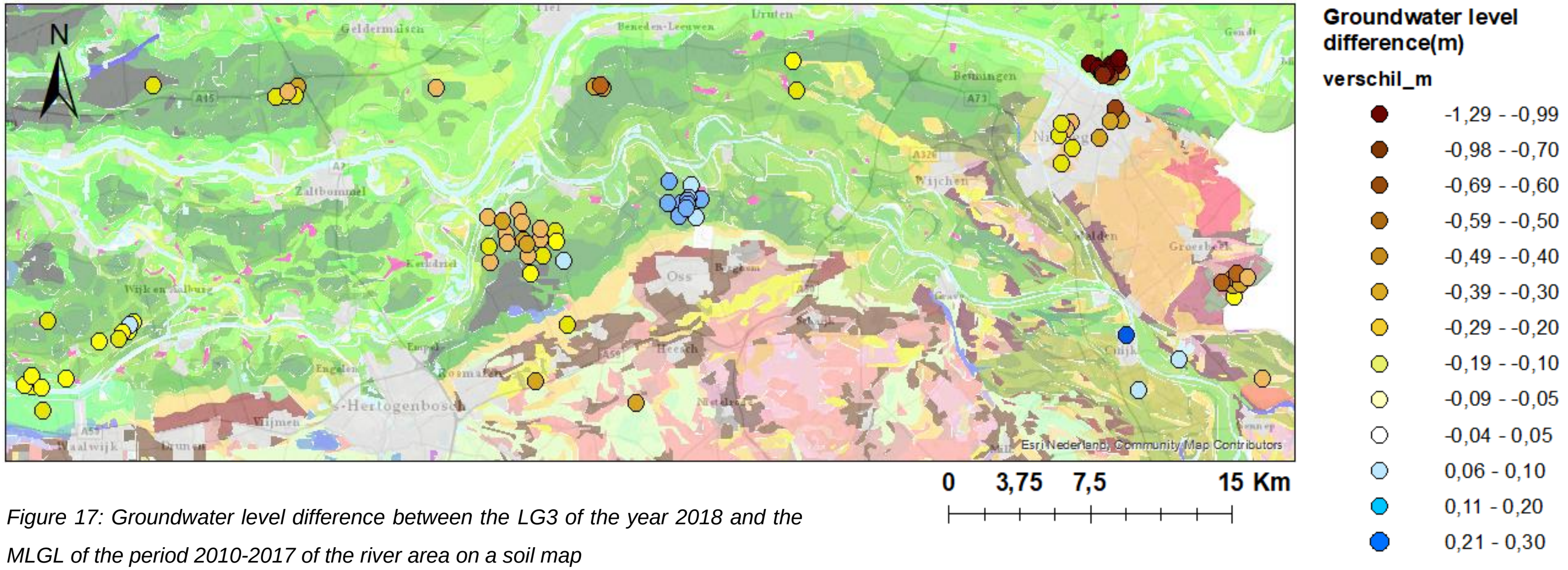

Figure 17: Groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 of the river area on a soil map

3.1.4 Comparing the pilot areas

The response of the groundwater levels to the drought in 2018 compared to the groundwater levels in 2010-2017 is summarized in the histogram in Figure 19. The dotted line marks the distinction between lowering and increasing groundwater levels. The sand area shows the most lowering of the groundwater levels of the three areas with an average drop from 35 cm. Peat areas are relatively the least sensitive for the drought speaking in terms of groundwater level drops and shows a groundwater level drop of on average 22 cm. The river area has a large range of groundwater level differences with the bulk of the measurement wells showing a decrease between 10 and 40 cm. The average groundwater level drop of the river area is 26 cm. Histograms the groundwater level difference of each individual research area can be found in Appendix 6.

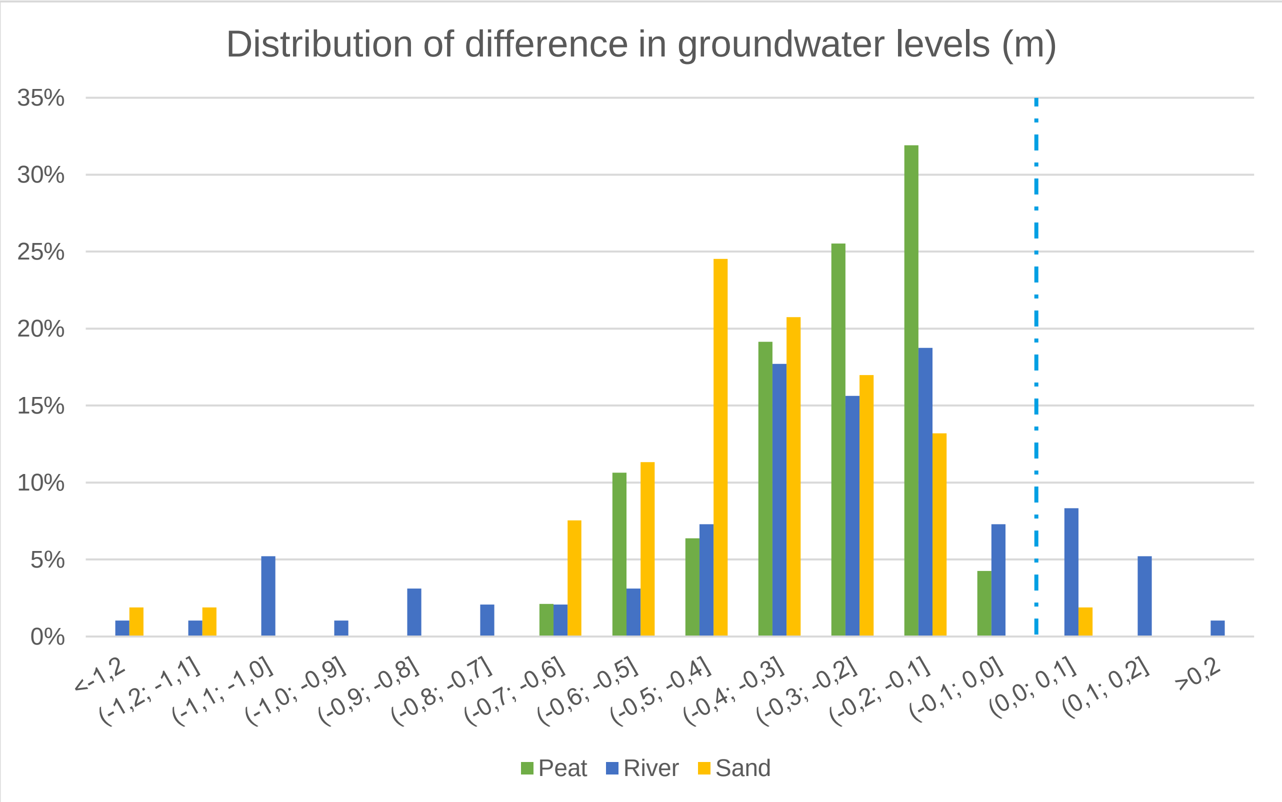

Figure 19: Distribution of difference in groundwater levels between the LG3 of 2018 and the MLGL of the time period 2010-2017 and the for all pilot areas (negative values indicate a lower groundwater level in 2018, positive values indicate a higher groundwater level in 2018).

As expected, almost all groundwater level data indicated that the groundwater level has gone down in 2018 in comparison to the period 2010-2017. However, in the river area there are some exceptions. First, the area above Oss just south of the Meuse, a special policy is in place managing the groundwater levels. In ‘Peilenplan Hertogswetering’ (Advies Waterbeheer, 2014) can be found that the measurement wells that have gone up are located in monitoring areas STA and OHL.

In ‘Peilenplan Hertogswetering’ can be found that for these monitoring areas there is no special policy to maintain high groundwater levels. The water authority indicates that because of the dry years the local policy has become to keep the groundwater levels high. At Teeffelen water from the river Meuse can be let in with a flow rate of 1000 l/s to keep the groundwater levels in the area above Oss at a desired height.

Wierdense Veld is a Natura 2000-area (Provincie Overijssel (a), 2020). The soil in the area contains a lot of peat and because of this it needs large quantities of water to maintain itself and grow. That would indicate high and stable groundwater levels. The results show that the groundwater level dropped at least 50 cm in Wierdense Veld which could have had large negative impacts on the peat.

3.2 Recurrence time of drought

For the analysis of the recurrence times of the lowest groundwater levels, the method presented in section 2.2.5 has been applied. The recurrence times of the LG3 of the year 2018 are determined with the use of the cumulative distribution function (CDF). The results of the other methods mentioned in section 2.2.5 can be found in Appendix 7. The dotted line is the LG3 of the year 2018 which intersects the exceedance frequencies predicted with the different methods. From these intersections the recurrence time of the LG3 of 2018 for each measurement well can be determined. Figure 20 shows that 2018 has the lowest LG3 of all years in the dataset. The method stops calculating after the lowest LG3 of the dataset is reached. Figure 20 and Table 2 show that the recurrence time of measurement well B28F0355 has a recurrence time of 98,8 years.

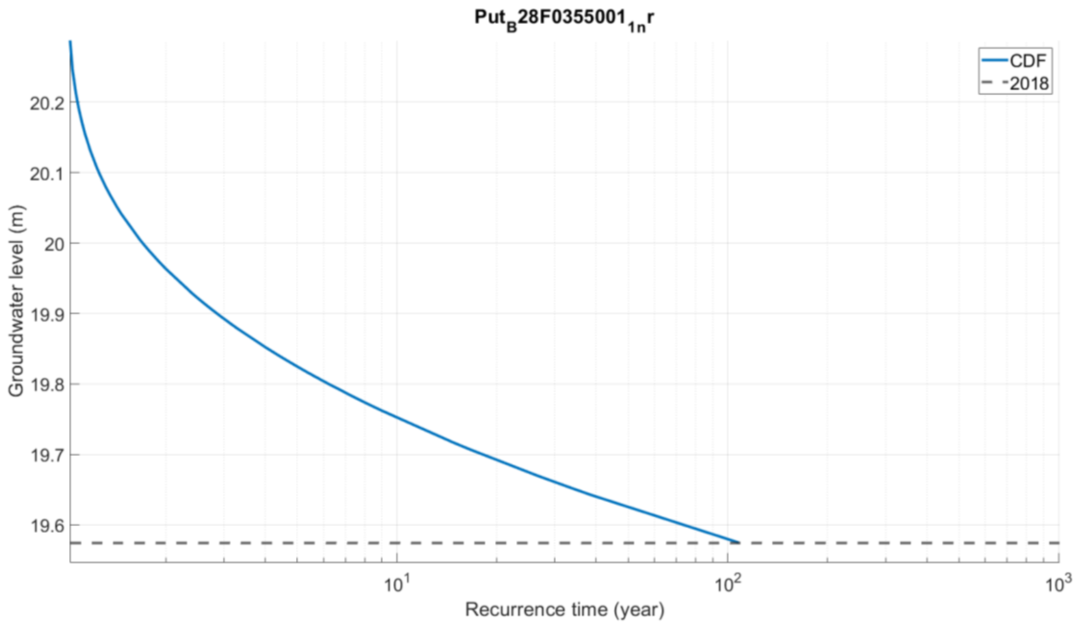

Figure 20: Visualisation of the recurrence times plotted against the groundwater level of measurement well B28F0355 for the cumulative distribution function in the sand area

3.2.1 Recurrence times of the sand area

Table 2 is the result of the method described in 2.2 and displays for each measurement well in the sand area what the rank, recurrence time and groundwater level difference is.The rank stands for how low the LG3 is compared to the rest of the dataset of that measurement well. So if the rank is ‘3’, this means there are two years that have a lower LG3 in the dataset (the original groundwater levels along with the reconstructed groundwater from the time series analyses) of that measurement well. The CDF is the recurrence time of the LG3 of 2018 with the use of the cumulative distribution function. The difference column is data collected from the analyses done in section 2.1. Sometimes the wells analysed in this section do not overlap the measurement wells in section 2.1 because of the different criteria for using groundwater level data. If so, N.A. is assigned to the measurement well in the ‘difference’ column.

Table 2: Recurrence times of the sand area using the cumulative distribution function and the corresponding groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 (negative values indicate a lower groundwater level in 2018, positive values indicate a higher groundwater level in 2018).

Measurement well	Rank	CDF (year)	Difference (m)
B28F0162002	7	10,9	-0,49
B28F0355001	1	98,6	N.A.
B28G0408001	2	61,4	-0,54
B28H0296001	2	46,7	-0,35
B28H0323001	4	18,0	-0,24
B28H0424001	5	28,0	-0,47
B28H0436001	7	10,9	-0,37
B28H0614001	2	111,7	-0,58
B28H0622001	3	47,3	-0,37
B28H0653001	2	12,6	-0,24
B28H0679001	2	51,2	-0,39
B28H0680001	3	17,6	-0,21
B29A0154001	3	25,6	N.A.
B29A0157001	2	72,2	N.A.
B29C0118001	3	72,4	-0,55
B29C0191001	1	79,3	-0,41
B29C0211001	1	182,2	-0,62
B29C0217001	4	20,4	-0,34
B29C0228001	2	53,3	-0,4
B34F1173001	2	105,0	N.A.
B34F1204001	6	10,0	-0,21
B34F1314001	12	5,6	-0,11
B34F1399001	4	21,6	-0,36
Average	3,5	50,5	-0,38
Median	3	46,7	-0,26

Table 2 shows that the average rank of the measurement wells is 3,5. This indicates that on average 2018 was between the third and fourth driest year in the dataset of the sand area. The average recurrence time of the LG3 groundwater levels is 50,5 years which is a lot drier than the recurrence time of 30 years based on precipitation and evaporation estimated by of the KNMI (Sluijter et al., 2018). The average groundwater level differences is a bit higher than the results of section 3.1 show (38 cm versus 35 cm). This due to not having the same measurement wells in this section compared to section 3.1 as a result of the method.

Additionally is examined whether there is a relation between the recurrence times of 2018 and the corresponding groundwater level difference. Figure 21 clearly shows that the sand area has such a relation. The greater the decline of the groundwater level, the greater the recurrence time. Figure 22 shows a spatial visualization of the measurement wells with their groundwater level differences and recurrence times. The larger the circle, the greater the recurrence time. The (Dutch) legend about the soil composition of Figure 22 can be found in Appendix 5.

