The effect of measures for nature restoration on groundwater levels in the nature reserve Strabrechtse Heide

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Summary

The Strabrechtse Heide is a large nature reserve which is situated South-East of the city of Eindhoven in the province Noord-Brabant, the Netherlands. This nature reserve is characterized by heathlands and the native species rely on relatively wet conditions. Continuous desiccation has threatened the presence of the native species. In order to counteract biodiversity loss, waterboard De Dommel has implemented nature restoration measures to rewet the Strabrechtse Heide. These measures were conducted in 2013 and 2014.

Time series analysis is performed to analyse the effect of the nature restoration measures on the groundwater levels in Strabrechtse Heide. The open source Python package Pastas for processing, simulating and analysing hydrological time series is used to analyse groundwater time series. Groundwater time series of several locations in the study area have been simulated to quantify the effect of the measures. Precipitation and evaporation data from KNMI, and the measured groundwater levels from 9 piezometers in the study area function as input data to create and calibrate the time series on. Pastas simulates groundwater behaviour through time, based on a calculated relationship between precipitation, evaporation and the measured groundwater level, where Pastas presumes that changes in groundwater level are caused by variability in precipitation and evaporation.

There are 2 groundwater simulations created per studied piezometer. One simulation is based on the calculated relationship between precipitation, evaporation and the groundwater level for period 2014-2019, which includes the effect of the measures. The other one is based on the calculated relationship between these three variables for period 2007-2012, that does not include the measures. All groundwater time series are solved and displayed for a fixed period: 2007-2019, where there is roughly 5 years present before the implementation of the nature restoration measures and 5 years after. Per piezometer, one simulation (2007-2012) is subtracted from the other (2014-2019) to quantify the exact effect of the measures on the groundwater level. Thereafter, the effect is averaged and defined for one year to show the average monthly and seasonal effect of the measures on the groundwater level. Rewetting of the study site is most important for the relatively dry spring and summer, because there is often a shortage in precipitation during these seasons.

The studied piezometers at Marijke Ven and near the measure ‘landcover change from pine forest to heathlands’ show dominant rewetting. The results for the other study locations show an alternation between rewetting and desiccation throughout the averaged year. Desiccation occurs mainly in fall and winter, whereas rewetting of the study site is dominantly present in spring and autumn. Desiccation is likely to be caused by a reduction in the amount of surface water that is present for infiltration due to the relocation of drainage channels, whereas rewetting of the study area in spring is likely to be caused by an increased ability to retain surface water in the study site, which would have been drained before the implementation of the nature restoration measures.

In conclusion, rewetting of the study site is not present for the entire period after the implementation of the measures (2014-2019), but because the study site is mainly rewetted during the dry seasons, the measures have probably resulted in more favourable conditions for the native species.

1. Introduction

The Strabrechtse Heide is a large nature reserve that covers an area of approximately 1,900 hectares (Buskens, 1988; Smits, 2007). This nature reserve is situated South-East of the city of Eindhoven in the province Noord-Brabant, the Netherlands (fig. 1.1). The exposed geological structures at the Earth's surface consist primarily of different types of sand that form a combination of rolling sand dunes and aeolian sand plains (Berendse, 1990). The present land cover in this area is characterized by an alteration between relatively dry areas, which form dominantly dry heathlands and lower situated wet areas, that form wet heathlands and marshes (Van Nunen, 2013).

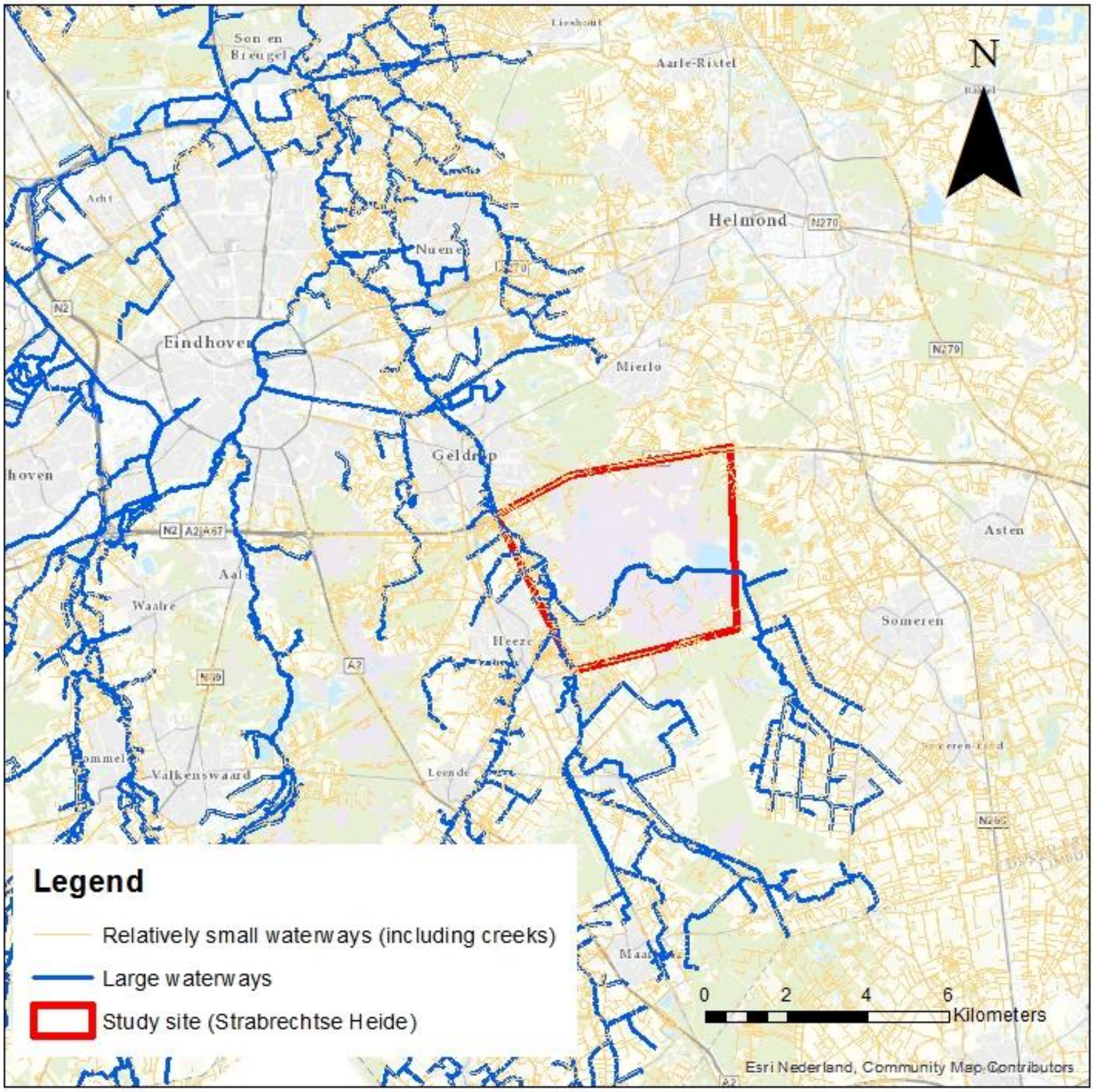

Figure 1.1: study site highlighted on a topographic map that describes a part of the Dutch province Noord-Brabant. Large waterways and small waterways are also depicted (author made: software ArcMap 10.3.1).

The Dutch authority has defined this nature reserve as a protected area with various unique organisms present that need to be protected (Verberk, 2009). One of these unique species is the *Lobelia Dortmanna* (fig. 1.2). This plant is highly rare and flourishes well in wet conditions, such as present in the Strabrechtse Heide (Van Den Boom, 2004).

Figure 1.2: photo of species Lobelia Dortmanna in nature reservation Strabrechtse Heide (Source: Ministerie van Landbouw, Natuur en Voedselkwaliteit, Natura 2000, n.d., Habitattype 'Zeer zwakgebufferde vennen', retrieved on 7-1-2014; https://www.synbiosys.alterra.nl/natura2000/gebiedendatabase.aspx?subj=habtypen&groep=3&id=3110).

The majority of Strabrechtse Heide consists of forest and heathlands (Osieck, 1998). Since the native species rely on relatively wet conditions, continuing desiccation as a result of climate change has been a major concern (Diemont, 1994; Geertsema, 2011; Verberk, 2009). Desiccation has created a large threat for the presence and wellbeing of the native organisms and thus interventions to restore nature were required (Smits, 2007; Verberk, 2009; Wansink, 2012). Besides the Dutch policy to maintain the unique biodiversity in this nature reserve, The Strabrechtse Heide is also involved in nature conservation policy which is called Natura 2000 (Evans, 2012; Janssen, 2014; Maiorano, 2007) (fig. 1.3). This policy is based upon agreements between the member states of the European Union and aims to designate special protection zones for animals, plants and habitats that are endangered to lower biodiversity loss (Bastian, 2013; Chiarucci, 2008; Maiorano, 2007).

The Strabrechtse Heide is owned by 4 parties and maintained by 2 waterboards. The land owners that own together the largest part of this nature reserve are: municipality Someren, municipality Heeze, Brabants Landschap (organisation that focusses on nature protection in Noord-Brabant) and Staatsbosbeheer (national public body, land owner and manager of several Dutch nature reserves). The parties that are involved in nature restoration practises and the maintenance of the nature in the area are waterboard De Dommel and waterboard Aa en Maas (fig. 1.3) (Vermue, 2012; Wansink, 2012). In order to counteract loss of unique native species in this region, mainly caused by desiccation, the Dutch waterboard De Dommel and waterboard Aa en Maas, have performed actions in 2013 and 2014 (Appendix 1). These actions were part of a project to restore the hydrological conditions in the area and essential to maintain and restore the unique ecosystem in the nature reserve (Muilwijk, 2013; Vermue, 2012).

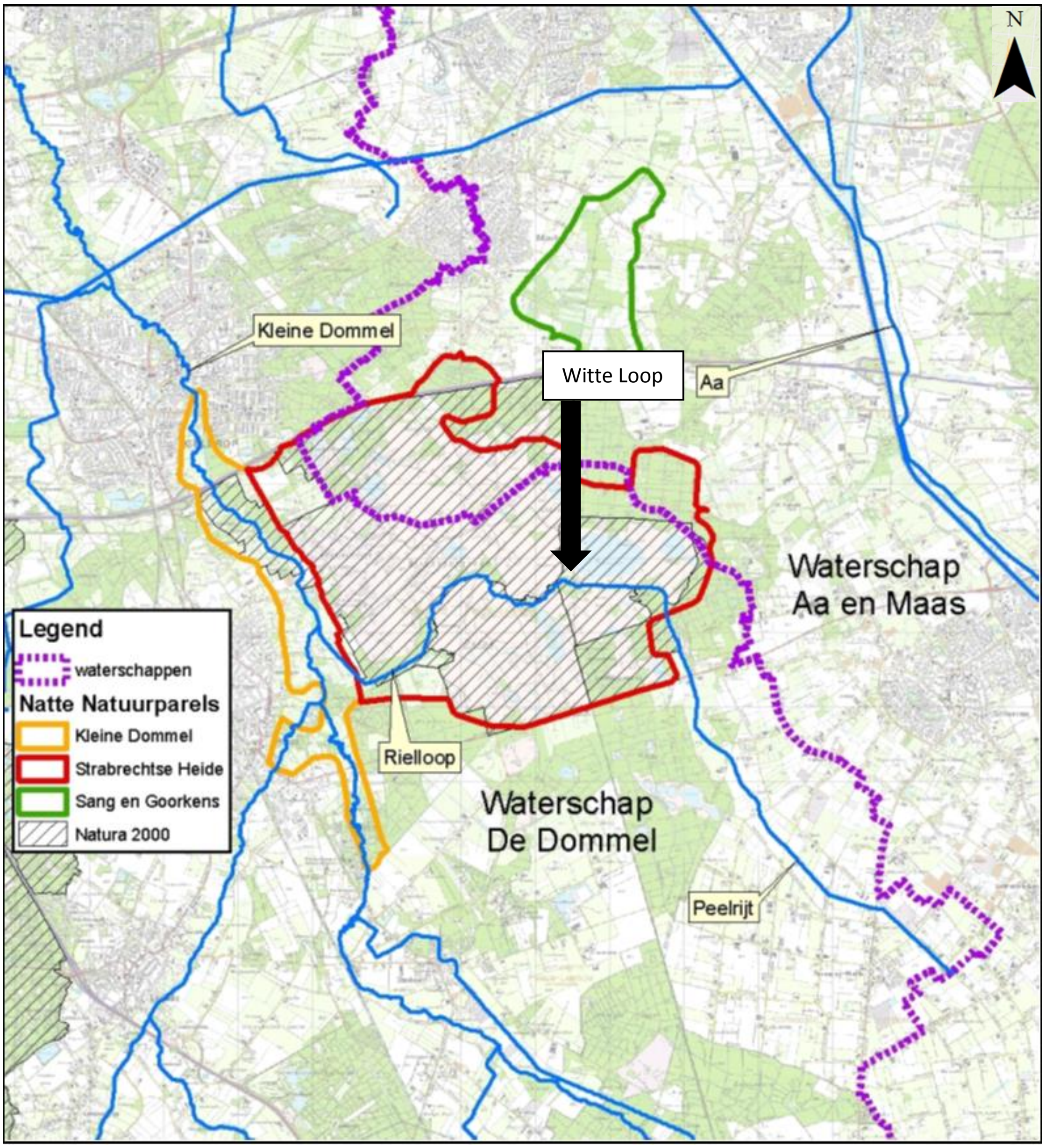

Figure 1.3: illustration of several Dutch nature reserves (categorized below 'Natte Natuurparels') in the Dutch province Noord-Brabant. The red borders defines the study site, Strabrechtse Heide. Further, the dotted purple line displays the border between waterboard 'De Dommel' and Aa en Maas. The Dutch term 'Natte Natuurparels' means nature reserves that are characterized by relatively wet soil conditions and in which the present organisms rely on these wet conditions. The term waterschap is the Dutch translation for waterboard. The blue lines define relatively large waterways. (initial figure is modified. There is no scale defined in this figure, which originates from Vermue, 2012).