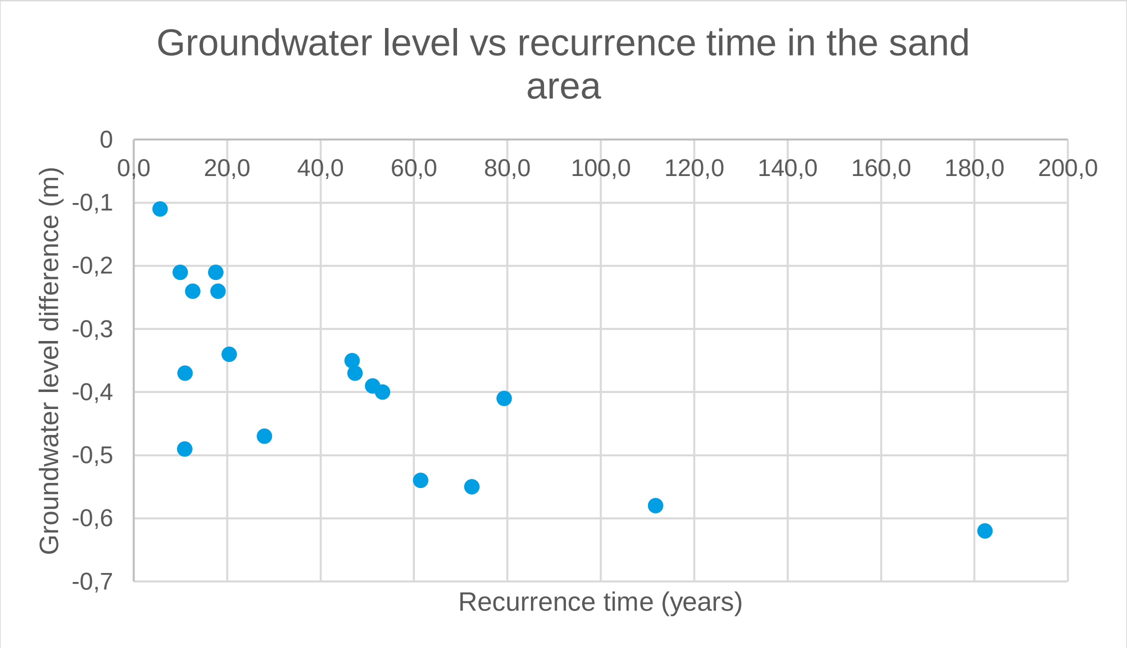

Figure 21: Distribution of recurrence times of the sand area plotted against the groundwater level difference of 2018

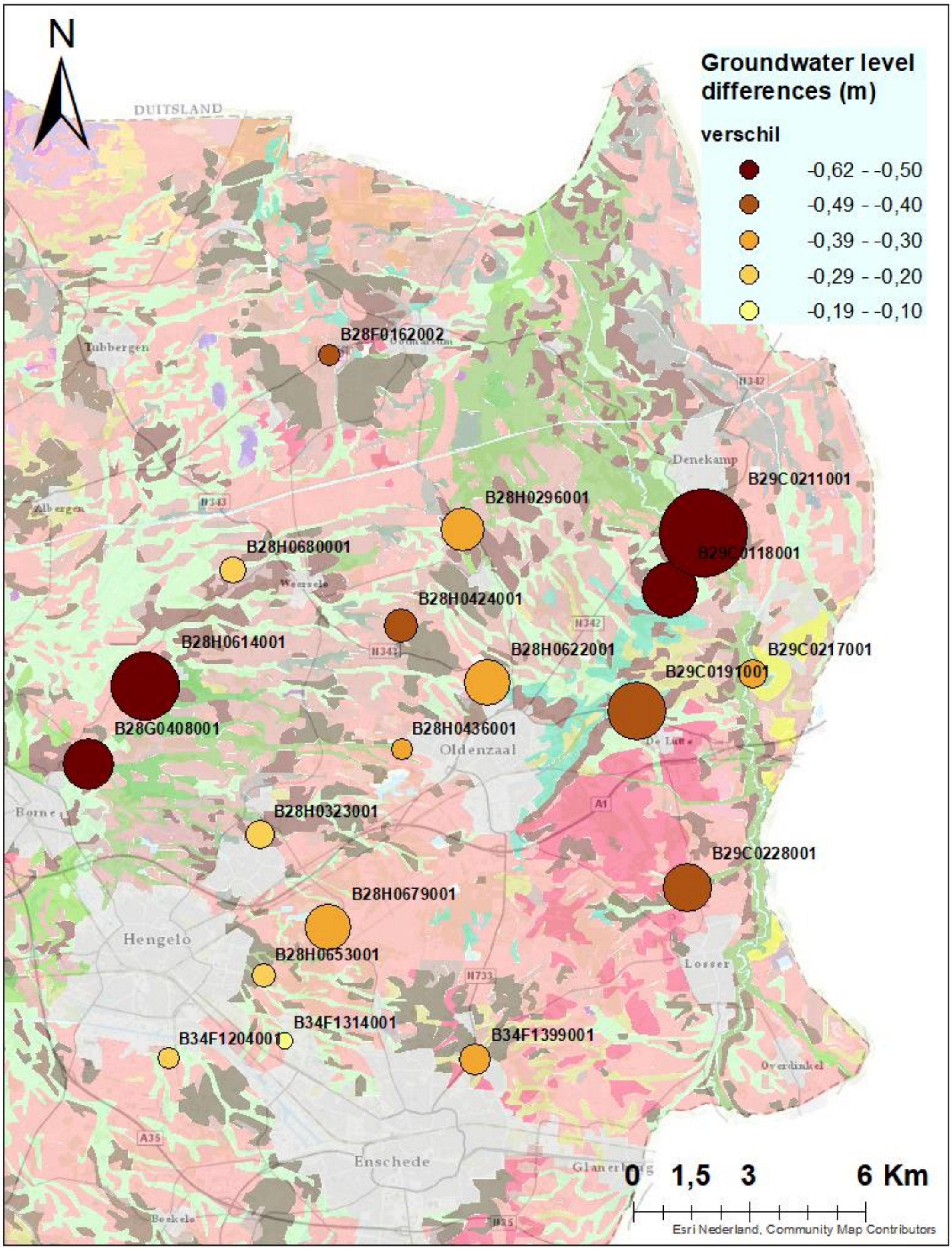

Figure 22: Recurrence times of the sand area displayed on a soil map

3.2.2 Recurrence times of the peat area

Table 3 shows that the average rank of the measurement wells is 2,2. This indicates that on average the 2018 was almost the second driest year in the dataset of the peat area. The average recurrence time of the LG3 of the groundwater levels is 91,0. In reality will this recurrence time probably be lower because some extremely high recurrence times raise the average. In contrast, the median is almost half of the average recurrence time with 47,9 years. This is still much higher than the recurrence time of 30 years based on precipitation and evaporation estimated by of the KNMI (Sluijter et al., 2018). The average groundwater level differences is a bit higher than the results of section 3.1 show (28 cm versus 22 cm). This due to not having the same measurement wells in this section compared to section 3.1 as a result of the method.

Table 3: Recurrence times of the peat area using the cumulative distribution function and the corresponding groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 (negative values indicate a lower groundwater level in 2018, positive values indicate a higher groundwater level in 2018).

Measurement well	Rank	CDF (year)	Difference (m)
B22D0062001	2	96,6	-0,23
B22D0237001	3	38,8	N.A.
B22D0239001	3	28,4	-0,22
B22D0333001	5	12,6	N.A.
B22D0342001	3	14,7	N.A.
B22D0354001	3	21,3	N.A.
B22G0051001	1	135,7	-0,27
B28B0236001	3	18,6	-0,51
B28D0276001	1	224,8	-0,27
B28D0340001	2	57,0	-0,48
B28D0348001	1	111,9	-0,49
B28E0032002	3	17,4	-0,25
B28E0034001	1	197,6	-0,28
B28E0047001	3	32,5	-0,13
B28E0166001	1	144,2	-0,27
B28E0181001	1	265,0	-0,25
B28E0214001	3	27,4	-0,15
B28E0261001	3	24,8	-0,11
B28G0344001	1	239,7	-0,24
B28G0391001	1	110,2	-0,29
Average	2,2	91,0	-0,28
Median	2,5	47,9	-0,26

From Table 3 and Figure 24 can be deduced that the observed 2018 groundwater levels in the peat area span a wide range of recurrence times. Figure 23 shows that no matter what the recurrence time is, it has a very stable groundwater level. The points within the green circle are measurement wells that lie in the centre of a peat colony of Engbertsdijksvenen, the white/purple area in Figure 24. These wells show a very small decline of the groundwater level in 2018 while still having a recurrence time of between 20 and 30 years. The groundwater levels differences between -0,2 and -0,3 meter are mostly observed not in a soil that contains peat but in areas close to the peat colonies. This indicates that the LG3 of 2018 in areas surrounding Engbertsdijksvenen was very extreme. The (Dutch) legend of the soil composition of Figure 24 can be found in Appendix 5.

The points in the red circle (Figure 23) can be found in the southwest part of the peat just below Wierdense Veld (Figure 24). This part of the area does not contain a lot of peat soil is characterized by high sand grounds. This explains why there is a larger drop in groundwater levels. The larger declines in groundwater levels at these high sand grounds have relatively short recurrence times indicating that greater groundwater level drops are more frequent in sand grounds.

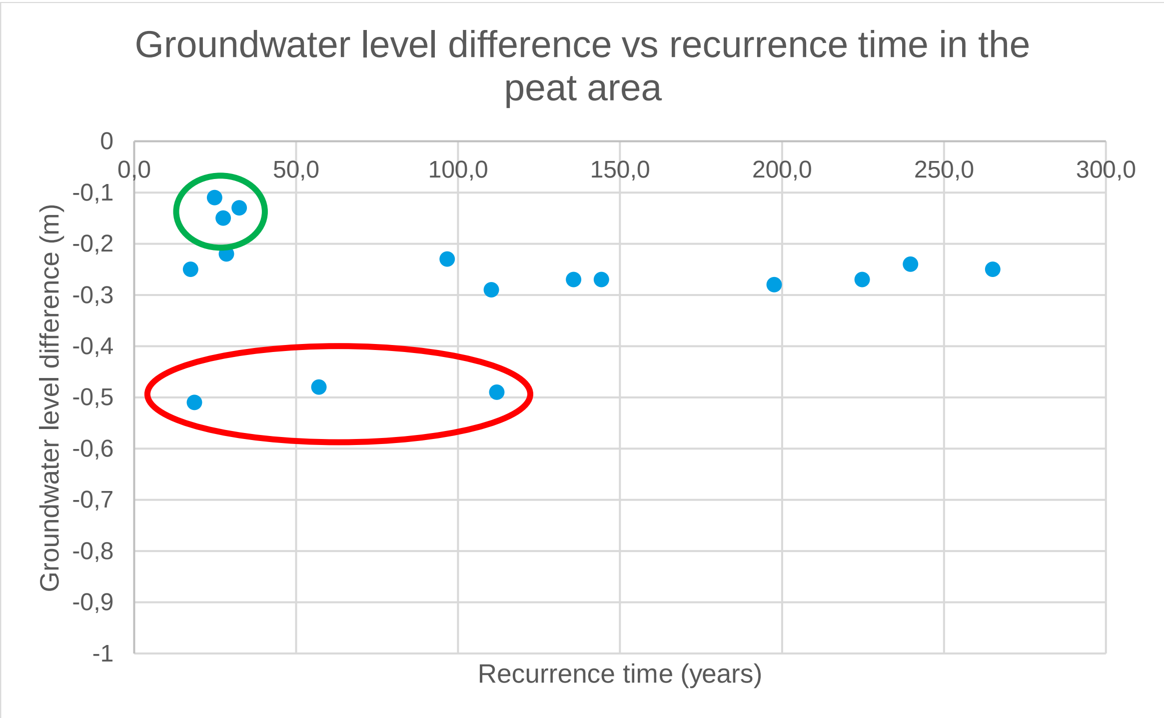

Figure 23: Groundwater level difference plotted against the recurrence time for the peat area

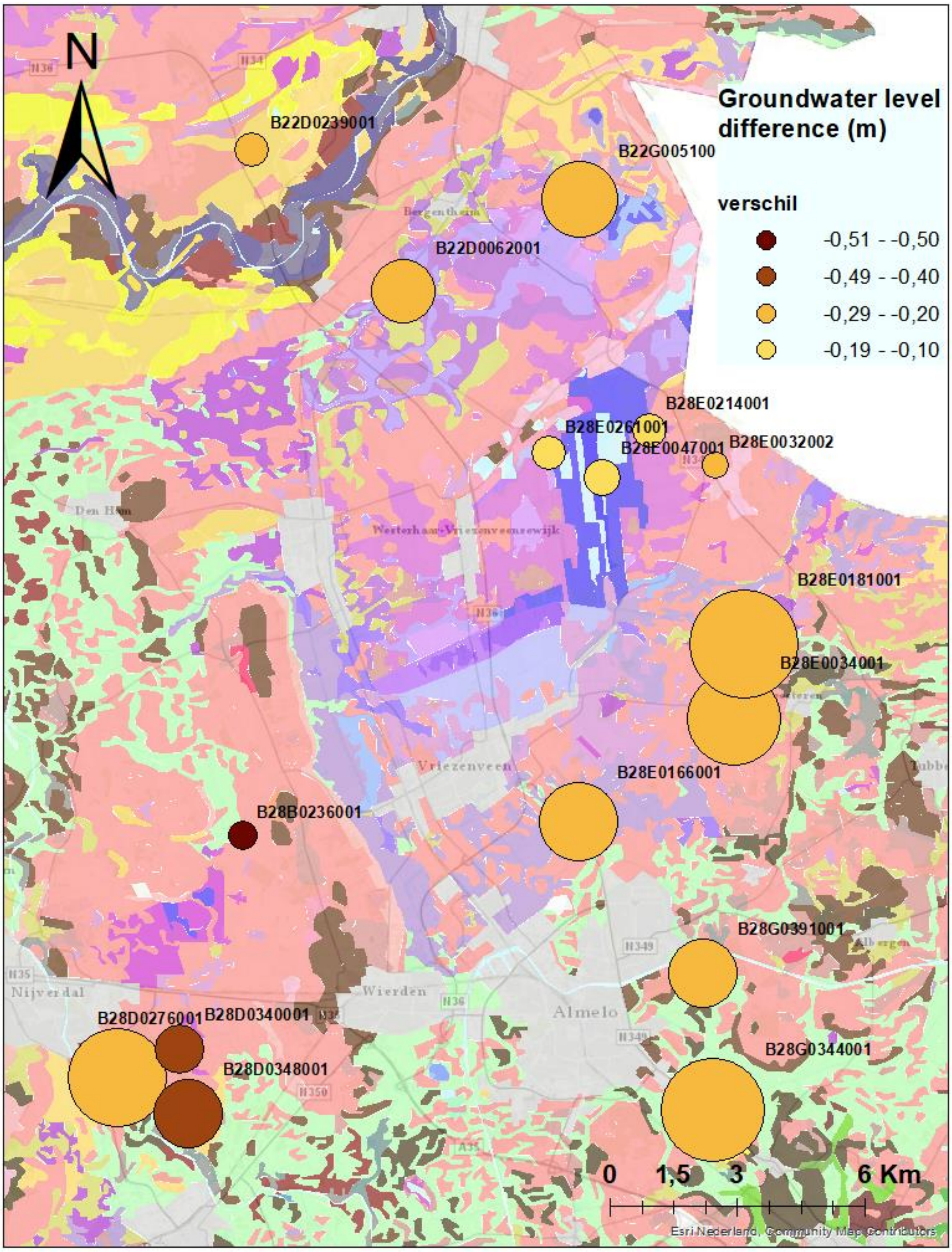

Figure 24: Recurrence times of the peat area displayed on a soil map

3.2.3 Recurrence times of the river area

The river area only has 7 measurement wells that complied with the criteria for the computation of the recurrence times. This is mainly due to low EVP values (below 70%). Only one of these wells also had data from for groundwater level difference between 2018 and the period of 2010-2017. Hence, it was not possible to plot the obtained recurrence time versus the groundwater level lowering in 2018.