1.1 Objective

The main objective of this study is to determine the exact effect of the nature restoration measures (further explanation chapter 2; Appendix 1) on the hydrological conditions in the nature reserve Strabrechtse heide. Waterboard De Dommel is highly interested in an independent research that clarifies the effect of the activities on the groundwater levels in the region. In addition, a nuanced view on the actual effect of the taken actions by De Dommel will provide information about how to accomplish nature restoration in the future.

1.2 Research questions and hypothesis

In order to quantify the effect of the nature restoration measures in the Strabrechtse Heide, the following research questions were defined:

1. How are groundwater levels in nature reserve Strabrechtse Heide affected by measures taken by waterboard 'De Dommel' for nature restoration?

   1.1 What measures were taken by waterboard De Dommel to restore nature in the nature reserve Strabrechtse Heide?
   1.2 What factors affect the groundwater levels in the Strabrechtse Heide?
   1.3 How can distinction be made between natural variability and the effect of the measures on the groundwater?

The hypothesis is that:

- The implemented nature restoration measures resulted in a reduction of the desiccation and a rise in groundwater level in the study site.

1.4 Thesis outline

This thesis is divided in 6 chapters. Chapter 2 provides a literature review that elaborates on theory that is used and it provides additional information on the study site. Thereafter, chapter 3 describes the relevant material and methods for this study. This chapter focuses on the general approach of this study, the methods of data collection, the methods of data analysis and finally defines how the methods and data analysis will contribute to answer the research question. Chapter 4 will elaborate on the results and the outcomes of this study will be provided. Chapter 5 will discuss the results and criticise the methods. This chapter also provides suggestions for future research. Finally, chapter 6 summarize the main conclusions of this study.

2. Theory

2.1 The study site more in detail

The Strabrechtse Heide is traditionally formed by heathlands. Agricultural activities were implemented on the heatlands in the past, but not anymore (Smits, 2009). Nature restoration has been a major issue in this nature reserve for decades (Vogels, 2009). Around 1952, the largest part of the Strabrechtse Heide was purchased from private land owners by the Dutch government who assigned the public body Staatsbosbeheer the responsibility to maintain the nature reserve (Smits, 2007; Smits, 2009). Controlled fires and shepherding were the dominant human interventions to maintain the unique heathlands until the mid-eighties in the 20th century. These actions focussed on reduction of ecological succession, which was essential to prevent the heathlands from becoming overgrown by trees and plants (Vogels, 2009). Nowadays, the primary actions to maintain the heathlands in this nature reserve include turfing (removing nutrients and the ability for vegetation to root due to removal of the upper stratum of the soil), mow-activities, shepherding, small scale cattle breeding and controlled nature burning (Vogels, 2009).

This study focusses on a sub-area within the nature reserve Strabrechtse Heide (fig. 2.1). The main reason for assigning a smaller study area within Strabrechtse Heide is the data availability and the fact that waterboard De Dommel has implemented most measures in this smaller area (Vermue, 2012). This area has a high density of groundwater observation pipes (piezometers), which are essential to analyse the effect of nature restoration activities on the groundwater level.

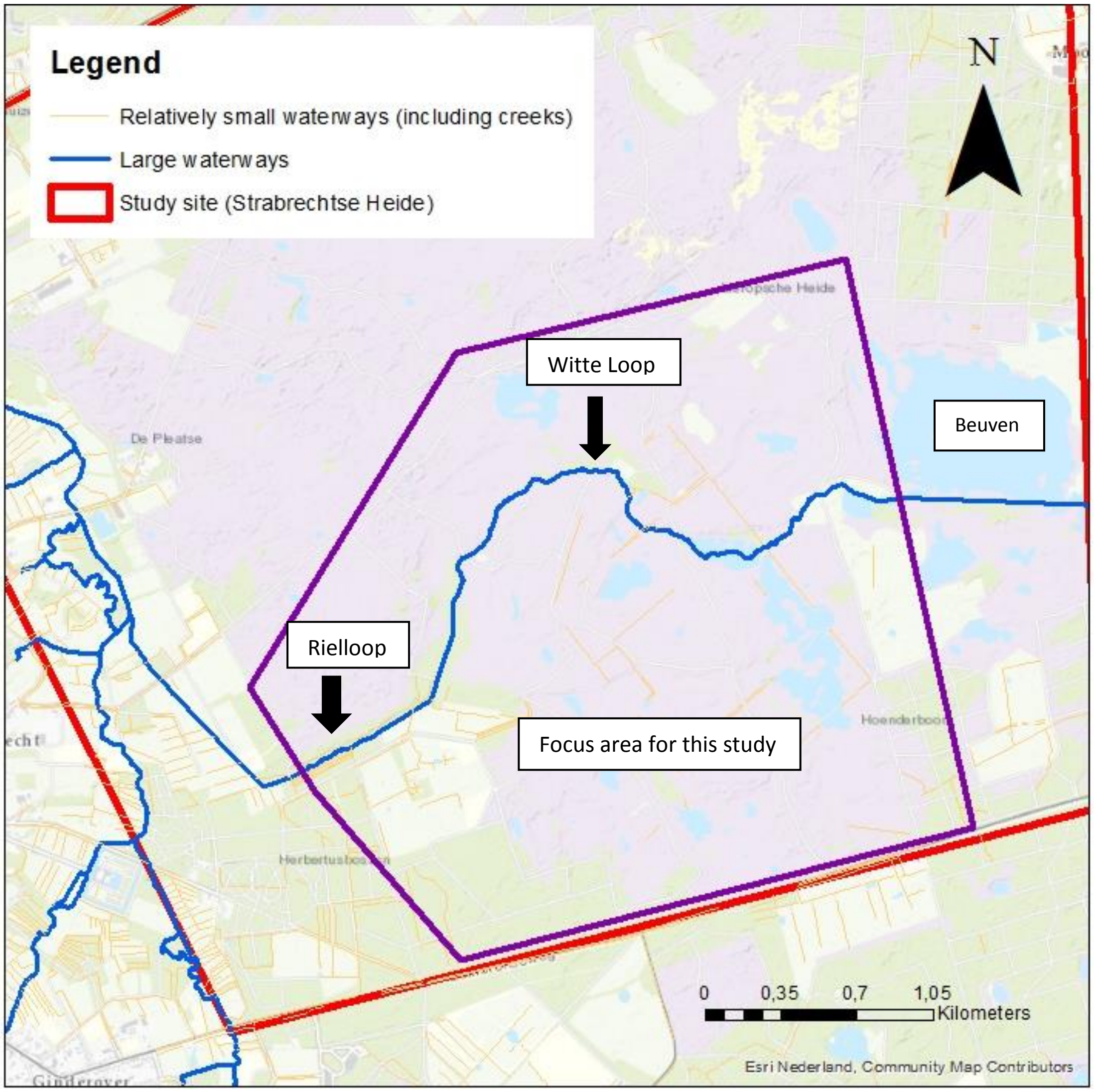

Figure 2.1: illustration of the focus area of this study (defined by the purple polygon) based upon data availability (piezometers) (author made: software ArcMap 10.3.1).

2.2 Factors that influence groundwater levels in the study area

The groundwater level is measured by 125 piezometers that are installed in the study area (fig. 2.2) (Bonte, 2003; Vermue, 2012).

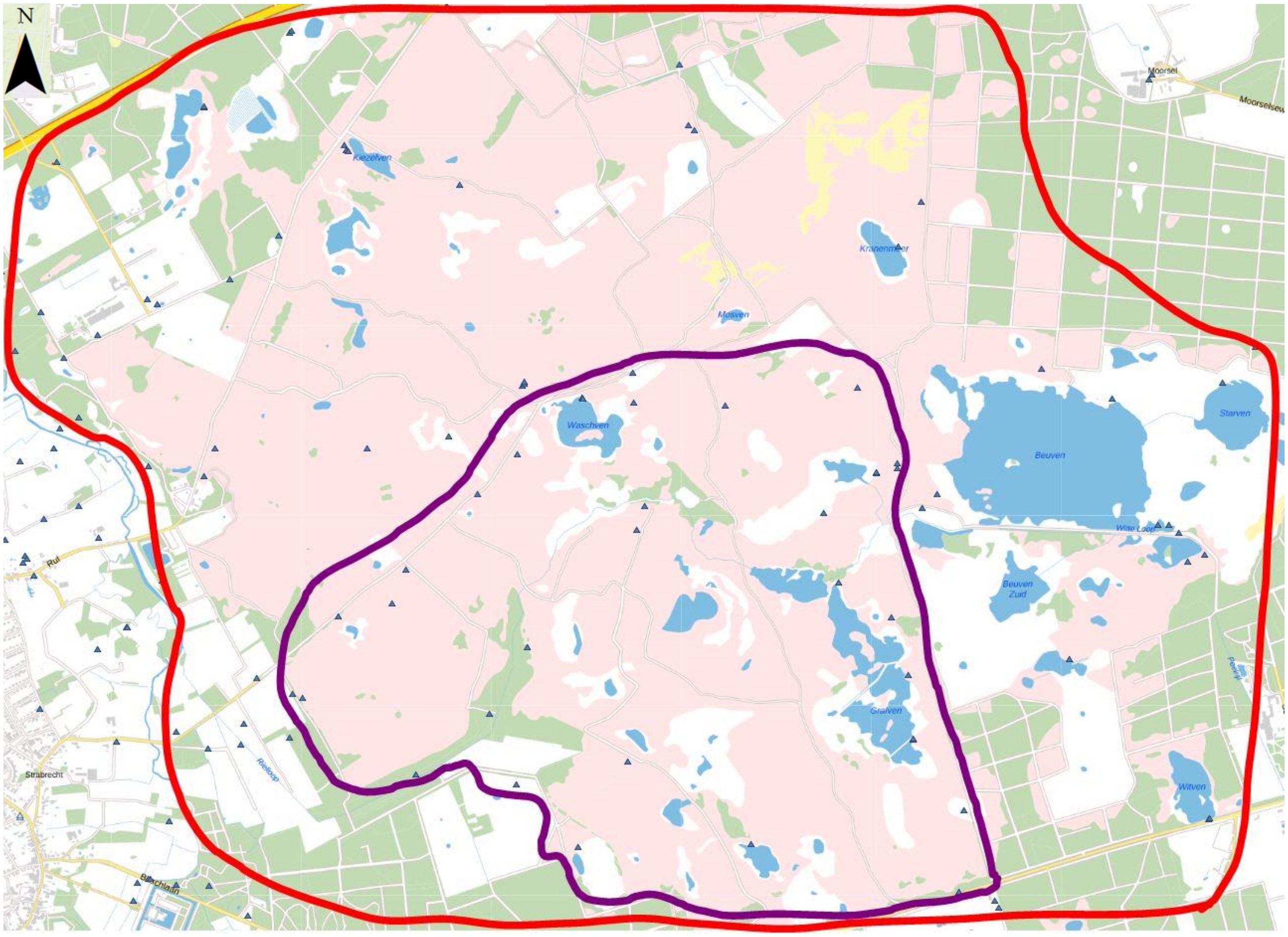

Figure 2.2: rough illustration of the Strabrechtse Heide (defined by the red border) and the specific study site (defined by the purple border). Specific study site is determined based upon spatial orientation of the conducted nature restoration measures (Appendix 1) and the location of piezometers that might clarify the effect of the measures on the groundwater. Blue triangles display the locations of piezometers. Definition of scale was not defined, however the size of the Strabrechtse Heide and the specific site has been illustrated in figure 1.1 and 2.1. (Initial figure is modified) (Source: DINOloket (Data en Informatie Van de Nederlandse Ondergrond), n.d., retrieved on 7-4-2019; https://www.dinoloket.nl/ondergrondgegevens).