Table 4: Recurrence times of the river area using the cumulative distribution function and the corresponding groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 (negative values indicate a lower groundwater level in 2018, positive values indicate a higher groundwater level in 2018).

Measurement well	Rank	CDF (year)	Difference (m)
B45B0328001	6	12,9	-0,09
B45B0453001	27	2,0	N.A.
B45B0491001	5	18,7	N.A.
B45B0492001	13	4,8	N.A.
B45B0496001	8	6,5	N.A.
B45B0564001	5	13,4	N.A.
B45E0502001	13	4,8	N.A.
Average	11,0	9,0	-0,09
Median	8	6,5	-0,09

Even though the river area does not have a lot of measurement wells that made it to the analyses, they all show a relatively low recurrence time. However, all remaining measurement wells are located between ‘s Hertogenbosch and Oss, so it is not a good representation of the entire area. The locations of the measurement wells from Table 4 can be found in Appendix 8.

3.2.4 Comparing the recurrence times of the research areas

Table 5 shows the average and median of the computed recurrence times for the 2018 groundwater levels of the sand and peat area. The river area is left out of this comparison, because of the poor representation of the area a comparison would be meaningless. Both the average and median are presented mainly because of the large difference between the two in the peat area. The average and median are so far apart due to the wide range of recurrence times in the area and representing both gives better insight in this spread. The sand area shows higher ranks than the peat area. This implies that the LG3's of 2018 are more rare in the peat area than in the sand area. The greater recurrence times in the peat area relative to the sand area confirm this. Even though the recurrence times are greater in the peat area, the groundwater level differences are greater in the sand area. This is due to the area characteristic of each area (section 3.1). The recurrence time of the precipitation and evaporation for 2018, 30 years, estimated by the KNMI is much lower than these groundwater level recurrence times.

Table 5: Average and median of the rank, recurrence time and groundwater level difference of the sand and peat area

	Sand area			Peat area		
	Rank	Recurrence time (years)	Difference (m)	Rank	Recurrence time (years)	Difference (m)
Average	3,5	50,5	-0,38	2,2	91,0	-0,28
Median	3	46,7	-0,26	2,5	47,9	-0,26

4 Discussion

In the sand area there are no clear patterns visible if looked at the groundwater level lowering in 2018 in combination with the height map or the soil map (Figure 13 and Figure 14). It seems that the lower elevated areas faced a greater groundwater level drop in 2018, which is counterintuitive and cannot be explained in this study. A smaller groundwater level drop is expected in these lower areas because the water flows from the higher laying areas to the lower laying areas. In the peat area, the groundwater levels have been quite stable at the locations where a lot of peat is present. Around the area of Engbertsdijksvenen greater groundwater level drops have been observed. The stable groundwater levels in the peat can be caused by its capacity to hold a lot of water and therefore it has a bigger buffer. It can also be caused by groundwater level policies. Peat grounds can contain a lot of water and the regional water authorities can bring in water to keep up the groundwater level and prevent for drought. Because peat needs stable groundwater levels to flourish the groundwater levels in Wierdense Veld are problematic. The groundwater levels in Wierdense veld have dropped more than 50 cm which is alarming because to the area being a Nature 2000-area with the goal to preserve the peat (Provincie Overijssel (a), 2020). Groundwater level differences in the river area are most likely heavily influenced by groundwater level policies. Most of the time this results in small deviations in groundwater levels between the LG3 of 2018 and the MLGL of 2010-2017.

The groundwater wells in the sand and peat areas were well spread over the study areas. This makes it possible to draw more balanced conclusions for the entire area. On the other hand, in the river area measurement wells were clustered in a few locations (Figure 18). This groundwater well distribution gives a distorted picture of the change of the groundwater levels within the area. For example, Figure 19 shows that almost 10% of the measurement wells show an one meter drop in the groundwater level. Figure 18 shows that there is a small area (7 km^2) above Nijmegen with a large groundwater level difference and with a lot of measurement wells present. This is only 0,5% of the entire area (which is around 1400 km^2). As a result these measurement wells give a distorted picture of the distribution of groundwater level differences in the river area.

The EVP was used to assess whether the groundwater level can be reconstructed accurately from precipitation and evaporation timeseries. When the EVP is below 70% the time series model is rejected because the reconstructions by the model do not match sufficiently with the observed groundwater levels. In this case there can be many other factors dictating the groundwater level. The number of rejected time series models were: 3 out 31 in the sand area, 15 out of 38 in the peat area and 73 out of 91 in the river area. Apparently, in the river area there are a lot of confounding factors influencing groundwater levels. These factors might be effects of for example irrigation or the presence of a river nearby. Also, the groundwater level policies can have large impacts. Consequently, certain groundwater measurement wells do not achieve the minimum EVP percentage. For example, the positive groundwater level differences in the river area are likely a result of the groundwater level policies because the groundwater levels have gone up or have relatively small drops. This effect cannot be explained by only evaporation and precipitation and therefore the groundwater levels cannot be reconstructed by the obtained model. To achieve higher

EVP percentages more datasets must be added that have a relation with the groundwater level. These explaining datasets could be flow rate data of nearby pumping stations or data of the discharge of a nearby river.

Comparing recurrence times and groundwater level difference show an expected result in the sand area, the greater the groundwater level drop the greater the recurrence time. The peat area shows a remarkable pattern though. In the central area with high peat concentrations (Engbertsdijksvenen), relatively small recurrence times and small groundwater level differences occurred. Even though the recurrence times are relatively small for the peat area, the recurrence times of the groundwater wells in Engbertsdijksvenen are still between 20 and 30 years. The surrounding area has a very wide range of recurrence times have while the groundwater level differences remain quite similar. Figure 25 shows that the left measurement well, which is in the area of Engbertsdijksvenen, has a smaller total groundwater level difference than the right measurement well which is located in the surrounding area. The recurrence time of the left measurement well in Figure 25 increases much faster per cm groundwater level drop than the right measurement well. This implies that soils with high peat concentrations have suffered less extreme than areas with lower peat concentrations. This could be due to the fact that Engbertsdijksvenen is listed as a Natura 2000-area and the groundwater level policy is to keep the groundwater level stable because that stimulates the preservation and growth of the peat.

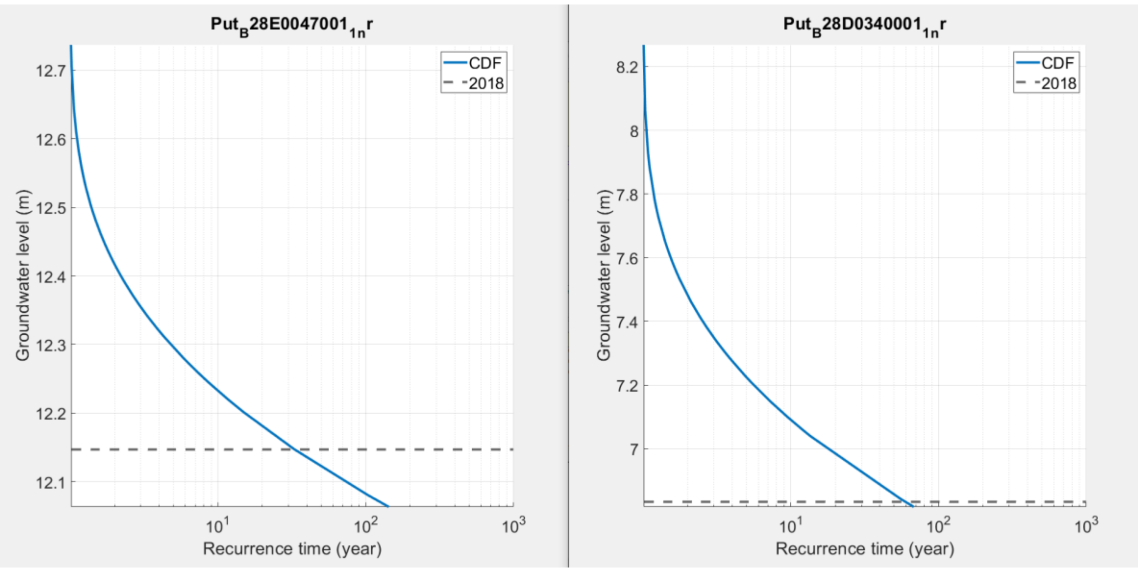

Figure 25: Comparison between the two CDF curves, left measurement well B28E0047 in Engbertsdijksvenen and right a measurement well B28D0340 in the area surrounding Engbertsdijksvenen

The river area has six measurement wells that matched the criteria for computing a recurrence time. These measurement wells were located relatively close together. All six groundwater wells show a relatively low recurrence time for the groundwater levels of 2018. However, because of the limited amount of groundwater wells and its poor distribution over this study area, no conclusions can be drawn regarding the drought effects in the entire river area.

At the time this research is carried out, there was not enough data to make an analysis for the year 2019 as is it done for the year 2018 because of a lack of groundwater level data (most of these data are still to be published). To do the same analysis for 2019, the measurement wells at least need data for the summer months of 2019. As mentioned in section 2.1.4, there should be data up till at least the 1st of October. In all three areas there are almost no measurement wells that meet this criterium. Those who do have useful data of 2019 do not meet the other criteria for groundwater well selection. Therefore groundwater levels of 2019 cannot be considered in this study.

Groundwater gets recharged precipitation and is lost due to evaporation. There are a lot of factors that influence the relation between the groundwater level, precipitation and evaporation. For example, the soil types, groundwater level policies and height of the ground level affect the impact of precipitation and evaporation on groundwater level changes. This can also be seen in the results of section 2.2 where a lot of the groundwater level data cannot be reconstructed from the precipitation and evaporation data. Another result that indicates the influence of other factors is the difference between recurrence times. For the precipitation and evaporation of 2018 the recurrence time is 30 years while the recurrence times for the groundwater levels in the sand and peat area are 51 and 91 years, respectively. It seems that other factors have had a large impact on the groundwater levels outside the precipitation and evaporation. This may be due the increasing pressure of the water use of society like the pumping of groundwater by farmers.

5 Conclusion

This study addresses the effect of droughts on groundwater levels in different soil types, focussing on the effects of the dry summer of 2018. The aim of this research is to quantify the hydrological drought in groundwater levels by analysing groundwater level data. With the use of the GxGL the difference between the lowest groundwater levels of 2018 and the period 2010-2017 is calculated. By using time series analyses existing groundwater level data of measurement wells are complemented with reconstructed groundwater levels with the use of precipitation and evaporation datasets. The complemented groundwater level data is used for the computation of recurrence times of groundwater levels. These recurrence times are linked to the deviating groundwater levels of the measurement wells and conclusions are drawn.

To what extent are the lowest measured groundwater levels in the pilot areas for 2018 deviating from the period between 2010 and 2017?

This study shows that in 2018 the groundwater levels in the study areas with all three soil types have gone down in comparison to the period 2010-2017 except for some local spots. The sand area showed an average groundwater level drop of the groundwater level of 35 cm. There are no patterns visible in the spatial distribution of the groundwater level drops outside a small difference between the lower and higher elevated areas. The lower elevated areas faced a greater groundwater level drop which is counterintuitive and cannot be explained in this study. The sand area has the greatest groundwater level drop because it is much more dependent on precipitation for its water supply than the other two areas.

The peat area showed an average drop of the groundwater level of 22 cm in 2018. Most places where a lot of peat is present, for example Engbertsdijksvenen, showed a smaller groundwater level drop of on average 15 cm. This small groundwater level drop is probably the result of the combination between the characteristic of peat to hold water and groundwater level policies. Natura 2000-area Wierdense Veld, next to Nijverdal, contains a lot of peat and shows a groundwater level drop of more than 50 cm. This is alarming because peat needs high, stable groundwater levels to flourish.

The river area has the widest range of groundwater level differences with an average drop of 26 cm in 2018. The groundwater level drop in the river area is higher than expected because of the large number of groundwater wells located in the city Nijmegen and the adjacent high sand ground.

Based on these findings, it can be concluded that there is a clear effect of the soil type on the groundwater level lowering during the extremely dry summer of 2018 for the studied areas. The results of this research are based on three research areas with each their own hydrological systems. If other areas are studied with the same soils but other hydrological systems, the results may look different. What also should be noted is that groundwater level policies can have a substantial impact on the groundwater level differences. For example, groundwater level policies are a likely cause of for the deviating groundwater trends observed in the river area north of Oss.