The groundwater level is influenced by several main factors and underlying principles. These are summarized in table 2.1. These factors and principles will be discussed in relation to the conditions present in the Strabrechtse heide.

Table 2.1: important factors affecting groundwater levels with the important principles behind each factor. These factors and principles hold in general when looking at groundwater flow. Table is author made.

Factors that affect groundwater	**Important principles per factor**	**Source**
Soil/Geology	- Field capacity - Hydraulic conductivity - Infiltration capacity - Percolation capacity - Evaporation rate (also influenced by vegetation), especially in soils with a high soil moisture - Impermeable layer(s) that forces water to stream towards the Earth's surface	Chen, X., Qi, H., 2004; Fossen, H., 2016; Hendriks, M., 2010; Maxwell, et al., 2007; Veihmeyer, et al., 1949
Relief	- Surface runoff determines water availability for infiltration and percolation - Groundwater flow: direction and hotspots (often in low situated areas) where groundwater stagnates, rises in the subsurface and reaches the surface.	Toth, J., 1963; Phillips, O. M., 2003; Sreedevi, P. D., et al., 2005
Vegetation	- Holds (surface) water and lower recharge capacity (ratio of surface water that flows towards deep groundwater reservoirs) - Might change transpiration and thus water availability that can infiltrate and percolate	Le Maitre, D., et al., 1999; Naumburg, E., et al., 2005
Surface water (streams and marches/lakes)	- Potential source for continuously replenishment of the groundwater reservoirs	Sophocleous, M., 2002; Fleckenstein, J. H., et al., 2010
Weather	- Determines the ratio between evaporation and precipitation and thus the water availability for infiltration and percolation	Chen, Z., et al., 2004; Gerla, P. J., Ronald, K. M., 1996
Human interventions	- Artificial interventions as irrigation and drainage alter the (local) groundwater levels	Foster, T., et al., 2014

The exposed geological structures at the Earth's surface in the nature reserve Strabrechtse Heide consist dominantly of different types of sand that form a combination of rolling sand dunes and aeolian sand plains (Muilwijk, 2013). The upper 20 metres of the subsurface consist of sand layers altered with locally smaller clay layers (Muilwijk, 2013). Sand has a larger hydraulic conductivity than clay, allowing water to infiltrate and percolate much easier (Chapuis, 2012; Goldenberg, 1984). Clay layers form impermeable layers and force water to flow in horizontal direction rather than vertical. As a consequence, the study site is characterized by seepage at locations where impermeable layers force water to flow towards the surface (Muilwijk, 2013). Underneath the upper 20 metres of the subsurface, one can find coarse sand layers. This formation is characterized by a large hydraulic conductivity, allowing water to easily recharge towards the deep groundwater (Muilwijk, 2013).

Elevation in the study area ranges roughly between 15 meter above sea level (m. asl) in the stream valley of the stream Witte Loop and Rielloop and 25 (m. asl) in the South-Eastern part of the study site (fig. 2.3).

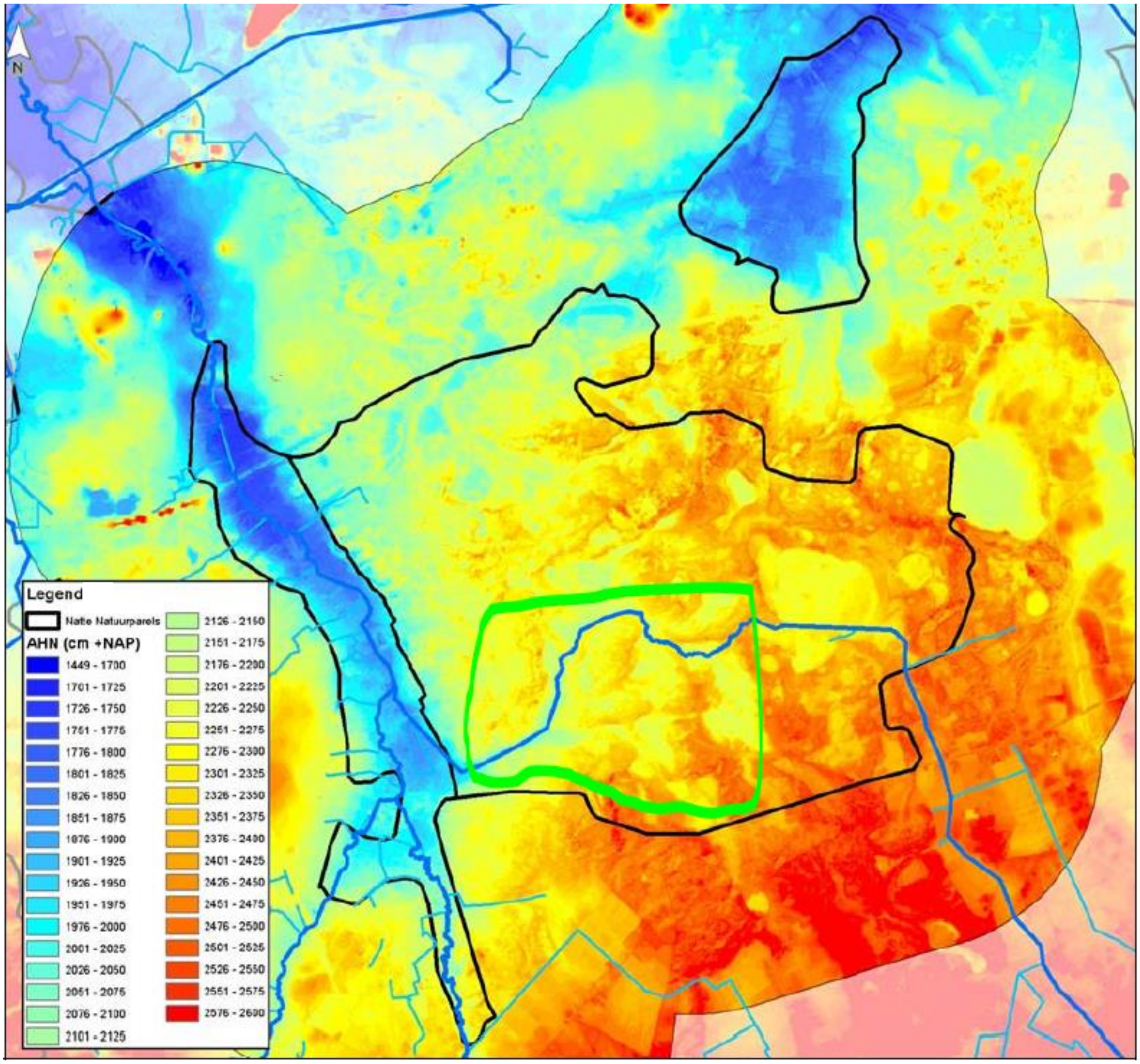

Figure 2.3: relief in the nature reserve Strabrechtse Heide with the specific study site defined by the green coloured border 'cm + NAP' means centimetres above sea level (Adapted from Vermue, 2012).

The difference in altitude in the study area causes groundwater to stream towards the lowest situated areas, the (stream) valleys. When the groundwater replenishment is large in periods characterized by extensive rainfall, seepage occurs in the stream valley causing water to change from groundwater to surface water (Muilwijk, 2013).

Different types of robust vegetation species (e.g. grasses and scrubs) are extensively represented on the heathlands of the Strabrechtse Heide (Vermue, 2012). The robust vegetation types that occur on the heathlands are orientated at the basis of the ecological succession and characterized by a relatively low transpiration rate (Vermue, 2012). Besides the heathlands, the Strabrechtse Heide is traditionally covered by pine forests, which has a high transpiration rate (Gehrels, 1996; Vermue, 2012). Pine trees are evergreen, meaning that the transpiration rate is relatively high in all seasons. These species root deep in the groundwater reservoir and thus affect the groundwater level significantly, because of high groundwater suction and transpiration rates throughout the whole year.

The Strabrechtse Heide and the study site are characterized by an extensive network of surface waters. Beuven is the largest fresh water marsh in this nature reserve which is partly replenished by groundwater (fig. 2.1) (Buskens, 1988; Wansink, 2012). Beuven and the surrounding area form a unique habitat for rare species such as *Lobelia Dortmanna* (chapter 1; fig. 1.2). The Witte Loop and Rielloop cross the area of the specific study site (fig. 2.1). These channels are fed by runoff and drainage from the Strabrechtse Heide itself, as well as precipitation and seepage. Besides these streams and Beuven, other surface waters are situated within the study site (fig. 1.3; 2.1). Most of the marshes were formed during the last ice age by wind erosion that created extensive depressions within the sand plains and dunes (Muilwijk, 2013). Impermeable clay layers at the bottom of these depressions inhibit water to infiltrate, causing water to collect and eventually form marches (Muilwijk, 2013). Most of the mentioned surface water reservoirs act as (indirect) source for groundwater in the study area, especially in periods with extensive rainfall when these surface waters are filled with water and water can infiltrate.

One of the most important factors that influence the groundwater level is the weather. The ratio between evaporation and precipitation is highly important. Evaporation is relatively high compared to precipitation during periods with high ambient temperatures and without significant rainfall. This ratio causes groundwater reservoirs to deplete. On the other hand, continuous periods with extensive rainfall and relatively low air temperatures result in a low ratio evaporation/precipitation, causing replenishment of groundwater reservoirs. The Strabrechtse Heide has an oceanic climate which is characterized by cool summers and mild winters, without extremes of frosts and air temperatures (Van den Boom, 2004). Van den Boom (2004) found that the average annual rainfall was 700 mm and the annual average air temperature 9-10°C. In 2018, The Dutch meteorological institute Koninklijk Nederlands Metereologisch Instituut (KNMI), recorded an annual air temperature in the Netherlands of 11,3 °C and an average annual rainfall of 607 mm (Huiskamp, A., 2019). The year 2018 has been defined as exceptional warm and dry for The Netherlands (Huiskamp, A., 2019). Evaporation was larger than groundwater replenishment by precipitation. As a result, groundwater levels in the whole country including the Strabrechtse Heide lowered substantially. As explained by Hoogland (2010), such exceptionally low groundwater levels endanger the present and native species that rely on relatively wet soil conditions.

Human interventions can strongly affect the groundwater level. Artificial activities such as irrigation practises, drainage activities and groundwater extraction either deplete or replenish the groundwater reservoir (Böhlke, 2002; Bouwer, 1987; Scanlon, 2012). There are several permanent groundwater extraction sites in the vicinity of the Strabrechtse heide. Furthermore, groundwater is used for irrigation in the surrounding areas which are extensively used for agriculture. However, both types of extraction have minor impact on the groundwater levels in the study site (Muilwijk, 2013).

The Strabrechte Heide is not significantly affected by groundwater and surface water from outside the area. Therefore, it is valid to focus only on groundwater dynamics within Strabrechtse Heide. There are no artificial activities in the surrounding area that have large impact on the groundwater level in Strabrechtse Heide. Further, surface water that flows from upstream of Peelrijt towards Strabrechtse Heide is drained Eastwards via the Peelrijt before it arrives at the nature reserve. This water holds chemicals from agricultural activities and is therefore harmful for the plants and animals in Strabrechtse Heide. To prevent this polluted water from entering Strabrechtse Heide, the stream Peelrijt is changed in 1986 and transports all this polluted water Eastwards (Muilwijk. 2013; Vermue, 2012).

2.3 Measures taken by waterboard De Dommel to restore nature

As mentioned in chapter 1, climate change has caused desiccation in the Strabrechtse Heide. To diminish nature loss and to improve nature restoration in this nature reserve, waterboard De Dommel has executed activities, mainly in 2013 and 2014 (chapter 1; Muilwijk, 2013; Vermue, 2012). The activities aimed at improvement of the hydrological circumstances, are defined in a set of measures that is called 'Gewenste Grond- en Oppervlaktewater Regime (GGOR)' (Muilwijk, 2013; Vermue, 2012; Wansink, 2012), roughly translated as 'desired ground- and surface water regime'. The GGOR is a product that is based upon the difference between the 'actual ground- and surface water regime (AGOR)', which considers the ground- and surface water regime before the implementation of the nature restoration measures (<2013), and the 'optimal ground- and surface water regime (OGOR)', which considers the required hydrological conditions for the native species to flourish (Muilwijk, 2013; Vermue, 2012). The GGOR is defined by the difference between the OGOR and the AGOR, and the political orientated interests.

All measures focused on rewetting of the Strabrechtse Heide and had as primary purpose to enlarge the water holding capacity in this nature reserve (Appendix 1). The main measures that are considered in the GGOR are: removing small drainage streams in the heathlands, changing land cover from pine forest to mixed forest without trees that are evergreen, bottom elevation of the streams Witte Loop and Rielloop (fig. 2.1) to maximum 50 centimetres below surface level, drainage restriction in the forests surrounding Strabrechtse Heide and changing the survey activities near Beuven (Vermue, 2013).

Besides the measures that are mentioned above and executed on larger scale in Strabrechtse Heide, there are different nature restoration actions implemented in the smaller area within Strabrechtse Heide that is defined as the main study site (Appendix 1; Muilwijk, 2013). Measures that are implemented in the smaller study site and that focussed on changing land cover had as main intention to lower transpiration from vegetation and thus to lower groundwater depletion (Appendix 1; table 2.1). Closing or changing existing streams and construction of dams, water spreaders and watersplashes had as primary intention to regulate surface runoff and drainage. Water can be kept in an area or drainage can be lowered, especially during dry periods and therefore counteract groundwater depletion (Appendix 1; table 2.1). Lastly, artificial elevation of streams and creeks lower drainage and groundwater depletion, since this action lowers seepage (Appendix 1; table 2.1; Muilwijk, 2013; Vermue, 2012).

2.4 Expectations based on conducted research before the actual implementation of the nature restoration measures

In Dutch hydrology, the groundwater level is often defined by 'gemiddeld hoogste grondwaterstand' (GHG), 'gemiddeld laagste grondwaterstand' (GLG) and 'gemiddeld voorjaarsgrondwaterstand' (GVG). The GHG can be translated by 'average highest groundwater level' (AHG), GLG by 'average lowest groundwater level' (ALG) and GVG by 'average spring groundwater level' (ASG). These 3 variables (often defined by one abbreviation 'GxG' and thus in English: AxG) can be calculated according to 2 principles. The first principle is called 'klassieke methode': to determine the AHG, the three highest groundwater levels in one hydrological year (April 1 to March 31) will be summed and that value will be divided by three to get the yearly average. Then, the average of the yearly determined highest groundwater level for at least 8 hydrological years in a row will form the AHG. The same principle holds for getting the ALG, however the 3 lowest measured groundwater levels will be used instead of the highest measured groundwater levels. There is a slight difference in defining the ASG. This value is also determined based upon the average of 3 values. The groundwater level measured at March 14, March 28 and April 14 (all in spring) are summed and divided by three to get a yearly average. The average value determined by at least 8 yearly average values form the ASG (Hendriks, 2010; Finke, 2005; Verhagen, 2019). The second principle is called 'kwantiel methode': recently developed technologies that register changes in pressure have create possibilities to measure groundwater levels with a larger frequency than in the past (Verhagen, 2019). Due to these innovations, the AHG, ALG and ASG can be assessed by more measurements compared to the 'klassieke methode', which is based on only 3 measurements per year for at least 8 years in a row. The 'kwantiel methode' is based on the frequency the ground water exceeds an earlier defined threshold value (Verhagen, 2019). The question is what the right percentage of exceedance is. This method is compared with the 'klassieke methode' and the outcome of the comparison was that the deviation of the AHG, ALG was lowest when exceedance percentile are 7% for calculation of the ALG and 95% for calculation of the AHG. In other words, 7% of the measured groundwater levels within the validation period lies below the defined ALG and 95% of the measured groundwater levels within the validation period lies below the defined ALG. The ASG is defined by taking the median of the values in the period between March 14 and April 15 (after resampling to daily values).[1]

Around 40 to 50% of the total nature reserve was expected to encounter a rise in groundwater level of at least 5 centimetres (Muilwijk, 2013; Vermue, 2012). For the specific study site (fig. 2.1), elevation of bottom creeks and maintenance of the existing dams in the stream Witte Loop (fig. 2.1; Appendix 1) rises the water holding capacity of the streams and lower soil- and groundwater drainage, since elevation of bottoms causes water in groundwater reservoirs to less frequently flow (seep) to surface water reservoirs from which water can relatively easy be drained off. The zone next to Witte Loop (fig. 2.1; fig. 2.3) is characterized by an AHG and an ASG which is located close below the surface level. Consequently, measures are expected to have minimal impact on the AVG and ASG, since initial groundwater levels cannot rise significantly (Muilwijk, 2013; Vermue, 2012). However, the nature restoration measures are supposed to cause a rise of approximately 10 to 20 centimetres regarding the ALG (Muilwijk, 2013; Vermue, 2012). The ALG at the stream Witte Loop is situated at significant depth beneath the surface, hence when groundwater replenishment is larger than the drainage flux an increase in ALG is expected

In close proximity of the Rielloop (fig. 2.1; Appendix 1), relatively large changes in groundwater level are expected as a result of the nature restoration measures. The AHG and the ASG are supposed to rise 20 to 30 centimetres maximum (Vermue, 2012). The ALG is expected to rise 40 to 50 centimetres maximum (Vermue, 2012). Due to the expected large increases in groundwater level, The Rielloop and the zone next to this stream are supposed to experience increased seepage and thus to be rewetted extensively (Muilwijk, 2013: Vermue, 2012).

The central heathlands in Strabrechtse Heide are expected to encounter an increase in groundwater level of 5 to 10 centimetres (Muilwijk, 2013). For the rest of the total nature reserve and the area in the specific study site (the upper part and the bottom part) it is hard to define a plausible range that

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[1] Caljé, R., van Steijn, T., Collenteur, R., n.d., pastas.stats.dutch module, retrieved on 9-18-2019: https://pastas.readthedocs.io/en/latest/API-docs/pastas.stats.dutch.html

describes groundwater changes. However, it is supposed that the combination of measures has resulted in a net increase in groundwater levels for the entire nature reserve.

2.5 Methods for groundwater analysis

Various methods can be used to study groundwater dynamics. Groundwater flow can be modelled by mathematical based models such as Flairs, 3D finite element method (FEM) and MODFLOW (Capparelli, 2011; Prommer, 2003; Vandenboer, 2014). Time series analysis is another method to study groundwater dynamics (Collenteur, 2019; Hatch, 2006). The last option is relevant for this study.

The effect of the measures on the groundwater level in Strabrechtse heide is analyzed with the open source Python package: Pastas for processing, simulating and analysing hydrological time series (Pastas: hydrological time series analysis, 2019). This software package is developed by Delft University of Technology and Artesia Hydrological Consultancy (Pastas, 2019). Since Pastas is developed and written in programming language Python, all programming tools that are available in Python can be used to model the hydrological time series (Pastas, 2019; Van Rossum, 2007). This allows the user to easily reproduce results or use other data sets without the need to write whole new scripts (Pastas, 2019).

As mentioned, the groundwater level is in principle determined by evaporation and precipitation. However, in most realistic scenarios a constant needs to be added to maintain minimal groundwater levels when the precipitation and evaporation fluxes are zero. The effect of precipitation and evaporation on the groundwater level in time series analysis is often mathematically defined as: $N(t) = P(t) - f * E(t)$, where N(t) is the groundwater recharge flux at time t, P(t) is the precipitation flux at time t and E(t) is the evaporation flux at time t. The evaporation term (E(t)) needs to be multiplied by factor f that is defined conform the present physical conditions (e.g. for potential evaporation, f might be 1) (Collenteur, 2019; Olsthoorn, 2008). The relationship between the groundwater replenishment flux and the actual groundwater level is assumed to be linear. In other words, a flux that becomes two times the initial value results in a twice as large effect on the groundwater level (Olsthoorn, 2008). In addition, the principle of superposition can be applied in case of a linear system. Although the effect on groundwater is modelled accurately, there might be some errors in the time series or there might even be a gap in data from the input datasets. Therefore, it could be hard to define a part of the time series. This part is defined by the model residue *r(t),* for each timestep. The model residues are correlated, meaning that the error at time step t can be partly defined by the error at $t - \Delta t$ (von Asmuth, 2005). In order to create an optimized and relatively accurate time series, error models can be applied. There are several types, but exponential functions are often used for optimisation of time series:

- $r(t) = r(t - \Delta t)e^{\frac{-\Delta t}{\alpha}} + \upsilon(t)$
- $\upsilon(t) = r(t) - r(t - \Delta t)e^{\frac{-\Delta t}{\alpha}}$

Where $r(t)$ are the residues (time dependent), $\upsilon(t)$ are the inconsistent noise which is the difference between the measured output variables (groundwater levels) and the modelled time series and α the error model parameter that defines the discrete noise process (von Asmuth, 2005). More detailed information about the parameter α and the mathematical theory behind time series analysis in general can be found in the study that is conducted by Von Asmuth, et al. (2005) and the study that is done by Collenteur, et al. (2019).

Transfer function noise (TFN) models are implemented in the Pastas software (Collenteur, 2019). TFN modeling tries to explain the observed head series by one or more observed (input) time series. The input time series that are used for describing the measured groundwater series are called stresses. A Pastas time series model needs time series for the stresses (input variables) and observation data to calibrate the model on.[2] Pastas is prepared to use specific data formats as input data to model time series. For Pastas, the most simple combination of stresses to describe the groundwater level are precipitation and evaporation. This is given earlier in this section by $N(t) = P(t) - f * E(t)$ (Collenteur, 2019).

3. Methods

The groundwater measurements in the study area will be used as input for Pastas. Time series will be created based on input variables such as precipitation and evaporation. After creation of the time series, these will be analysed critically in order to define the effect of the measures on the groundwater level in Strabrechtse Heide.

3.1 Data collection

For a proper analysis of the research questions, several types of data(sets) are necessary.

First, groundwater data will be collected. The groundwater data originate from piezometers that are installed in the study area (section 2.2; fig. 2.2). The groundwater data (head observations) will be loaded from DINOloket, a database for Dutch soil and subsurface related data. There are 125 piezometers situated in the entire area of the nature reserve Strabrechtse Heide (section 2.2). However, there are some criteria on which a secondary selection process will be performed. Only the piezometers that pass this procedure are suitable for addressing the research question. Firstly, the focus area of this study is situated within the larger area of the total nature reserve Strabrechste Heide and thus the piezometers need to be situated in this focus area (fig. 2.1; 2.2). Secondly, only the piezometers that have recorded the groundwater level before, during and after implementation of the rewetting measures can be used for a proper analysis. The measures were performed in 2013 and 2014 (chapter 1 and 2). Hence selection only included that started measuring the groundwater level before 2013-01-01 and either ended measuring after 2015-01-01 or are still measuring the groundwater level. Lastly, are only included when surface level is registered. Some datasets from individual piezometers lack this data. Unfortunately, Pastas cannot use groundwater datasets that do not include a value for the surface level.

Second, precipitation and evaporation data will be downloaded from the Dutch meteorological institute KNMI (section 2.2). These datasets are essential to develop hydrological time series with Pastas (section 2.4). The precipitation and evaporation data that will be used, come from the KNMI weather stations that are located nearby Strabrechtse Heide. The relevant weather station that registers precipitation is situated in Someren, a Dutch municipality which lies approximately 5 kilometres from Strabrechtse Heide. The evaporation data is calculated using Makkink and comes from a weather station that is situated in Eindhoven, a relatively large city approximately 10 kilometres from the study site (Hiemstra, 2011). There might be slightly deviation regarding the used data and the actual precipitation and evaporation, since the used datasets are defined by stations some distance from Strabrechtse Heide. Precipitation and evaporation might differ spatially, but there are no closer weather stations that can be used to gather these data.

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[2] Collenteur, R.A., Bakker, M., Calje, R., Schaars, F., n.d., Concepts of PASTAS, retrieved on 7-4-2019, https://pastas.readthedocs.io/en/latest/concepts.html

The last type of data which is essential for this study are surface water measurements. At several locations in the study area the surface water level is measured on a continuously base. The surface water datasets are already available at the waterboard De Dommel.

3.2 Methods of data analysis

3.2.1 Creating a map with locations of the piezometers and the measures

After the selection procedure of piezometers that will be used in this study is accomplished, a map with the locations of the piezometers is created. Moreover, the nature restoration measures will be plotted as well in this map. The spatial orientation of the piezometers relative to the orientation of the measures, might give insight in which piezometers are supposed to register the largest impact of the measures. The locations of the selected piezometers will be plotted in Python. A two-dimensional plot will be created with on the axes the x- and y-coordinate. In addition, shapefiles of the measures (polygons, lines and points) will be created in GIS -software ArcMap 10.3.1. These shapefiles will be uploaded in Python and plotted in the same figure. Furthermore, the shapefile of the specific study site (fig. 2.1), the large waterways (fig. 1.1; 2.1) and the responsibility border which defines the area in which waterboard De Dommel is responsible for nature maintenance, will be plotted (fig. 1.3).

3.2.2 Approach to verify the desiccation

The nature restoration measures had as primary function to rewet the Strabrechtse Heide. In other words, desiccation was supposed to occur, which –as stated in chapter 1- forms a large threat for the nature reserve and the native species. The first important task that will strengthen the urgency of the implementation of the nature restoration measures and this study is to show the real occurrence of desiccation from the groundwater data. In order to do so, the AxG (Dutch GxG) will be calculated with the groundwater data from the selected piezometers and the calculation will be done according to the 'kwantiel methode' (section 2.4; 3.1) for a period of 8 years.