What are the recurrence times of the measured groundwater levels in 2018 for the studied areas and what is the relation with the groundwater level difference between 2018 and the period 2010-2017?

The recurrence time of the drought in the summer of 2018 based on the amount of precipitation and evaporation is 30 years and applies to the whole of the Netherlands (Sluijter et al., 2018). Both the median and the average recurrence times for the associated lowering of the groundwater levels in the sand and peat areas are well above that. The average recurrences times are 51 years for the sand area and 91 years for the peat area. The river area recurrence time has very limited accuracy and therefore is not taken into account. From the data, it can be concluded that the groundwater lowering was much more extreme than the calculations based on the precipitation and evaporation suggested.

A relation between the recurrence times and groundwater level differences is found for the sand area. When the groundwater level drop increases, the recurrence time increases too. The peat area shows no such relation. Measurement wells that are placed in Engbertsdijksvenen have a smaller groundwater level drop and a lower recurrence time in comparison with the other measurement wells in the peat area. The lower recurrence times are probably due to groundwater level policies in the area. The area surrounding Engbertsdijksvenen have very high recurrence times which indicates that a groundwater level drop between 20 and 30 cm is extremely rare in that area. This can be explained by the presence of the large quantity of water in peat colonies. From this can also be deduced that a groundwater level drop of 35 cm in the sand area is less extreme than a 22 cm groundwater level drop in the peat area. The river area does not have enough data to draw conclusions about these relations.

The weather in the future will become more extreme (Lenderink et al., 2011). As a result more rain will fall in time periods and longer periods of time without any rainfall. Those long dry periods will have their effect on groundwater levels. Because of the expected longer absence of rainfall, the groundwater levels are anticipated to drop lower than in the past and the recurrence times of the groundwater levels estimated in this research will go down. Because of the increasing population, the water demand will increase simultaneously, which causes the groundwater levels to decline even further. In the future, the people of the Netherlands will have to adapt their water systems and water use to counter the increasing problem of hydrological drought.

6 Recommendations

To get more knowledge about the groundwater levels and their reactions in the research areas more data must be collected. Only data from DINOloket.nl is used in this research. Provinces, municipalities and water boards have their own data and a site like vitens.lizard.net also contains groundwater level data of measurement wells. Especially in the river area this option would allow a much broader analyzation.

Not only the amount of data from measurement wells was a bottleneck, also the amount of useful data limited the number of results of the research. This was because of the incompleteness of the data in combination with choices made within the tool of Tauw. An estimated 25% of the data was discarded because of this. One of the main reasons is the way missing groundwater level data were filled in. When a value is missing the number -9999 is filled in. When this number is taken into account in the calculation of the MLGL the number goes to extreme depths which of course is wrong. Also the tool does not take certain measurement wells into account in its calculations so its output data does not contain all the wells that should have gone in. During this research it has not become clear what blocked these measurement wells. So, to increase the amount of groundwater level data to work with, the tool must be improved.

An analysis with the LG3 of 2019 with the MLGL of 2010-2017 is not included in this research because the lack of sufficient data. If this data is collected the method as described in this research can be used to analyse the severity of the drought of the summer of 2019. When the analysis of 2019 is done the data of the two years can be compared to see how groundwater levels in 2019 reacted relative to those in 2018. When the data is compared the impact of two consecutive dry summers can be seen, if any. It is possible that areas have not fully recovered from the drought of 2018 and the effects should be visible in the groundwater level data of 2019. If those are compared, conclusions can be drawn upon the recovery of the groundwater levels per area. For example, if the sand area shows even lower groundwater levels while the peat area does not, this might be due the dependence of precipitation of the sand area in combination with the water regulation in the peat area. Further research can compare groundwater levels of 2018 and 2019 and investigate whether the sand area is much more sensitive for consecutive dry summers.

The river and peat area have limited analyses on their recurrence times, mainly because the low EVP rates of the model reconstructions of the groundwater levels discussed in section 262.2.5. That indicates that the areas area influenced by more than precipitation and evaporation. For example a pumping station nearby or a dried up ditch. Further research can look into this additional explanatory data and look for explanations of the observed groundwater levels.

The drought recurrence times of the areas are in this research compared with the drought recurrence time of 30 years estimated by the KNMI. However, this 30 years an estimation for the entire Netherlands. In reality this can differ per area in the Netherlands. Further research can give an estimation of the recurrence time per area and give a more precise answer on the relative severity of the drought.

The research areas all have different soil types and different hydrological systems. This research mainly focused on the differences between soil types and conclusions are drawn based on those differences. Further research could look into the effects of a different hydrological system. For example, a sand area which has a high water supply will have different results than this research.

In the future the weather will be more extreme and as a result the droughts also endure longer. Droughts like seen in 2018 are expected to happen more often in the future. The groundwater will probably more often not be fully recovered when the next dry period arrives and will drop down even further. As a result of the greater drop of groundwater levels in the future causes the computed recurrence times to go down. In other words, these extremely low groundwater levels will be reached more often. To know estimate the effects of the more extreme weather in the future further research must be carried out. To a large extent the same method as described in 2.2 can be used. Instead of using time series analysis to reconstruct groundwater levels in the past they will be used to predict groundwater levels in the future. The precipitation and evaporation series are already predicted by the KNMI for multiple climate scenarios and the precipitation data can be withdrawn from http://www.klimaatscenarios.nl/toekomstig_weer/transformatie/index.html (KNMI (b), 2015). These can be added to the measured precipitation and evaporation datasets from 1957-2020 to create a precipitation and evaporation datasets from 1957-2100. Using this 1957-2100 datasets of precipitation and evaporation the time series analysis can be performed. These will create a dataset from 1957 to 2100 with groundwater levels. The groundwater level dataset can be used to compute the recurrence time of 2018. The recurrence time of 2018 of the study with predicted future groundwater levels can be compared with the recurrence time of this study and conclusions based on the differences can be drawn. Likely the recurrence time of the study with the dataset ranging from 1957 to 2100 will have a lower recurrence time in 2018 due to the longer enduring droughts that are predicted for the future.

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8 Appendices

Appendix 1 Groundwater and soil

How the groundwater reacts to periods of drought depends on the composition of the soil. The main factors of the soil which are important for the groundwater levels are the porosity and the permeability. The more porous the sediment, the more water it can hold (Figure 26). Sand has a porosity between 25 to 40%, clay 35 to 80%. So, clay is way more porous than sand. Clay has a lot of very small spaces and in between it holds a lot of water. Porosity is defined as the fraction of the material volume that is pore space (5), in this case often the amount of water the soil can hold (Fitts, 2013).

$$n = \frac{V_v}{V_t} \quad (5)$$

V_v is the volume of voids in the total material V_t.

Material	n (%)
Narrowly graded silt, sand, gravel	30–50
Widely graded silt, sand, gravel	20–35
Clay, clay–silt	35–60
Sandstone	5–30
Limestone, dolomite	0–40
Shale	0–10
Crystalline rock	0–10
Massive granite	0–0.5

Figure 26: Porosity (Fitts, 2013)

Water often infiltrates into the ground till the point it hits an impermeable layer like clay. Permeability (m/s) is the rate which water flows through the ground (Figure 27). Clay has a low permeability because of the way its particles are arranged. These are like little plates which form a solid layer. Despite its low permeability it does have a high porosity. So it holds a lot of water but does not let it through. Sand does have a very high permeability because its grains are not able to stop the water. This also makes it does have a fast recharge rate: rain and other flows can easily access the soil. For the same reason clay has a slow recharge rate.

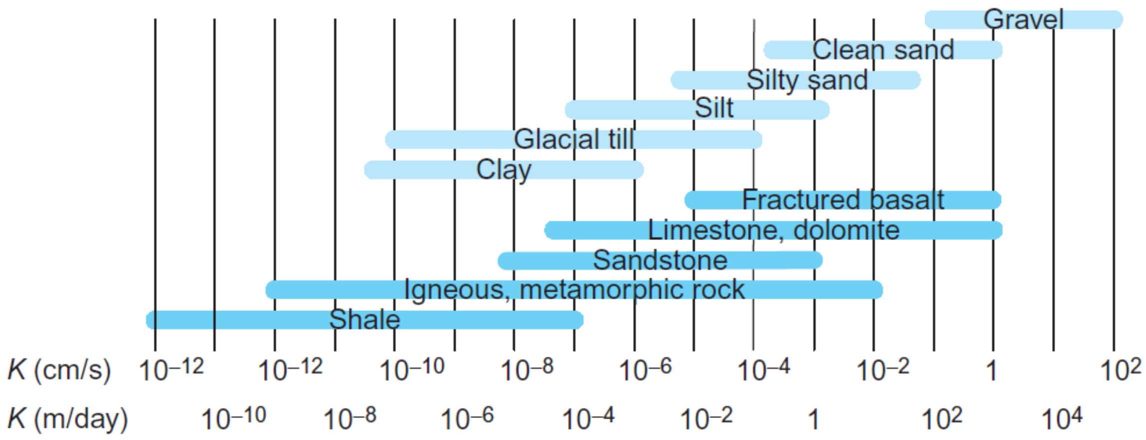

Figure 27: Permeability of soils (Fitts, 2013)

Land subsidence can be a problem when a lot of water is pumped from the ground. The water in the pore spaces holds up the soil. When it is gone the ground compacts under its own weight. The ground can also hold less water following this compaction because the porosity is going down. Long continuous droughts can therefore have big impacts on an area because it can permanently change the porosity and hence the water storage capacity within the soil.

Appendix 2 Area characteristics

Cross sections

For each of the pilot areas cross sections are used to help explaining the deviating groundwater levels. On DINOloket.nl several soil measurements can be found which display the soil composition reaching from the surface to sometimes more than 100 meter deep. The model REGIS II (TNO (b), 2020) visualizes the hydrogeological characteristics of the soil. By drawing lines over a map, like displayed in Figure 29, a cross section of the soil below can be retrieved. From the line drawn in Figure 29, Figure 28 is retrieved. The cross sections are provided from measurement point to measurement point to give an exact start and endpoint. The cross sections are made from north to south and from west to east.

Area explanations

Each area has its own composition. In section 3.2 is a short introduction what factors are looked at for the response to droughts. With the use of the cross sections we know what the soil composition for each area looks like and we will use that to explain how the soil should react. (OBN, 2020)

Appendix 2a Sand

The selected sand area is characterized as a brook valley landscape. The ground gets fed by the groundwater from higher grounds. Because of the presence of barrages and layers of clay beneath the surface the area is very diverse. This area is sensitive for groundwater levels going down because of the possible acidification of the ground. This happens when groundwater levels drop and anaerobic processes are taken over by aerobic processes which increase the nitrate concentration. A dry ground has also more capacity to absorb rainwater which has a lower PH value than groundwater. (Stuijfzand, van Turnhout, & Esselink, 2004, p. 32) Most of the water supply is dependent on precipitation and because of sands high permeability a lot of water is flowing away relatively fast. This water goes into streams and then gets carried to lower grounds. Because of this, sand areas need rainwater supply on a regular basis, otherwise the ecosystem dries out. When there is a long meteorological drought streams can dry out which will result in dropping groundwater levels due to the lack of water pressure. The cross sections of the sand area (Figure 28 and Figure 30) show that the top layers are sand layers above a clay layer. The sand layer varies in thickness from 30 to 60 meters thick layer.

For the sand area, the North-Souht (NS) line is drawn from a point directly above Ootmarsum to the centre of Enschede (Figure 29). The West-East (WE) line is drawn from a point just north of Albergen to just east of Denekamp (laying against the German border)(Figure 31).

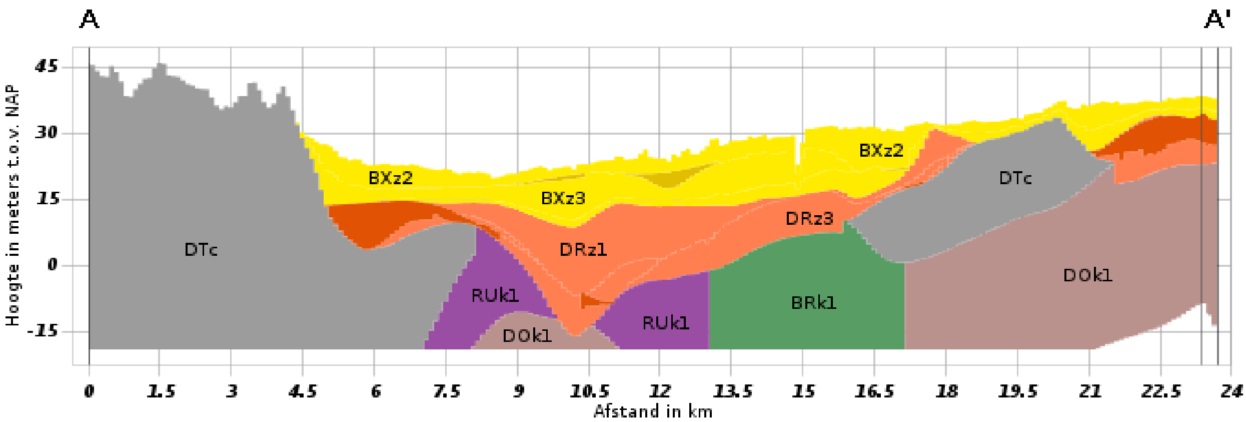

Figure 28: Cross section of the sand area from North to Sound (NS)

Figure 29: Top view of the cross section in the sand area (NS)