The AxG plots are based upon groundwater data that comes from individual piezometers. Due to large differences in local soil and hydrological circumstances regarding the location of individual piezometers (section 2.1; 2.2, 2.4: Appendix 1), it might be hard to clarify the presence of desiccation by the results for all studied piezometers. If the AxG plots show contradictory groundwater behaviours, desiccation in the study area cannot be proven according to this method. Consequently, another method might be necessary to use to prove declining groundwater levels. For this method, a long and complete groundwater dataset is required that contain recorded groundwater level for several decades of years. Linear regression will be used to analyse the dataset. From this dataset a selection is made that contains only the groundwater level for April, for all recorded years. The hydrological year starts in April and the groundwater level in April is crucial for the plant growth in spring and summer, since these two seasons are characterized by net evaporation, compared to precipitation (section 2.2; tab. 2.1). The fluctuation in groundwater levels for the different April months over the years will be analysed with linear regression in Python. Since desiccation causes continuous lowering of the groundwater level, a negative regression coefficient is expected.

3.2.3 Using the Pastas package to determine the effect of the measures

Pastas time series are constructed via *pandas time series*.[3] *Pandas* is an open source library that provides high-performance, easy to use data analysis tools and data structures for the Python programming language (Idris, 2014; McKinney, 2011). The first step in Pastas to analyse a time series is to load a time series of head observations.[3] The head observations need to be stored as a *pandas.series* object where the date and time are relevant.[4] Initially, the variations in observed heads are believed to be caused by two stresses: evaporation and precipitation (section 2.5). These stresses are already obtained as datasets and need to be loaded in *pandas* as well.[4] Once, all the input data (time series) are read from the data files, a time series model will be made by Pastas. The relationship between the input variables and the groundwater level is calculated within a fit- period. For this specific study, two fit-periods are relevant that define either the relationship between the input variables precipitation and evaporation, and the measured groundwater level before or after the implementation of nature restoration measures. To create time series that can be compared accurately, the extent of both fit-periods will be equal: 2007 to 2012 is used as a fit-period before the implementation of the measures, 2014 to 2019 as a fit-period after the implementation of the measures. In addition, the fit-periods have to cover at least the longest response duration for the area, which is approximately 600 days for Strabrechtse Heide, based on a study with similar landscape and hydrological conditions (Beekman, W., 2018; Caljé. R., 2018). The duration time defines the period it takes from the aquifer to respond to recharge. The duration time is variable, dependent on the flow line of the water. Since, the longest duration time for the study site is thus approximately 600 days, a fit-period of 5 years is long enough.

Pastas eventually describes a time series simulation which defines to what extent the variation in groundwater levels can be caused by variations between the input stresses (e.g. precipitation and evaporation). One can add or remove other stresses (e.g. groundwater extraction and surface water data) if it is supposed to improve the time series. If it appears that the selected piezometers are located closely to surface water bodies, surface water might be added as additional input stress (section 3.1). This can be done relatively easily, because Pastas makes use of solid language scripts in Python and the relevant script has only to be written once (section 2.5).[4]

Per piezometer, two time series will be created. One based on fit-period 2007-2012 and the other one based on fit-period 2014-2019. The time series based on fit-period 2007-2012 will be extrapolated to 2019, for each selected piezometer. These time series are created without any influence of the measures, since the fit-period is established on a period before implementation of the measures. However, the effect of the measures is supposed to be present in the groundwater measurements after 2014. In other words, if nature restoration measures had any effect on the groundwater level, the fit between the simulated groundwater levels and measurement is likely to decrease after 2013. This procedure will provide a quick qualitative estimate to what extent the measures had effect on the groundwater level. However, the effect of the measures on ground water is not proven yet and the quantitative analysis still needs to be executed.

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[3] Collenteur, R.A., Bakker, M., Calje, R., Schaars, F., n.d., Time Series Analysis with Pastas, retrieved on 7-4-2019, https://pastas.readthedocs.io/en/latest/examples/006_fix_parameters_leastquares.ipynb.html

[4] Collenteur, R.A., Bakker, M., Calje, R., Schaars, F., n.d., Time Series Analysis with Pastas, retrieved on 7-4-2019, https://pastas.readthedocs.io/en/latest/examples/006_fix_parameters_leastquares.ipynb.html

After the qualitative analysis of Pastas time series per piezometers an elaborated analysis will be performed to finally answer the main research question.

For this analysis, the time series based on fit-period 2007-2012, are used in combination with the time series based on fit-period 2014-2019. The latter is extrapolated backwards in time and assumed to be affected by the nature restoration measures. The next step is to subtract simulation 1, 2007-2012 from simulation 2, 2014-2019. The outcome is the quantitative effect of the measures on the groundwater level through time. However, the outcome represents the effect on the groundwater level for several years in a row. From hydrological point of view, it would be more convenient to consider the effect of the measures per season, since rewetting of the Strabrechtse Heide is most important during spring and summer, due to the large evaporation flux compared to precipitation which desiccates the nature reserve and threatens the plant growth during these dry seasons (chapter 1; section 2.1). Therefore, the effect of the measures defined over several years will be averaged for each month and the average effect per month will be plotted per piezometer.

Variability in precipitation and evaporation strongly causes fluctuations in groundwater level. Persistent periods of drought causes substantial drop in the groundwater level, whereas lasting periods characterized by significant precipitation might cause the groundwater level to increase drastically (section 2.1). In other words, it is difficult to separate and quantify the effect of the measures relative to the influence of weather variability on the groundwater level. However, by subtracting one simulated groundwater level from the other such as discussed above, one can argue that the effect of weather on groundwater is filtered out. Both simulations contain a daily-based simulated groundwater behaviour, which is defined by weather variables (precipitation, evaporation; table 2.1). Due to the fact that both simulations are extrapolated, the time range of interest, considering both simulations will set similar to each other. In other words, a simulated groundwater level that is defined for a certain moment in time will be subtracted from the other simulated groundwater level that defines exact the same moment in time. Due to the similarity for moment in time and the orientation in field among both simulations, subtraction will filter the influence of weather out and the effect of the measures will be left.

The use of Pastas software such as explained in this section will provide an elaborated and scientific integer answer to the main research question that is: *how are groundwater levels in nature reserve Strabrechtse Heide affected by measures taken by waterboard 'De Dommel' for nature restoration?*

4. Results

4.1 Data collection

The essential input datasets for evaporation and precipitation are obtained from the national meteorological institute KNMI (section 3.1). There are 125 piezometer present in the entire nature reserve Strabrechtse Heide (fig. 4.1). The outcome of the selection procedure defined 58 piezometers in the entire nature reserve to be usable for this study (black dots; fig. 4.1). However, this study focusses on a sub-area that lies within the nature reserve and consequently only approximately 17 piezometers that are situated within the specific study site could be included in the Pastas analysis. There has been done a secondary selection procedure to get the final set of piezometers for further analysis (fig. 4.2).

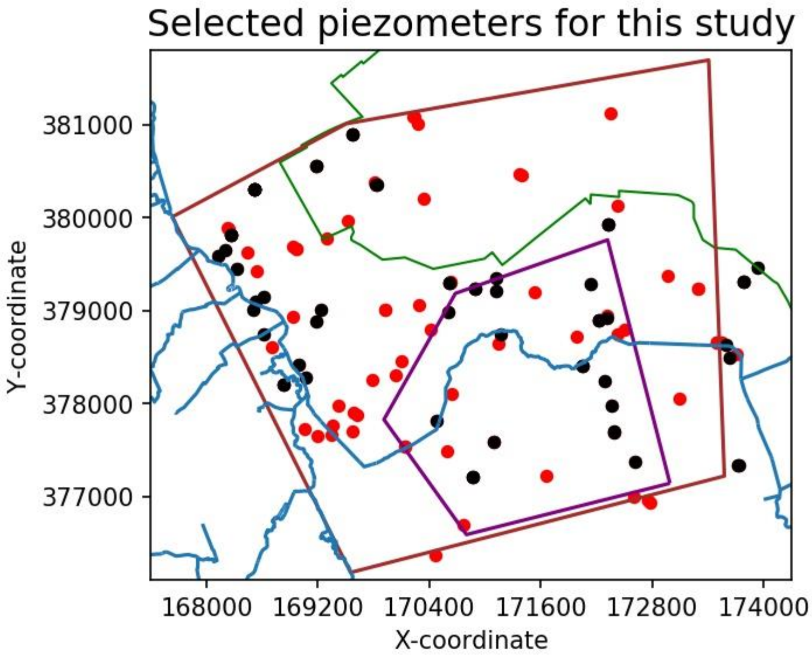

Figure 4.1: relevant piezometers for this study. Red and black dots define the 125 piezometers in nature reserve Strabrechtse Heide (border in brown). Piezometers in black can be used for this study. The red ones cannot be used due to missing data. Further, blue line defines the relatively large waterways in the region, purple line defines the borders of the specific study site and the green line the border between area responsibilities for the Waterboard De Dommel and Waterboard Aa en Maas (Den Bosch, The Netherlands). Figure is author made with the use of GIS-software ArcMap 10.3.1 and programming language Python.

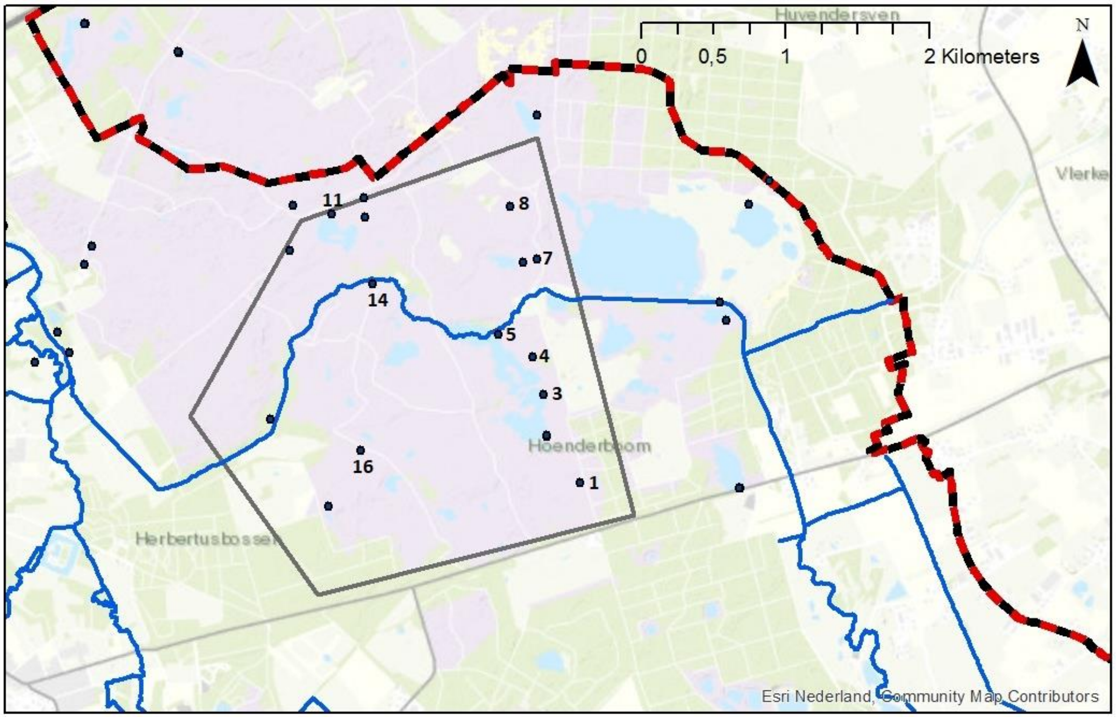

Figure 4.2: piezometers that will be used for Pastas time series analysis (blackish numbered dots) on a topographic map. The blue line defines the relatively large waterways in the region, grey line defines the borders of the specific study site and the blackish/reddish dotted line the border between area responsibilities for the Waterboard De Dommel and Waterboard Aa en Maas (Den Bosch, The Netherlands). Figure is author made with the use of GIS-software ArcMap 10.3.1.

The main reason for the secondary selection procedure is the completeness of the groundwater datasets and the location in field relative to the nature restoration measures (Appendix 1). Some piezometers in the study site passed the first selection procedure but have large gaps in the groundwater data. Those are left out the final selection (fig. 4.2). The secondary selection procedure resulted into 9 piezometers that will be used for Pastas time series analysis. Those 9 piezometers are numbered and displayed in figure 4.2.