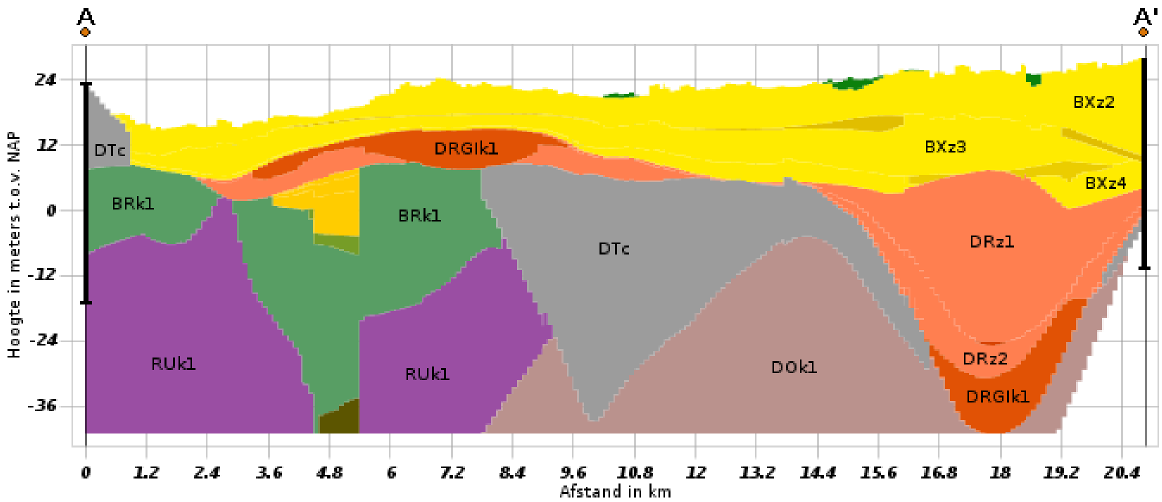

Figure 30: Cross section of the sand area from West to East (WE)

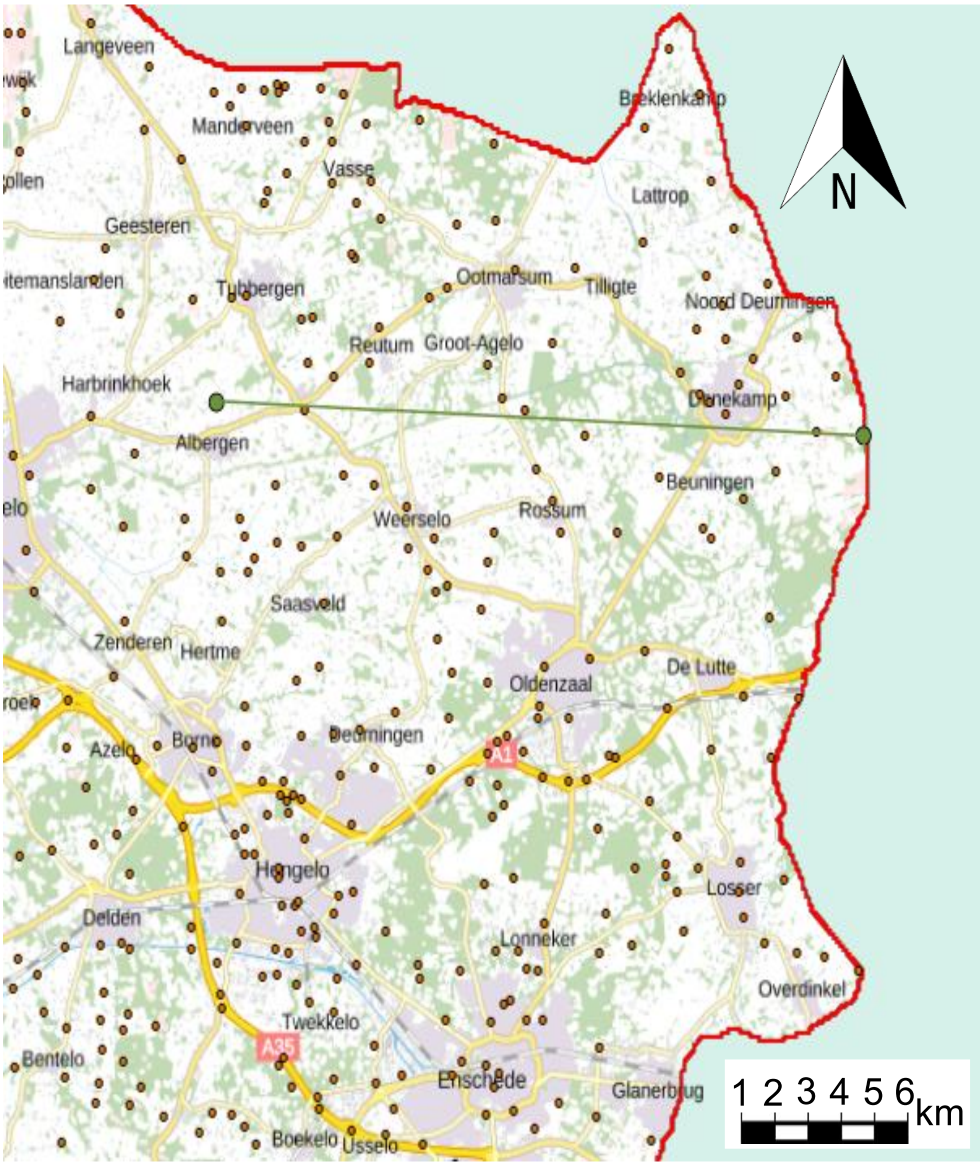

Figure 31: Top view of the cross section in the sand area (WE)

Appendix 2b Peat

Peat

Peat is only present when an abundance of water is available. When the groundwater level is high there is a minimal breakdown of peat. It operates best at stable groundwater levels with a maximum of 30 centimetres fluctuation. Nowadays these areas often need additional water to maintain the ecosystem. When groundwater levels drop, the ground acidifies. (Stuijfzand, van Turnhout, & Esselink, 2004, p. 34) When the areas fall dry, they cannot restore and degrade. Peat functions as a sponge, it attracts and holds water in wet times and slowly releases it in dry times. Because of this mechanics, groundwater levels will slowly go down in dry times and restore quick in wet times. But when a longer dry period happens it cannot sustain itself and will lose its function and will most likely transition into a sand-like hydrological system. This shortens the residence time of the area. At the start of the 20th century a lot of peat mining has happened. Right now the government is interested in keeping the peat areas intact because when peat areas degrade they release a lot of CO^2. Therefore the groundwater level is controlled in a lot of these areas and they are often appointed as Natura 2000-areas.

The cross sections of the peat area (Figure 32 and Figure 34) show that the sand layers vary from 40 to 90 meters deep. The peat colony area NS-line is drawn from Bergentheim to just south of Almelo (Figure 33). The WE-line is drawn from a point in Hallerhoek to a point between Langeveen and Geesteren (Figure 35).

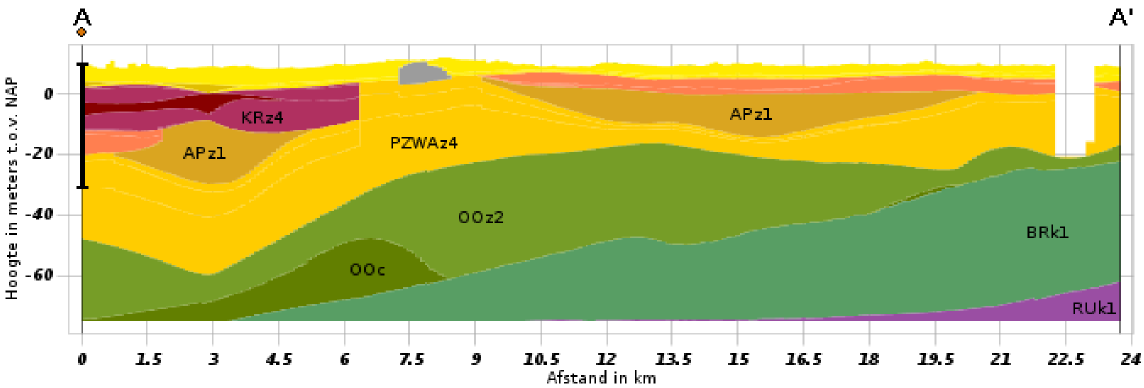

Figure 32: Cross section of the peat area from North to Sound (NS)

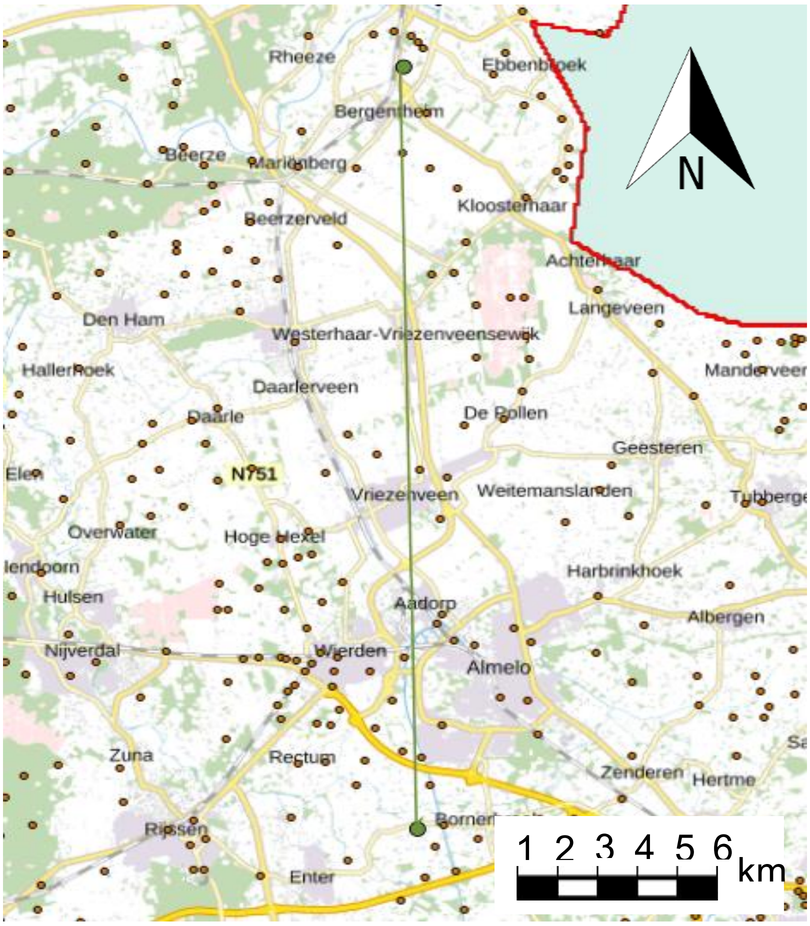

Figure 33: Top view of the cross section in the peat area (NS)

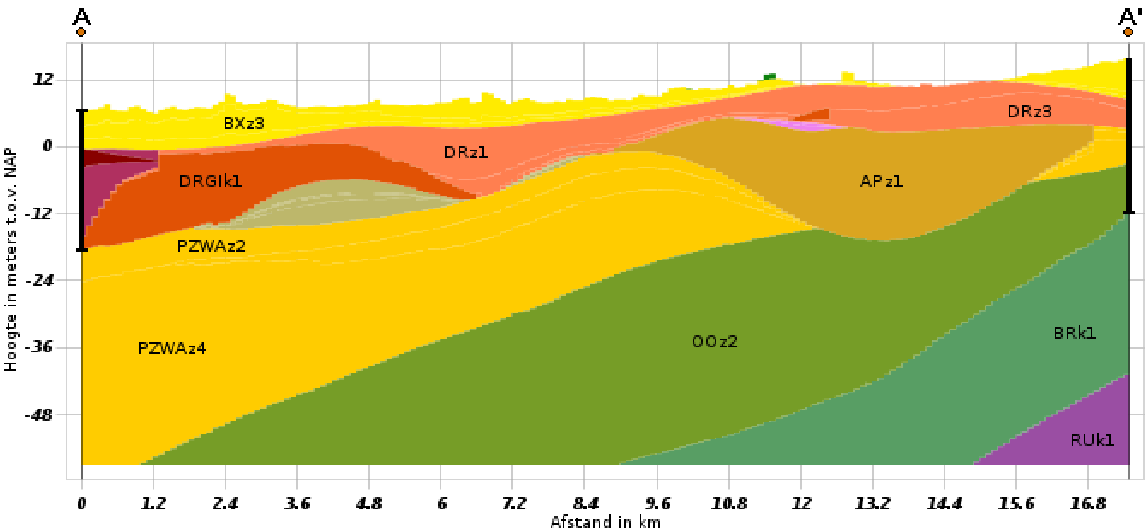

Figure 34: Cross section of the peat area from West to East (WE)

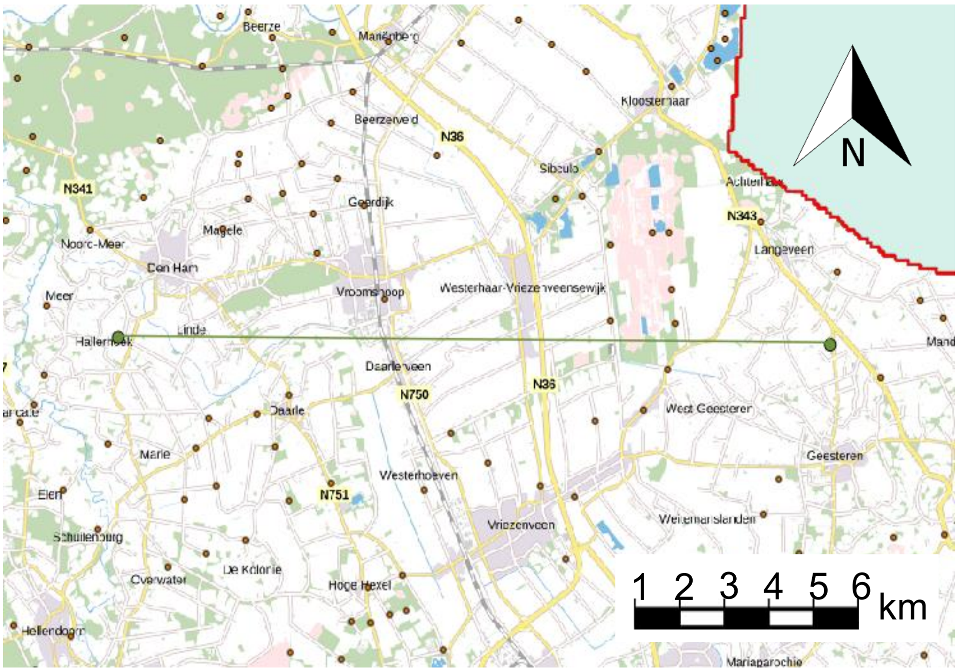

Figure 35: Top view of the cross section in the peat area (WE)

Appendix 2c River

River

Rivers have influence on the landscape. Due to the constant presence of water, groundwater levels close to the river are often stable. In the last two centuries the focus of river management has become discharging the water as fast as possible. This has the consequence that the area somewhat further away of the river is not as influenced at it once was. This in combination with the construction of summer quays, groynes and breakwaters, the groundwater level is lower in certain area's than it was back in the days. The areas around rivers often include multiple clay layers. What this means is that those layers hold a lot of water and lose it very slowly. Because of the presence of the river the drought will not have a huge impact on the groundwater levels. This also comes with the fact that in the river area a lot of irrigation is going on what also helps stabilizing the groundwater levels.