The 9 piezometers are displayed relative to the taken nature restoration measures (fig. 4.3). Figure 4.3 is based on the nature restoration map which is defined in Appendix 1. The distance between the piezometers and the taken measures is variable (fig. 4.3). In addition, the density of the measures is largest close to the Witte Loop (fig. 4.3). If the measures affect the groundwater level, one can argue that the effect will decrease with increasing distance from the measures. Piezometers 1, 3, 4 and 5 are situated along a line with the largest density of human interventions at piezometer 5 and the lowest density at piezometer 1 (fig. 4.3).

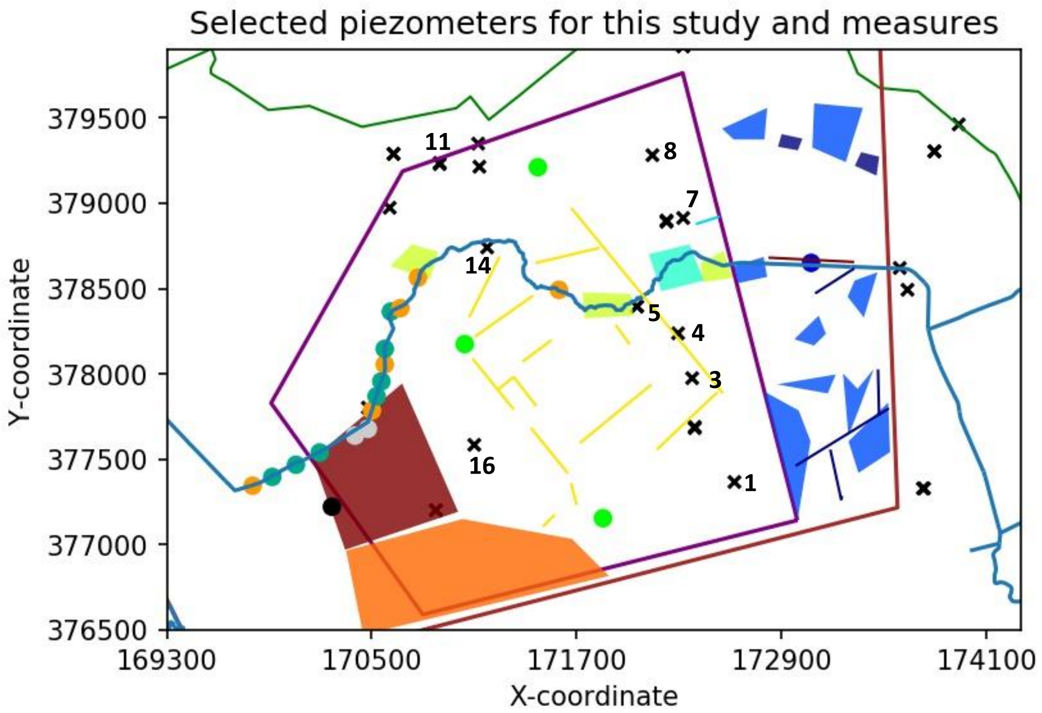

Figure 4.3: selected piezometers for this study (black crosses) and measures. Besides the measures that are defined by either lines, points or polygons, the blue line that goes across the specific study site defines the relatively large waterways in the region, the purple line that forms a pentagon defines the borders of the specific study site and the green line in the upper part of this figure, the border between area responsibilities for the Waterboard De Dommel and Waterboard Aa en Maas (Den Bosch, The Netherlands). The colour legend for the conducted measures by Waterboard De Dommel is as follows:

Colorlegend of the artificial measures defined by polygons:

- ● Developing searching area for zone where shoreweed flourishes
- ● Landcover change from pine forest to heatland (municipality Someren)
- ● Removing upper 15 cm of topsoil
- ● Removing upper 25 cm of topsoil + maintaining forest/shrubs in current conditions
- ● Rewetting forest
- ● Rewetting grassland

Colorlegend of the artificial measures defined by lines:

- ● Closing streams
- ● Developing a natural drainage channel
- ● Elevating bottom of streams (30cm)
- ● Elevating shore

Colorlegend of the artificial measures defined by points:

- ● Changing existing dams
- ● Changing settings artificial water spreader
- ● Construction of local sand replenishment in stream Witte Loop
- ● Maintaining construction that divides stream areas
- ● Maintaining existing dams and elevating bottom of creeks (30cm)
- ● New manually controlled dams

Figure is author made with the use of GIS-software ArcMap 10.3.1 and programming language Python.

4.2 Desiccation

The GxG/AxG time series that are used to verify desiccation are defined in Appendix 2. Table 4.1 provides an overview of the changes in GHG/AHG, GLG/ALG and GVG/ASG, based on Appendix 2. Most piezometers show a net increased GHG/AHG from the start of measuring, even before implementation of the nature restoration measures, which is inconsistent with desiccation (tab. 4.1; Appendix 2). The GLG/ALG and GVG/ASG for the 9 piezometers show various behaviours which do not provide a conclusive result that verifies desiccation (tab. 4.1; Appendix 2). Important implication is that the calculation of these variables is based on average values for the GHG/AHG, GLG/ALG and GVG/ASG that are defined for periods of 8 years (section 3.2.2). Yearly variability in groundwater level and slight desiccation might be averaged out. In addition, The GxG/AxG simulations are based on entire years and thus 4 different seasons, which might lower the reliability for verification of (slight) desiccation through time due to seasonal variability in weather with variations in weather extremities.

*Table 4.1: changes in GHG/AHG, GLG/ALG and GVG/ASG for verification of desiccation (section 3.2.2) per piezometer/ dataset. Piezometer 5 has 2 groundwater datasets, because this piezometer has 2 filters which are installed on different depths (filter 2 is deeper located than filter 1). Both filters are installed in a sand layer which is separated by an impermeable clay layer (tab. 2.1). *highly steep gradients (circa 20 cm. changes in 1 year) are unlikely and probably caused by errors in the data. Those part of the plots are not representative and need to be excluded from the interpretation (author made and based upon Appendix 2).*

Piezometer (groundwater dataset)	Piezometer code (relevant for Appendix 2)	Changes in GHG/AHG, GLG/ALG and GVG/ASG for verification of desiccation (section 3.2.2).
1	B51H0341_1	GHG/AHG: net increased from start of measuring GLG/ALG: net increased from start of measuring GVG/ASG: net increased from start of measuring
3	B51H0407_1	GHG/AHG: net increased from start of measuring* GLG/ALG: circa 10 cm. lower level from start of measuring GVG/ASG: slight lower level, but minor
4	B51H0404_1	GHG/AHG: net increased from start of measuring* GLG/ALG: circa 15 cm. lower level from start of measuring GVG/ASG: no net changes
5 (filter number 1)	B51H1880_1	GHG/AHG: circa 10 cm. increased level from start of measuring GLG/ALG: net lowered from start of measuring* GVG/ASG: net lowered from start of measuring
5 (filter number 2)	B51H1880_2	GHG/AHG: circa 10 cm. increased level from start of measuring GLG/ALG: net lowered from start of measuring* GVG/ASG: net lowered from start of measuring
7	B51H0389_1	GHG/AHG: net lowered from start of measuring GLG/ALG: net lowered from start of measuring GVG/ASG: net lowered from start of measuring*
8	B51H0405_1	GHG/AHG: net increased from start of measuring* GLG/ALG: circa 15 cm. increased level from start of measuring GVG/ASG: no net changes
11	B51H1876_1	GHG/AHG: net lowered from start of measuring* GLG/ALG: net lowered from start of measuring* GVG/ASG: net lowered from start of measuring*
14	B51H0345_1	GHG/AHG: circa 5 cm. increased level from start of measuring GLG/ALG: circa 40 cm. increased level from start of measuring GVG/ASG: net lowered from start of measuring
16	B51H0342_2	GHG/AHG: circa 10 cm. increased level from start of measuring GLG/ALG: net lowered level from start of measuring GVG/ASG: circa 10 cm. increased level from start of measuring

Waterboard De Dommel argues that in the field desiccation is visible in Strabrechste Heide for at least the last 10 years. After it became clear that the GxG/AxG simulations are not so representative for assessing desiccation, another method is used to verify the presence of desiccation. Linear regression has been performed on a long and complete groundwater dataset (fig. 4.4). This groundwater dataset comes from a piezometer which is situated South-East from the Strabrechtse Heide. The groundwater level is plotted for the month April for several years in a row (section 3.2.2). This piezometer is preferred to the piezometers which are located in Strabrechtse Heide due to the length of the data record. Desiccation is barely visible on a short time series and much better on a longer time series (fig. 4.4). The groundwater datasets that are recorded in Strabrechtse Heide are (much) shorter than the one used for linear regression.

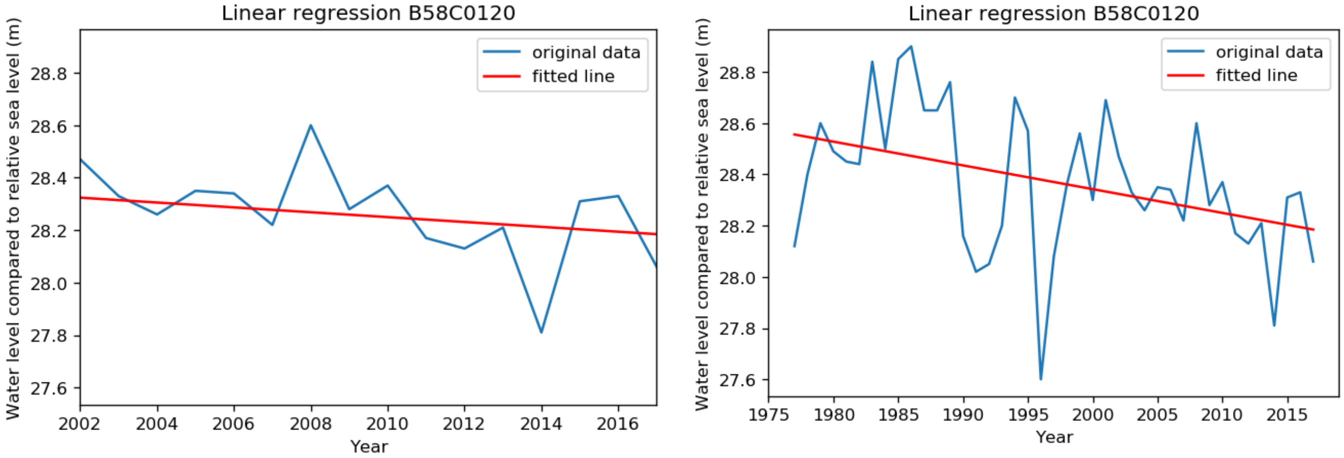

Figure 4.4: groundwater level plotted (blue) and linear regression based on the groundwater data (red) from piezometer B58C0120. On the y-axis the groundwater level and on the x-axis the months April per year (section 3.2.2). This piezometer is situated in Northern Limburg, South-East from Strabrechtse Heide (figure is author made with Python).

In conclusion, desiccation seems to be present in both the field and in groundwater data. Therefore the implementation of the nature restoration measures to rewet Strabrechtse Heide was urgent.

4.3 Pastas time series

To get a first nuanced and qualitative impression of the effect of the measures on the groundwater level in the study site, the Raw groundwater measurements are studied per piezometer. There is no significant change in the (raw) measured groundwater level visible after 2014 that might be related to the measures. The high peak for 2016, defined for almost all piezometers, is probably caused by an exceptionally wet 2016, whereas the low peaks after 2018 are probably caused by an exceptionally dry 2018 and 2019 so far (Appendix 3).

After studying the Raw groundwater measurements, a Pastas time series is analysed per individual piezometer, based on fit-period 2007-2012 (see Appendix 3 for individual plots). The virtual groundwater level is simulated for period 2007-2019, which defines the total length of the period of interest (2007-2012: 2014-2019). The EVP is defined in the bottom right of each plot and is expressed in percentage with an optimum of 100%, meaning that the simulation matches the measured time series perfectly (Appendix 3, tab. 4.2). The EVP is calculated based on the extent the simulation matches the measured groundwater level in the defined fit-period. In other words, the EVP does not encounter to what extent the simulation matches the measures before and after the assigned fit-period.

Table 4.2: EVP for the individual timeseries based on fit-period 2007-2012 and qualitative impression of the impact of the nature restoration measures on the groundwater level. The EVP is expressed in percentage with an optimum of 100%, meaning that the simulation fits the measured time series perfectly (Appendix 3, tab. 4.2). The EVP is calculated based on the extent the simulation fits the measured groundwater level in the defined fit-period. In other words, the EVP does not encounter the fit before and after the assigned fit-period. EVP for piezometers 7 and 8 might be improved by adding surface water data as input variable to Pastas time series, since there is extensive surface water replenishment here (Marijke Ven). However, there is no proper surface water dataset available and thus such data have not been added as input variable (author made and based on Appendix 3).