The cross sections (Figure 36 and Figure 38) show that the upper most layers of the river area are against the expectations holding a lot of sand. This means that the area has a fast infiltration of the ground. In combination with the presence of rivers this will result in a stable groundwater level around the rivers.

For the river area, the north-south (NS) line is drawn from the east of Tiel to Loosbroek (Figure 37). The West-East (WE) line is drawn from Vuren to a point east of Groesbeek (laying against the German border) (Figure 39).

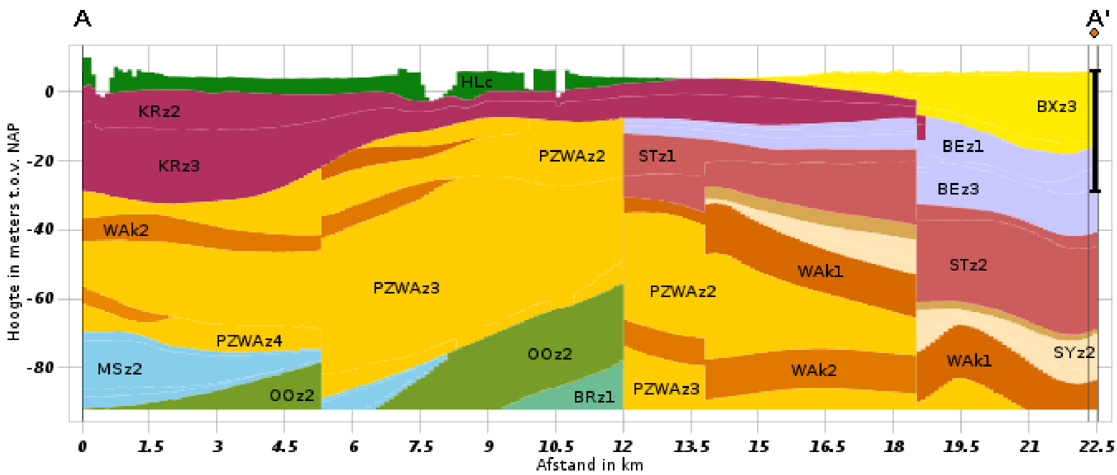

Figure 36: Cross section of the River area from North to South (NS)

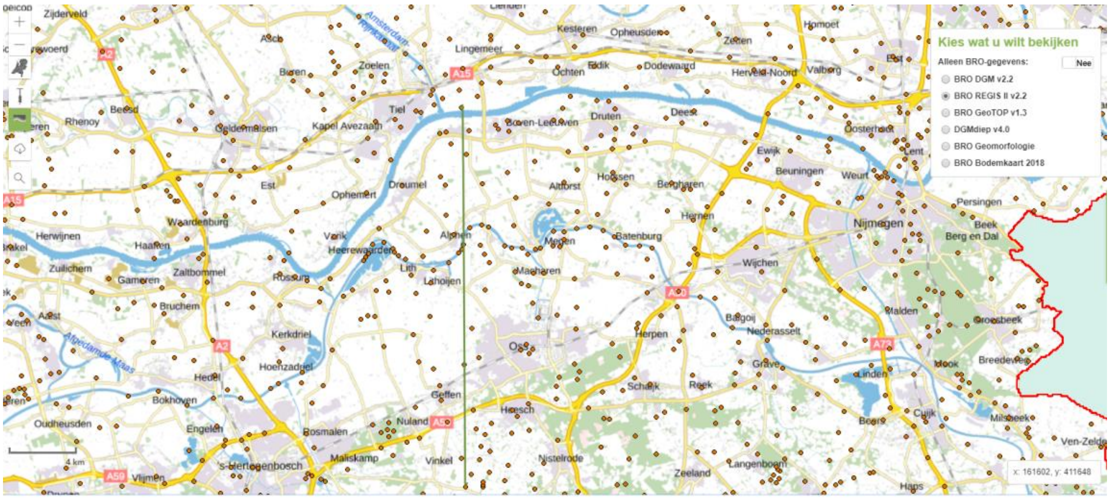

Figure 37: Top view of the cross section in the river area (NS)

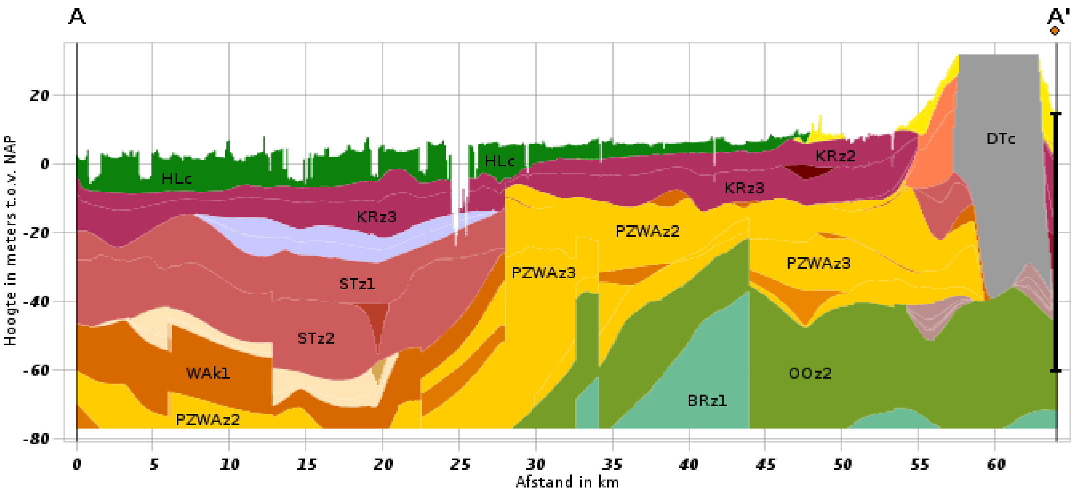

Figure 38: Cross section of the river area from West to East (WE)

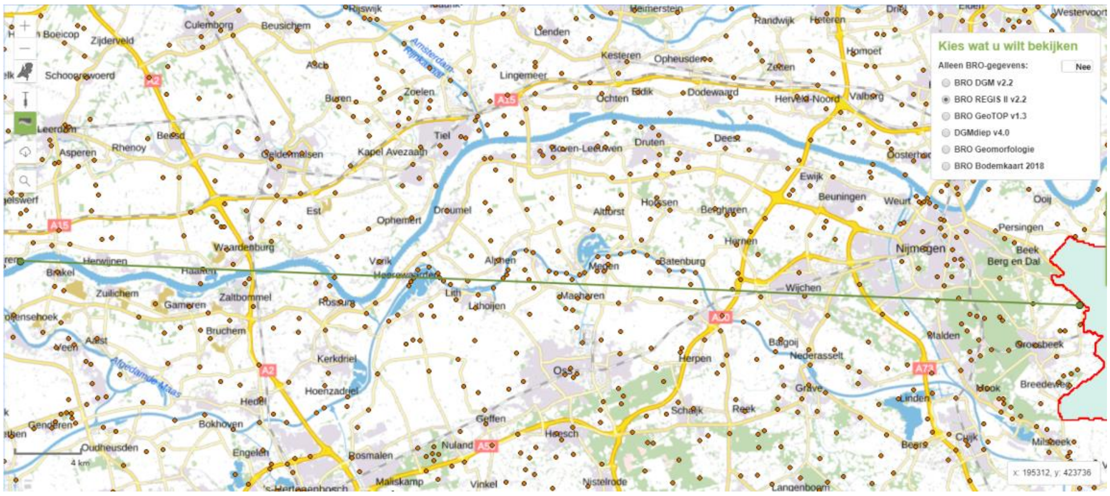

Figure 39: Top view of the cross section in the river area (WE)

Appendix 3 Monitoring wells

The backbone of this research is data. It is the data that is analysed and combined with knowledge which will give answers to the research questions. Because data is so important, it is also important to know where it came from. Therefore we dive in some theory of the monitoring wells using *Handboek meten van grondwaterstanden in peilbuizen* (Bouma, Maasbommel, & Schuurmans, 2012).

Appendix 3a Definition

A monitoring well is used to determine the groundwater level. It is often a steel pipe into the ground with a filter on the bottom side (Figure 40). Groundwater flows through this filter and levels with the groundwater level. Because a monitoring well is only one vertical tube into the ground, these wells are point monitoring devices and can only provide good representations of the groundwater levels of an area if multiple monitoring wells are present. To give a good view of an area, multiple spatially distributed measurement wells are needed (Averink, 2013).

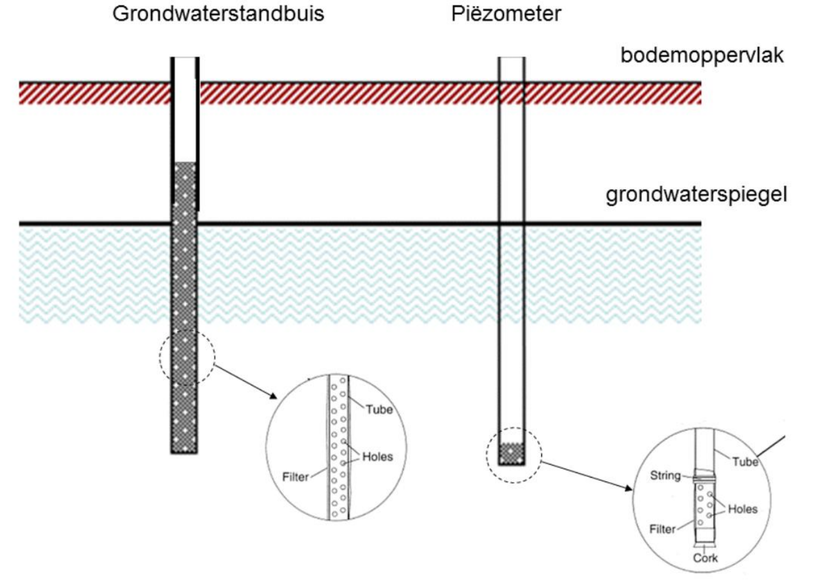

Figure 40: Groundwater wells (Ritzema, et al., 2012)

Appendix 3b Placement

Groundwater wells are tactically placed so they are not affected by local factors. This is done so the measured groundwater level corresponds with the groundwater level of the surrounding area. To secure that the measurements are not influenced by local factors some rules of where **not** to place them are drawn:

- In pits or at height because of rainwater flow into or away from the monitoring well.
- Close to a waterway because of the groundwater level normally deviates strongly around there. Minimum distances from waterways are:
    - River or canal: minimum of 100 meter
    - (Main)waterways: minimum of 25 meter and if possible 50 meter
    - Ditch or trench: minimum of 10 meter and if possible 25 meter
- When groundwater is withdrawn from the area
- Hardening of the ground. In cities this is unavoidable so a 10 meters distance of buildings is required.
- Closer than 15 meters to trees.
- Drainage and local supply, for example when rainwater gets transported somewhere else through the sewage system.

Appendix 3c Methods

There are multiple ways groundwater levels are measured. First there are manually operated gauges: the classical analogue level gauge and the newer contact gauge. The classical analogue level gauge makes a sound when it hits the water, the contact gauge lights up a lamp or gives a sound when an electrode that is send down hits the water. Both use a measuring tape that is used to see how deep the gauge is and thus what the groundwater level is.

Second there are data loggers. These use the water pressure to determine the groundwater levels and give an electric signal so the groundwater level can be converted to data more often. In this category also ultrasonic sensors can be placed, which make use of a pulse that reflects on the water and is registered by the sensor.

Sometimes there are multiple measurements wells placed at one spot. For example, these are used for mapping of deeper aquifers or research on salination with the use of the piezometer (Figure 40). When the data is retrieved it is important to retrieve it from the unconfined aquifer because that is the layer which is interesting for this research as stated in section 1.2.

Appendix 4 Methods for the computation of recurrence times

The method of Weibull (Booij, 2017)

$$P(x \geq X) = \frac{r}{N+1} \quad (6)$$

The method of Gringorten (Booij, 2017)

$$P(x \geq X) = \frac{r - 0.44}{N + 0.12} \quad (7)$$

In the formulas, *r* is the rank of the measurements and *N* is the total number of measurements. These two methods focus on the rank of all the groundwater levels. When using Weibull it is not possible that the recurrence time exceeds the duration of the dataset. So for this research it is not possible that the recurrence time gets exceeds 62 years.

The following equations are parts of the generalized extreme value (GEV) distribution, also known as the Gumbel distribution (Palutikof et al., 1999). This distribution can be used when the measurement well data follows a Gumbel distribution.

$$F(x) = \exp[-(1 - ky)^{\frac{1}{k}}] \qquad k \neq 0 \quad (8)$$

$$F(x) = \exp[-\exp(-y)] \qquad k = 0 \quad (9)$$

The shape parameter *k* determines the type of extreme value distribution. In this research the value of 0.5772 is chosen because the groundwater well data behaves similar to discharge distributions (Booij, 2017). The standardized or reduced variate y is given by:

$$y = \frac{x - \beta}{\alpha} \quad (10)$$

$$\beta = \mu - \gamma\alpha \quad (11)$$

$$\alpha = \frac{\sigma\sqrt{6}}{\pi} \quad (12)$$

x is the stochastic variable, the groundwater level in this case, *μ* is the mean of the distribution and *σ* is the standard deviation.

Appendix 5 Legends of soil maps

Figure 41: (Dutch) Legend of the soil map of the sand area

Figure 42: (Dutch) Legend of the soil map of the peat area

Soil types of the river area (Dutch)

- Linge-uiterwaardgronden
- Overslaggronden
- Petgaten
- Radebrikgronden; fijnzandige lichte zavel
- Tuineerdgronden; zandige leem
- Lage enkeerdgronden; leemarm en zwak lemig fijn zand
- Haarpodzolgronden; leemarm en zwak lemig fijn zand
- Haarpodzolgronden; grof zand
- Veldpodzolgronden; leemarm en zwak lemig fijn zand
- Veldpodzolgronden; lemig fijn zand
- Veldpodzolgronden; grof zand
- Ooivaaggronden, lichte zavel
- Poldervaaggronden; lichte zavel
- Poldervaaggronden; zware zavel
- Poldervaaggronden; klei
- Ooivaaggronden met roest beginnend dieper dan 80 cm; zandige leem in situ
- Poldervaaggronden; zandige leem in situ
- Kalkrijke poldervaaggronden; zware zavel, profielverloop 5
- Kalkrijke poldervaaggronden; lichte klei, profielverloop 5
- Kalkrijke poldervaaggronden; klei, profielverloop 2
- Kalkrijke nesvaaggronden; klei
- Kalkrijke drechtvaaggronden; klei, profielverloop 1
- Kalkhoudende ooivaaggronden; lichte zavel
- Kalkloze ooivaaggronden; lichte zavel
- Kalkhoudende ooivaaggronden; zware zavel en lichte klei
- Kalkloze ooivaaggronden; zware zavel en lichte klei
- Kalkloze poldervaaggronden; lichte zavel, profielverloop 4
- Holtpodzolgronden; leemarm en zwak lemig fijn zand
- Holtpodzolgronden; grof zand
- Kalkhoudende vorstvaaggronden; fijn zand
- Vorstvaaggronden; leemarm en zwak lemig fijn zand
- Vorstvaaggronden; lemig fijn zand
- Vorstvaaggronden; grof zand
- Duinvaaggronden; leemarm en zwak lemig fijn zand
- Duinvaaggronden; grof zand
- Vlakvaaggronden; leemarm en zwak lemig fijn zand
- Vlakvaaggronden; lemig fijn zand
- Vlakvaaggronden; grof zand
- Kalkhoudende vlakvaaggronden; grof zand
- Kalkhoudende vlakvaaggronden; matig fijn zand
- Hoge bruine enkeerdgronden; leemarm en zwak lemig fijn zand
- Hoge bruine enkeerdgronden; lemig fijn zand
- Hoge bruine enkeerdgronden; grof zand
- Kamppodzolgronden; leemarm en zwak lemig fijn zand
- Kamppodzolgronden; grof zand
- Laarpodzolgronden; leemarm en zwak lemig fijn zand
- Laarpodzolgronden; grof zand
- Loopodzolgronden; grof zand
- Akkereerdgronden; leemarm en zwak lemig fijn zand
- Akkereerdgronden; grof zand
- Waardveengronden op bosveen (of eutroof broekveen)
- Waardveengronden op (meestal niet-gerijpte) zavel of klei, beginnend ondieper dan 120 cm
- Waardveengronden op zand, beginnend ondieper dan 120 cm
- Kalkhoudende poldervaaggronden; lichte zavel, profielverloop 5
- Kalkloze poldervaaggronden; lichte zavel, profielverloop 5
- Kalkloze poldervaaggronden; zware klei, profielverloop 2
- Kalkloze poldervaaggronden; zware klei, profielverloop 4
- Kalkhoudende poldervaaggronden; zware klei, profielverloop 5
- Kalkhoudende poldervaaggronden; zware klei, profielverloop 3, of 3 en 4 , of 4
- Kalkloze poldervaaggronden; zware klei, profielverloop 3, of 3 en 4
- Kalkhoudende poldervaaggronden; zavel, profielverloop 2
- Kalkloze poldervaaggronden; zavel en lichte klei, profielverloop 2
- Kalkhoudende poldervaaggronden; zavel en lichte klei, profielverloop 3, of 3 en 4, of 4
- Kalkloze poldervaaggronden; zavel en lichte klei, profielverloop 3, of 3 en 4
- Kalkhoudende poldervaaggronden; klei, profielverloop 2
- Kalkloze poldervaaggronden; zware zavel en lichte klei, profielverloop 4
- Kalkhoudende poldervaaggronden; zware zavel en lichte klei, profielverloop 5
- Kalkloze poldervaaggronden; zware zavel en lichte klei, profielverloop 5
- Kalkloze nesvaaggronden; zware klei
- Kalkhoudende nesvaaggronden; zavel en lichte klei
- Kalkloze nesvaaggronden; zavel en lichte klei
- Kalkhoudende drechtvaaggronden; profielverloop 1
- Kalkloze drechtvaaggronden; profielverloop 1
- Vlierveengronden op zeggeveen, rietzeggeveen of (mesotroof) broekveen
- Moerige eerdgronden met een moerige bovengrond of moerige tussenlaag op gerijpte zavel of klei
- Moerige podzolgronden met een zavel- of een kleidek en een moerige tussenlaag
- Moerige eerdgronden met een zavel- of kleidek en een moerige tussenlaag op zand
- Leek-/woudeerdgronden; lichte zavel
- Leek-/woudeerdgronden; zware zavel
- Leek-/woudeerdgronden; zandige leem; colluvium in dal
- Kalkarme leek-/woudeerdgronden; klei, profielverloop 3, of 3 en 4 of 4
- Weideveengronden op zeggeveen, rietzeggeveen of (mesotroof) broekveen
- Weideveengronden op zand, beginnend ondieper dan 120 cm
- Beekeerdgronden; leemarm en zwak lemig fijn zand
- Beekeerdgronden; lemig fijn zand
- Beekeerdgronden; grof zand
- Gooreerdgronden; leemarm en zwak lemig fijn zand
- Gooreerdgronden; lemig fijn zand
- Gooreerdgronden; grof zand
- Moerige eerdgronden met een moerige bovengrond op zand
- Hoge zwarte enkeerdgronden; leemarm en zwak lemig fijn zand
- Hoge zwarte enkeerdgronden; lemig fijn zand
- Hoge zwarte enkeerdgronden; grof zand
- Meerveengronden op zand met humuspodzol, beginnend ondieper dan 120 cm
- Moerige eerdgronden met een zanddek en een moerige tussenlaag op zand
- Zand-, leem- of grindgroeve
- Afgegraven
- Opgehoogd of opgespoten
- Oude bewoningsplaatsen
- Moeras
- Water
- Bebouwing
- Dijk

Figure 43: (Dutch) Legend of the soil map of the river area

Appendix 6 **Histograms**

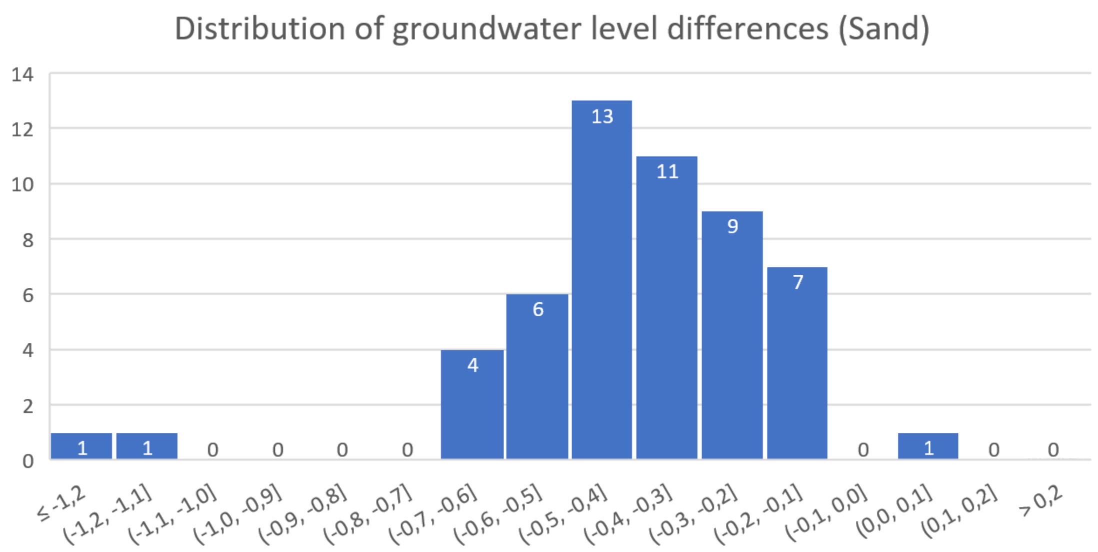

Figure 44: Histogram of the groundwater level differences between the LG3 of 2018 and the MLGL of the time period 2010-2017 in the sand area

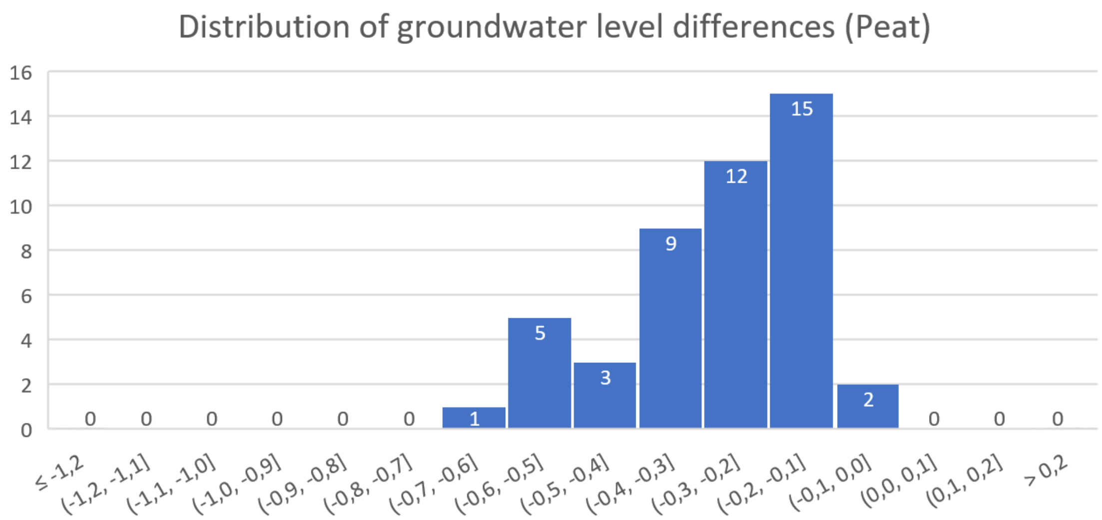

Figure 45: Histogram of the groundwater level differences between the LG3 of 2018 and the MLGL of the time period 2010-2017 in the peat area

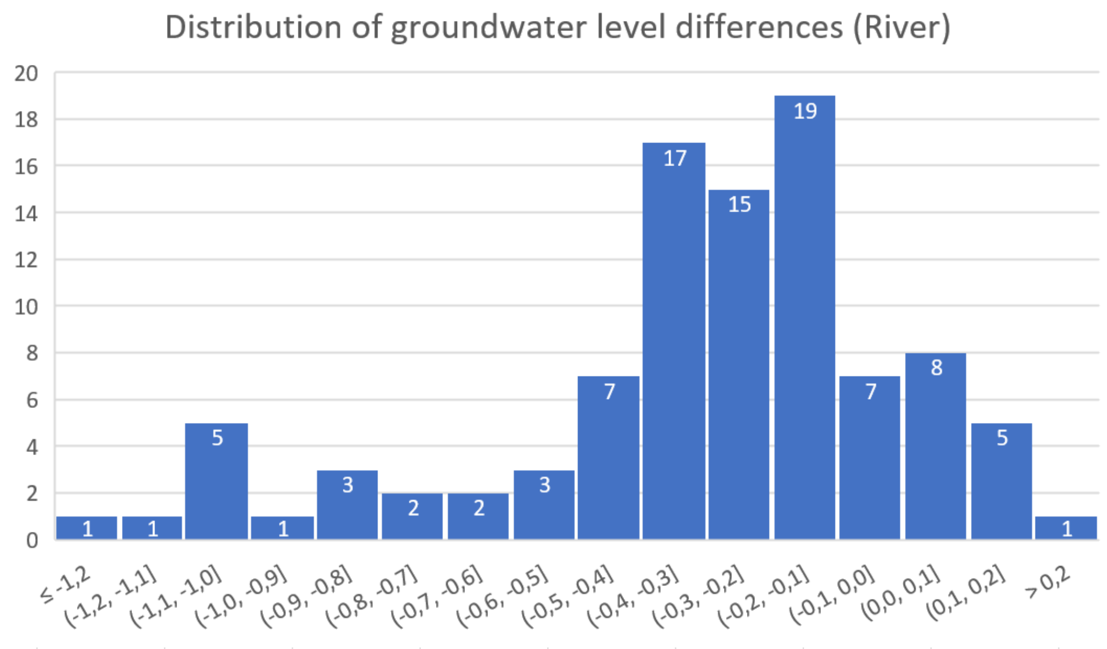

Figure 46: Histogram of the groundwater level differences between the LG3 of 2018 and the MLGL of the period 2010-2017 in the river area

Appendix 7 Results of the other methods to compute the recurrence times

Figure 47, Figure 48 and Figure 49 show that the different methods provide different outcomes for one single measurement well which is chosen randomly. Every line displays another method. The dotted line is the LG3 of the year 2018 which intersects the exceedance frequencies predicted with the different methods. From these intersections the recurrence time of the LG3 of 2018 for each measurement well can be determined. The recurrence times for each measurement well can be found in Table 6, Table 7 and Table 8.