Piezometer (groundwater dataset)	Piezometer code (relevant for Appendix 2)	Pastas time series, fit on 2007-2012, before implementation of the measures (Appendix 3).
1	B51H0341_1	EVP: 87.89, no significant change in fit after 2014
3	B51H0407_1	EVP: 83.91, no significant change in fit after 2014
4	B51H0404_1	EVP: 89.24, no significant change in fit after 2014
5 (filter number 1)	B51H1880_1	EVP: 0.0, no significant change in fit after 2014. Large deviation between simulated ground water and measured ground water. This will be addressed in chapter 5.
5 (filter number 2)	B51H1880_2	EVP: 92.65, moderate degradation in fit after 2014
7	B51H0389_1	EVP: 73.35, slightly changed fit after 2014
8	B51H0405_1	EVP: 63.1, slightly changed fit after 2014
11	B51H1876_1	EVP: 94.4, moderate degradation in fit after 2014
14	B51H0345_1	EVP: 90.46, no significant change in fit after 2014
16	B51H0342_2	EVP: 89.16, no significant change in fit after 2014

As already argued in section 3.2.3, the simulated groundwater levels for period 2007-2012 are based on precipitation and evaporation, without the impact of measures. If the measures had large impact on the groundwater, the match between the measured groundwater levels would decrease after 2014. This is not the case for the majority of the studied piezometers (tab. 4.2; Appendix 3). In conclusion, based on this qualitative analysis, one can argue that the measures did not have a significant effect on the groundwater levels. However, the effect might be small and barely visible in the plots, since the unit on the y-axis is ‘meters’ (Appendix 3). Therefore, quantitative analysis, as addressed in section 3.2.3 is performed.

The simulated groundwater levels for the individual piezometers are shown in Appendix 4. The majority of the plots show highly similar behaviours between both simulations, suggesting no significant influence of the nature restoration measures through time (Appendix 4). However, plot 5 (filter number 1 and 2) and plot 11 show significant deviation between both simulated groundwater behaviours.

In order to quantify the exact effect of the measures on the groundwater level in Strabrechtse Heide, Simulation is subtracted from Simulation2. After that, the effect over several years is averaged per month and plotted per piezometer (Appendix 5). All plots show a positive peak somewhere throughout the displayed year, implying a positive outcome from ‘Simulated2-Simulated’ and thus rewetting (Appendix 5). However, the plots that show the effect of the measures on the groundwater level, measured by piezometer 3, 4, 5, 8, 11, 14, and 16, also describe a negative value for the sum ‘Simulated2-Simulated’, which seems to argue for desiccation part of the year.

5. Discussion

5.1 Critical view on the used methods

The nature restoration measures were conducted between 2013 and 2014. Although it is known that all the measures were fully implemented at the end of 2014, the exact start – and end date regarding implementation of the individual measures is not known. This gap in knowledge has restricted the possibility to get a more specific causal connection between the implementation of individual measures and changes in groundwater level. In other words, the lack of knowledge makes the outcomes of this study less concrete and the analysis of the results dominantly based on the effect of the entire set of the measures on the groundwater level, instead of assigning certain changes in groundwater level to specific measures. A nuanced monitor plan requires an adequate operation log that includes the start- and end date of the conducted nature restoration measures and the exact location per individual measure. Waterboard De Dommel has omitted to keep an operational log. The waterboard will probably evaluate the effect of the nature restoration measures on the groundwater level at Strabrechtse Heide in some time. If the waterboard had registered the implementation of the measures accurately, it might have been much easier to establish causal links between (local) changes in groundwater level and individual nature restoration measures. In other words, it is highly recommended to keep an operational log during the implementation of future projects.

Piezometer 3, 4, 5, 7, 11 and 14 are situated near a surface water body (fig. 4.2). The initial idea was to use an additional input variable 'surface water' in Pastas for these piezometers. Groundwater interacts with surface water (tab. 2.1), implying that the groundwater simulation might be improved by adding surface water as input variable, besides precipitation and evaporation. For instance, the EVP values for piezometer 7 and 8, near Marijke Ven, are relatively low compared to the other EVP values (tab. 4.2). These simulations (and the values for EVP) might be improved by adding surface water as input variable, since Marijke Ven is substantially replenished by surface water. Surface water level measurements are available for several locations at the study site. Datasets start somewhere between 2012 and 2015, dependent on location. In other words, the surface water datasets do not match the first fit-period (2007-2012), which restricts the implementation of surface water as input variable, since the relationship between surface water, precipitation, evaporation and the groundwater level cannot be calculated properly by Pastas. From all the created Pastas time series, the simulated groundwater behaviour for piezometer 5 (filter number 1) shows the largest divergence compared to the measured groundwater level (Appendix 4). This piezometer is located next to water stream Witte Loop and the groundwater level here is often situated slightly beneath or at the surface level (fig. 5.1). The high peaks for the groundwater level are flattened. Groundwater that reaches the surface level would have been defined as a flat line and that is not the case here. The measured groundwater level at the location of piezometer 5, filter number 1, is therefore likely to be interrupted by measurement errors, which can be the reason for the flattened high peaks (fig. 5.1). In addition, the used value for the surface level based on hand measurements in field, that does not correspond to the surface level measurements coming from aerial survey maps that are available at waterboard De Dommel. On the other hand, the lower peaks are still sharp. The alternation between flattened peaks and sharp lower peaks causes an unpredictable trend in the groundwater behaviour. Consequently, Pastas is not able to model the relationship between the system variables correctly, especially because surface water as input variable is not taken into account. In contrast to the simulated phreatic groundwater level for piezometer 5 -filter number 1-, Simulation2 for the same piezometer and filter number, but based on another fit-period, shows a more familiar virtual groundwater behaviour (Appendix 4). This simulation is based on fit-period 2014-2019, where the groundwater level is far beneath surface level most of the time. This simulation is likely to be clean from measurement errors and clean from (abrupt) change to surface water (section 2.1; fig. 5.1). As a result, Pastas was able to find a more realistic relationship among precipitation, evaporation and the measured groundwater level.

Pastas does not consider the stop of subsoil at surface level and presumes that the entire vertical profile in which a water level is defined/modelled is subsoil. Consequently, the high peaks for the simulated groundwater levels may even be situated above surface level, which is off course impossible. This deviation is seen in the results for piezometers 1, 3, 5 (filter number 1 and 2), 11 and 14 (Appendix 3).

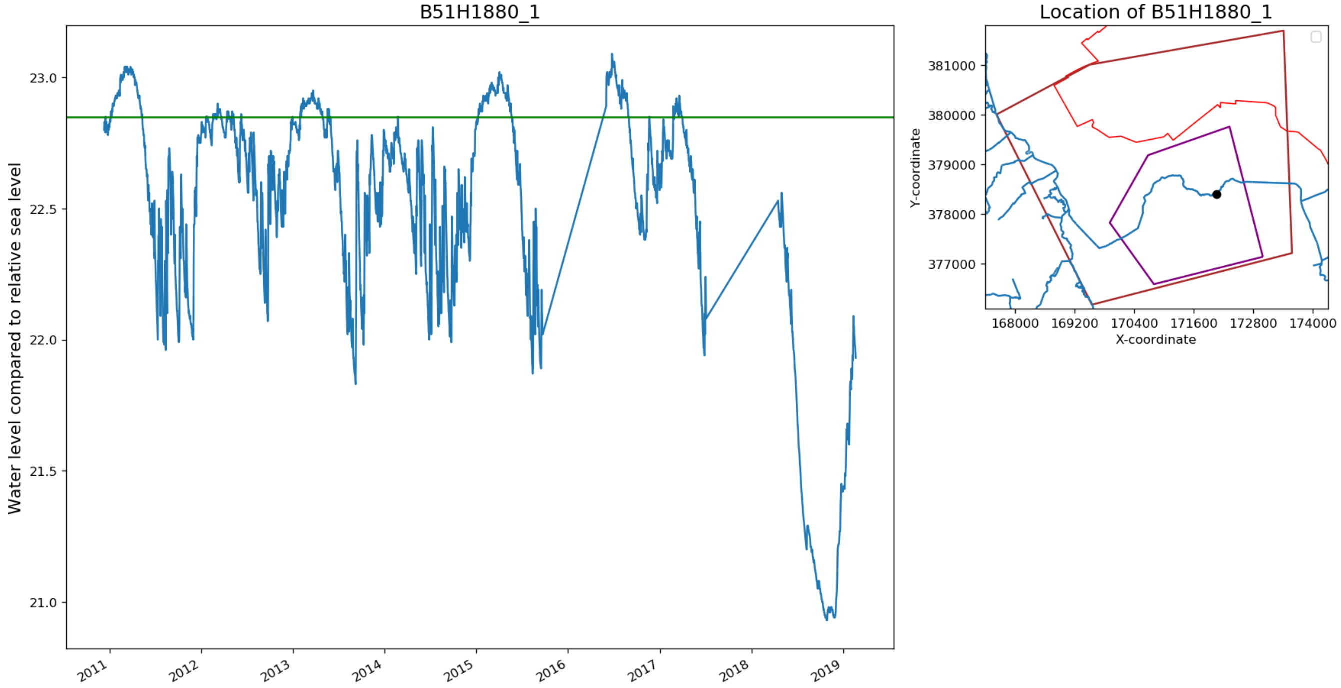

Figure 5.1: measured groundwater level (blue) by piezometer 5, filter number 1. Further, the surface level is plotted as a green horizontal line and the locations of the piezometer is plotted in the upper right. Figure is created in Python with as input the groundwater dataset defined created by piezometer 5 (tab. 4.1/4.2 for clarification of the code in the title).

Groundwater datasets, recorded by piezometer 5 and 11 begin at the end of 2010. The simulated groundwater levels based on fit-period 2007-2012 are calculated with the use of only 1-1.5 year groundwater data. This period was characterized by deficient precipitation (Appendix 6). The short simulation period makes the results for piezometer 5 and 11 more specific and less representative to consider the behaviour of groundwater on longer timescale (2007-2019). For these piezometers the modelled groundwater level, Simulation and Simulation2, show the largest difference between each other, which is partly caused by the restriction in groundwater data for fit-period 2007-2012 (Appendix 4).

The Pastas package in Python is a proper method to describe time series. Pastas simplifies the reality and in this study the groundwater level is explained by only 2 variables: precipitation and evaporation. In reality, groundwater is influenced by much more variables than precipitation and evaporation. For instance, Pastas does not fully encounter subsoil stratification and a variable hydraulic conductivity which affects infiltration. The defined relationship between precipitation, evaporation and the groundwater level (indirectly) includes the influence of subsoil characteristics such as the hydraulic conductivity and the type of the subsoil. However, Pastas approaches the influence of these parameters on the groundwater level according to a linear relationship, which is not necessarily true in reality. Nevertheless, Pastas still defines reality quite accurate, which is verified by the similarity in behaviour regarding the simulated groundwater levels and the measured groundwater levels, and the high values for EVP (tab. 4.2; Appendix 3).

The influence of weather on the groundwater level is filtered out by subtracting Simulation from Simulation2. The average monthly effect of the measures on the groundwater level is defined as final result (Appendix 5). Although the influence of the weather is filtered out by subtracting one simulation from the other, both simulations are still based on a simplification of the reality, such as defined above. Weather extremities cause relatively large differences between the simulated groundwater level and the measurements, since the non-linear behaviour regarding the relationship among precipitation, evaporation and the groundwater level becomes larger when weather becomes extremer. The weather in period 2007-2012 was less extreme than in 2014-2019. This might enlarge the deviation between each individual simulated groundwater level and the corresponding measured groundwater level, mainly for simulated groundwater levels for fit-period 2014-2019. The deviation that defines the error between each simulated groundwater time series and the corresponding measured groundwater time series is not filtered out by subtracting Simulation from Simulation2 (Appendix 4).

5.2 Discussing the results

The following paragraphs will discuss the results of time-series analysis related to the hydrology in the study site and the nature restoration measures. For clarification the topographic map, with the locations of the piezometers and several important surface water bodies, is displayed (fig. 5.2). Further, the figures that show the effect of the measures are defined in clusters (fig. 5.5 – 5.8). This has been done to verify whether the influence of the nature restoration measures on the groundwater level decreases with increasing distance from the implementation of the measures.