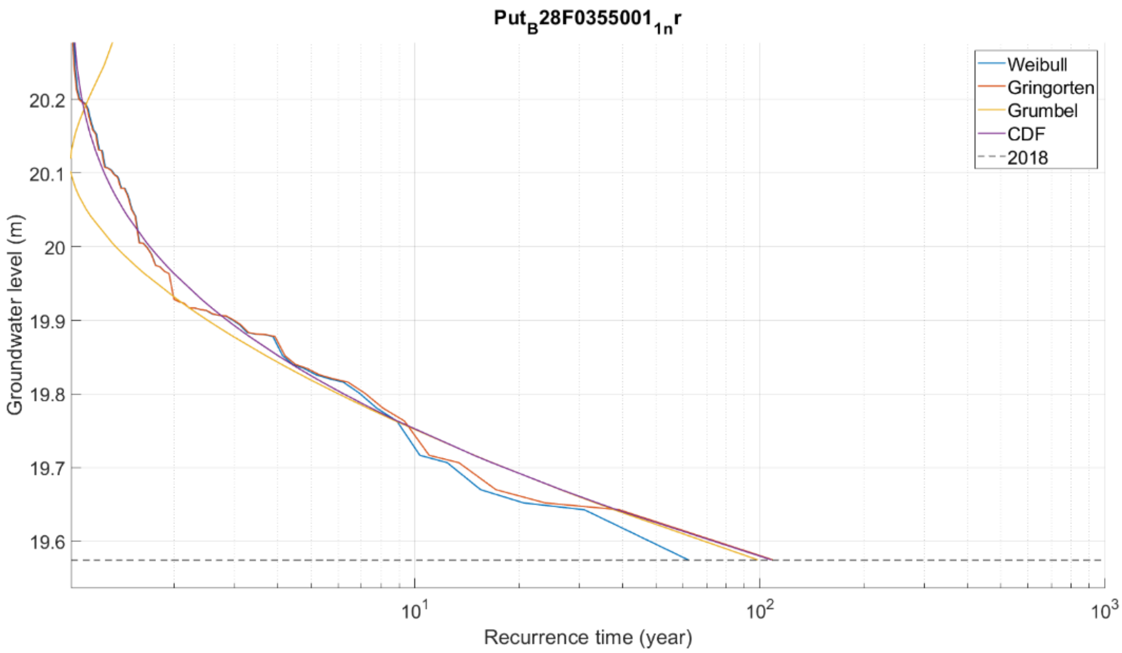

Figure 47: Visualisation of the recurrence times plotted against the groundwater level of measurement well B28F0355 for four different methods in the sand area.

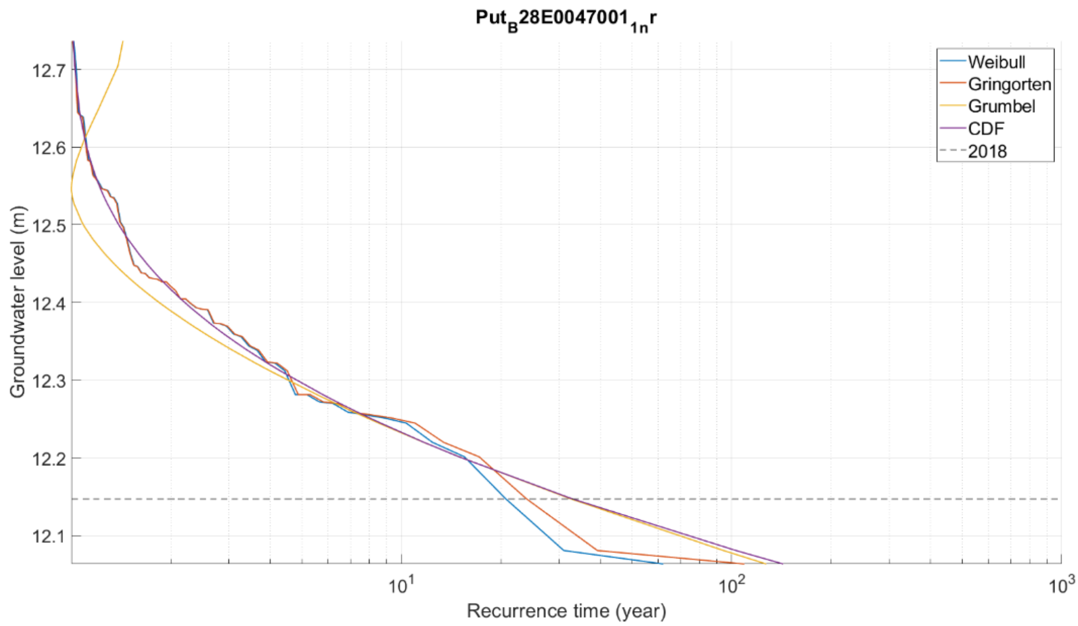

Figure 48: Visualisation of the recurrence times plotted against the groundwater level of measurement well B28E0047 for four different methods in the peat area.

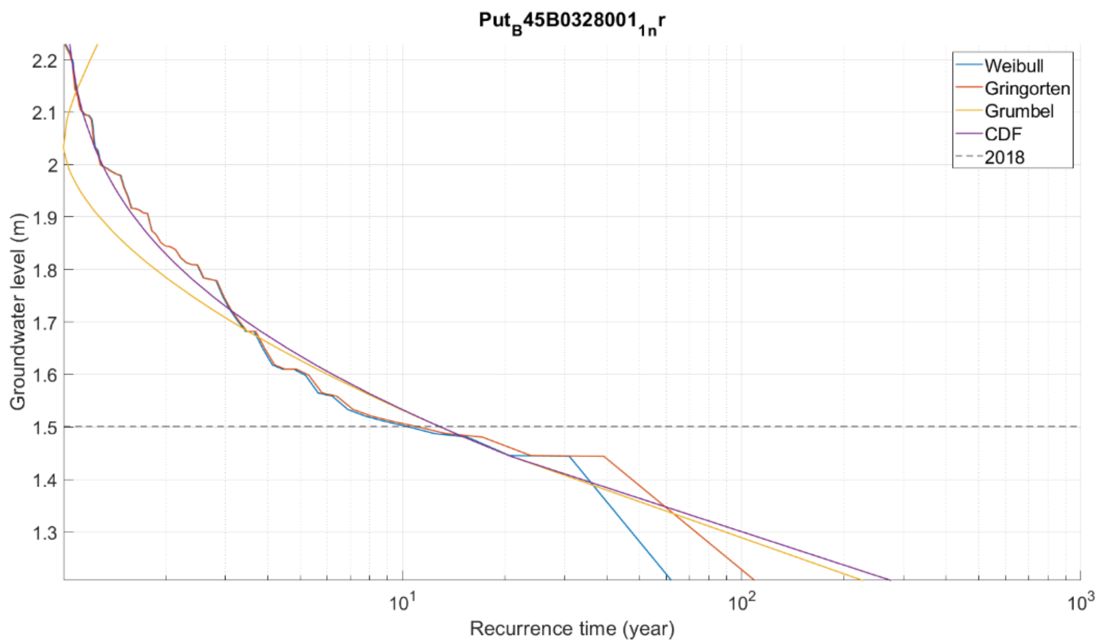

Figure 49: Visualisation of the recurrence times plotted against the groundwater level of measurement well B45B0328 for four different methods in the river area.

Table 6: Recurrence times of the sand area including all four methods used and the corresponding groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 (negative values indicate a lower groundwater level in 2018, positive values indicate a higher groundwater level in 2018).

Measurement well	Rank	Weibull (year)	Gringorten (year)	Gumbel (year)	CDF (year)	Difference (m)
B28F0162002	7	8,9	9,3	10,9	10,9	-0,49
B28F0355001	1	62,0	109,1	108,0	98,6	N.A.
B28G0408001	2	31,0	39,2	64,4	61,4	-0,54
B28H0296001	2	31,0	39,2	48,1	46,7	-0,35
B28H0323001	4	15,5	17,2	18,0	18,0	-0,24
B28H0424001	5	12,4	13,4	28,1	28,0	-0,47
B28H0436001	7	8,9	9,3	11,0	10,9	-0,37
B28H0614001	2	31,0	39,2	124,0	111,7	-0,58
B28H0622001	3	20,7	23,9	48,8	47,3	-0,37
B28H0653001	2	31,0	39,2	12,6	12,6	-0.24
B28H0679001	2	31,0	39,2	53,0	51,2	-0,39
B28H0680001	3	20,7	23,9	17,5	17,6	-0,21
B29A0154001	3	20,7	23,9	25,7	25,6	N.A.
B29A0157001	2	31,0	39,2	76,8	72,2	N.A.
B29C0118001	3	20,7	23,9	77,0	72,4	-0,55
B29C0191001	1	62,0	109,1	85,1	79,3	-0,41
B29C0211001	1	62,0	109,1	214,3	182,2	-0,62
B29C0217001	4	15,5	17,2	20,4	20,4	-0,34
B29C0228001	2	31,0	39,2	55,4	53,3	-0,4
B34F1173001	2	31,0	39,2	115,7	105,0	N.A.
B34F1204001	6	10,3	11,0	10,0	10,0	-0,21
B34F1314001	12	5,2	5,3	5,8	5,6	-0,11
B34F1399001	4	15,5	17,2	21,6	21,6	-0,36
Average	3,5	26,5	36,4	54,4	50,5	-0,38
Median	3	20,7	23,9	48,1	46,7	-0,26

Table 7: Recurrence times of the peat area including all four methods used and the corresponding groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 (negative values indicate a lower groundwater level in 2018, positive values indicate a higher groundwater level in 2018).

Measurement well	Rank	Weibull (year)	Gringorten (year)	Gumbel (year)	CDF (year)	Difference (m)
B22D0062001	2	31,0	39,2	105,5	96,6	-0,23
B22D0237001	3	20,7	23,9	39,5	38,8	N.A.
B22D0239001	3	20,7	23,9	28,6	28,4	-0,22
B22D0333001	5	12,4	13,4	12,6	12,6	N.A.
B22D0342001	3	20,7	23,9	14,6	14,7	N.A.
B22D0354001	3	20,7	23,9	21,2	21,3	N.A.
B22G0051001	1	62,0	109,1	153,8	135,7	-0,27
B28B0236001	3	20,7	23,9	18,6	18,6	-0,51
B28D0276001	1	62,0	109,1	272,0	224,8	-0,27
B28D0340001	2	31,0	39,2	59,5	57,0	-0,48
B28D0348001	1	62,0	109,1	124,2	111,9	-0,49
B28E0032002	3	20,7	23,9	17,4	17,4	-0,25
B28E0034001	1	62,0	109,1	234,9	197,6	-0,28
B28E0047001	3	20,7	23,9	328,1	32,5	-0,13
B28E0166001	1	62,0	109,1	164,8	144,2	-0,27
B28E0181001	1	62,0	109,1	32,9	265,0	-0,25
B28E0214001	3	20,7	23,9	27,6	27,4	-0,15
B28E0261001	3	20,7	23,9	24,9	24,8	-0,11
B28G0344001	1	62,0	109,1	292,8	239,7	-0,24
B28G0391001	1	62,0	109,1	122,1	110,2	-0,29
Average	2,2	37,8	59,0	104,8	91,0	-0,28
Median	2,5	25,8	31,5	49,5	47,9	-0,26

Table 8: Recurrence times of the river area including all four methods used and the corresponding groundwater level difference between the LG3 of the year 2018 and the MLGL of the period 2010-2017 (negative values indicate a lower groundwater level in 2018, positive values indicate a higher groundwater level in 2018).

Measurement well	Rank	Weibull (year)	Gringorten (year)	Gumbel (year)	CDF (year)	Difference (m)
B45B0328001	6	10,3	11,0	12,9	12,9	-0,09
B45B0453001	27	2,3	2,3	2,3	2,0	N.A.
B45B0491001	5	12,4	13,4	18,6	18,7	N.A.
B45B0492001	13	4,8	4,9	5,0	4,8	N.A.
B45B0496001	8	7,8	8,1	6,7	6,5	N.A.
B45B0564001	5	12,4	13,4	13,3	13,4	N.A.
B45E0502001	13	4,8	4,9	5,1	4,8	N.A.
Average	11,0	7,8	8,3	9,1	9,0	-0,09
Median	8	7,8	8,1	6,7	6,5	-0,09

Appendix 8 Locations of the groundwater measurement wells after the calculation of the recurrence times in the river area

The (Dutch) legend about the soil composition of Figure 50 can be found in Appendix 7.

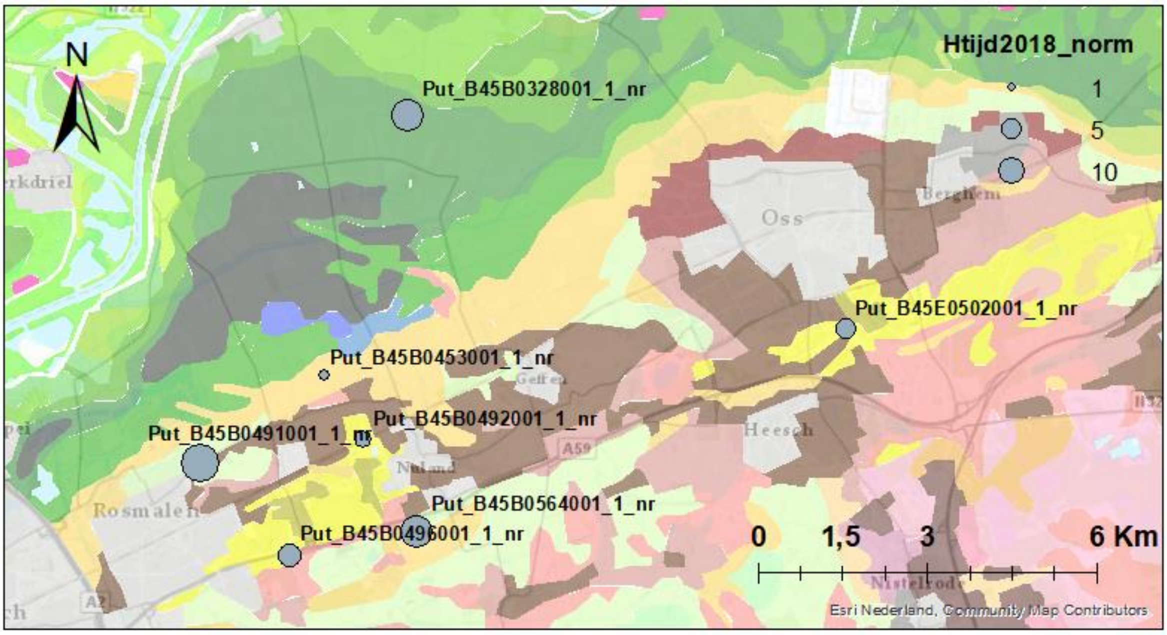

Figure 50: Recurrence times of the river area displayed on a soil map