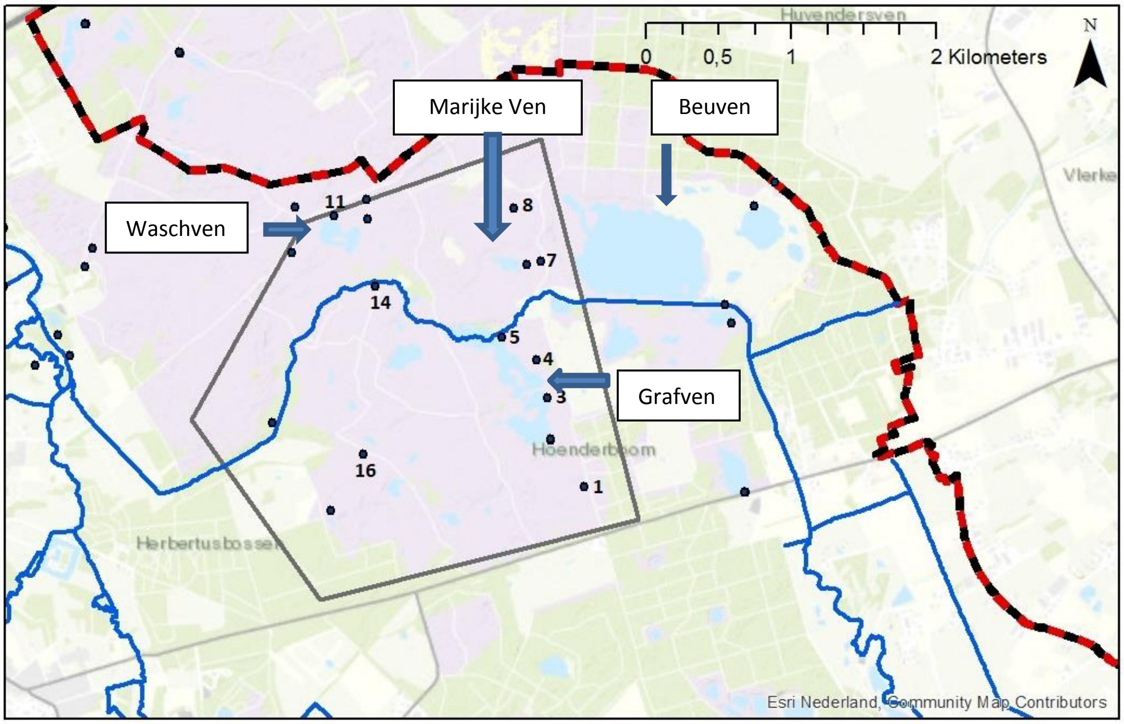

Figure 5.2: piezometers that are used for Pastas time series analysis (black numbered dots) on a topographic map.The blue line defines the relatively large waterways in the region, grey line defines the borders of the specific study site and the black/red dotted line the border between area responsibilities for the Waterboard De Dommel and Waterboard Aa en Maas (Den Bosch, The Netherlands). Several important surface water bodies that are essential for the analysis are marked. Figure is author made with the use of GIS-software ArcMap 10.3.1

The majority of the results show an alternation between positive and negative trends, with a positive peak dominantly in spring and summer (fig. 5.5 – 5.8). Positive values represent rewetting, whereas negative values mean desiccation. As stated earlier, the results for piezometers 5 and 11 are less reliable and thus difficult to interpret. Piezometers 1, 7 and 8 show major rewetting (fig. 5.5; 5.6). Piezometers 7 and 8 are situated in and near Marijke Ven, which is significantly fed by the drainage channel that was constructed as one of the nature restoration measures (fig. 5.3; 5.4). Water flows from upper section of Witte Loop via this channel towards Marijke Ven (fig. 5.3). This drainage channel and the constructed dam, that is situated slightly downstream from the location where the drainage channel meets Witte Loop, have significantly changed the surface water drainage through Strabrechtse Heide after 2014. Before the conduction of the nature restoration measures, surface water used to flow via Peelrijt and the upper section of Witte Loop further downstream through Witte Loop and Rielloop (section 2.2). However, the construction of the drainage channel and the dam have lowered water drainage further downstream through Witte Loop and Rielloop (fig. 5.4; Appendix 1). Due to the construction of the channel, the water flux from Peelrijt to Marijke Ven is increased after 2014.

Although there is an impermeable clay layer present in the subsoil at Marijke Ven that lowers the infiltration capacity substantially, the amount of surface water close to piezometers 7 and 8 and the infiltration of surface water is increased after 2014. This seems a plausible cause for the (dominant) year-round rewetting, which shown by the relevant plots (fig. 5.4).

Figure 5.3: satellite image that covers a small part of the study area. Beuven is depicted. Further, the drainage channel that causes water to flow from Peelrijt/Witte Loop to Marijke Ven is shown within the red circle (source: Google Maps, retrieved on: 11-28-2019).

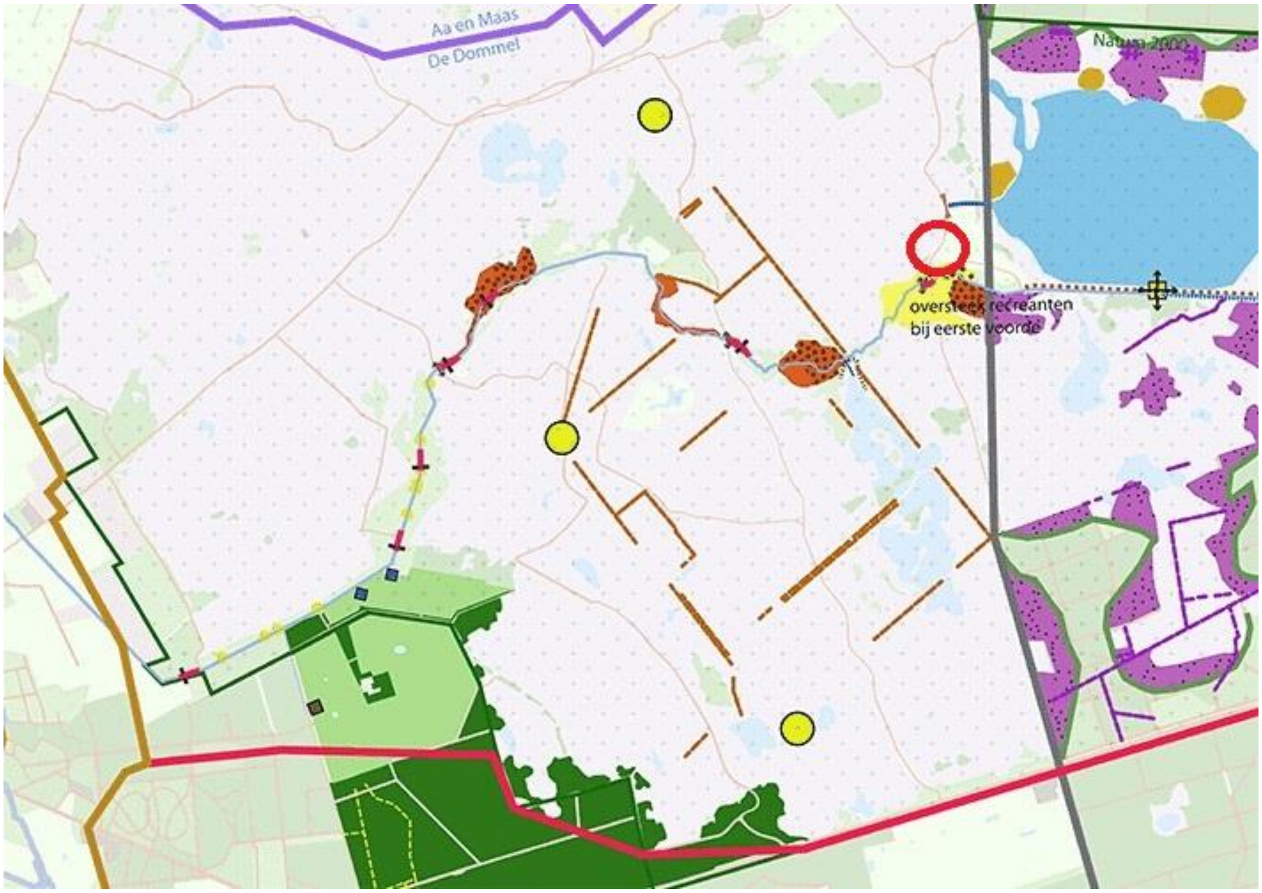

Figure 5.4: map of the taken nature restoration measures, based on Appendix 1, with the location of the drainage channel that causes water to flow from Peelrijt/Witte Loop to Marijke Ven (depicted within the red circle).

The environment in and surrounding Beuven is an important habitat for the native species that are supposed to be protected by the nature restoration measures. In order to increase water regulation in Beuven, a dam and a water spreader are placed in the drainage channel South from Beuven (Appendix 1; fig. 4.3). Via this drainage channel, water used to be drained from Beuven to Witte Loop, after which it flew further downstream. Water drainage from Beuven to Witte Loop only occurred when there was too much water in Beuven.

Although the construction of the dams and the sand replenishments in Witte Loop and Rielloop has increased the ability to retain surface water in these channels, the amount of surface water that flows through Witte Loop and Rielloop is decreased after 2014. The reduction in the available amount of surface water in Witte Loop and Rielloop has caused a reduction in infiltration in the surroundings of these channels. Especially downstream from the constructed dams, because water in Witte Loop is retained by the dams and cannot easily flow further downstream. Consequently, local groundwater replenishment fluxes near Witte Loop and Rielloop are lowered, which eventually has resulted in lowered groundwater levels for autumn and winter in close proximity of these channels (fig. 5.5). Declined groundwater levels along Witte Loop and Rielloop have probably increased infiltration of surface water from Grafven after 2014. Consequently, the period during which Grafven is dry might be increased after 2014. In conclusion, it is likely that the combination of declined groundwater levels round Witte Loop and Rielloop and the fact that the buffer capacity of Grafven is likely to be depleted after 2014, has resulted in net desiccation for autumn and winter surrounding the Witte Loop(fig. 5.5).

Piezometers 3 and 4 are placed downstream from the drainage channel towards Marijke Ven and the dam that is constructed slightly downstream from this drainage channel (fig. 5.3; 5.4). If these piezometers were placed slightly upstream from these dam and channel, it would be likely that the results for piezometer 3 and 4 would have shown dominant rewetting year-round. Surface water would have been retained in front of the dam, which would likely cause increased infiltration slightly upstream from the dam and thus raised groundwater levels in front of the dam. Actually, the results for piezometers 7 and 8 show this expected effect, since groundwater at these locations is replenished by surface water from upstream the dam.

During spring and summer, there is net rewetting in the surroundings of Grafven and Witte Loop (fig. 5.5). As stated earlier, the increased capacity to retain surface water in Witte Loop might have elevated infiltration during these relatively dry seasons, which eventually has caused net rewetting (fig. 5.5). Water in Witte Loop and Rielloop comes from Strabrechtse Heide itself. During warm summers, Witte Loop and Rielloop are used to dry up for a substantial period. Drying up of these channels used to occur even before the nature restoration measures were implemented. In other words, Witte Loop and Rielloop were not extensively fed in warm summers by water from Peelrijt before the implementation of the nature restoration measures. As a result, water levels were frequently low in Witte Loop and Rielloop during summer before the implementation of the measures (2013-2014). Since 2014, water that is present in Witte Loop, is not automatically drained out of the Strabrechtste Heide, but retained in front of the dams. The Witte Loop and Rielloop are used to be fed by seepage. In other words, water that flows through Witte Loop and Rielloop due to seepage or overland flow can be trapped in front of the dams in these channels, which increase the amount of water that can infiltrate and replenish the groundwater reservoir. This phenomena even occurs in relatively dry summers when there is no extensive rainfall, but still seepage.

Rewetting of the study site in dry spring and summer, when the evaporation flux is larger than the precipitation flux, is highly urgent for maintaining the biodiversity and the presence of the rare native species in the study site. Piezometer 1 is located at such a distance from Witte Loop that the groundwater level here is little influenced by the discussed changes in surface water dynamics surrounding Grafven, Marijke Ven, Witte loop and Rielloop after 2014. Therefore, the behaviour of groundwater at this location is supposed to be less interrupted by other processes than the direct influence of the nature restoration measures on the groundwater level. The results for piezometer 1 show dominant rewetting (fig. 5.5). Rewetting at this location is supposed to be caused by the land cover change from pine forest to heathlands, which is implemented relatively close to piezometer 1 (Appendix 1; fig. 4.3). Destruction of these evergreen trees lowered evaporation, which has increased the amount of water that is available for groundwater replenishment leading to a higher groundwater level at piezometer 1.

Piezometer 11 shows desiccation almost year-round (fig. 5.5). First, the reliability of the simulations is questionable, since the simulated groundwater level for 2007-2012 is not optimally calculated. However, according to waterboard De Dommel, a dam was destroyed in Witte Loop, near piezometer 11(fig. 5.2). The destruction of this dam is not shown as nature restoration measure on the relevant maps (Appendix 1; fig. 4.3). The destruction of the dam has increased surface water drainage via Witte Loop near Waschven. As a result, water is drained further downstream instead of being retained in Witte Loop near Waschven. Therefore, the amount of water that infiltrates here is probably decreased after 2014. Consequently, the local groundwater level declined, which is likely to have increased infiltration from water in Waschven after 2014. The expected increase of infiltration from surface water in Waschven has probably caused Waschven to be dry a significant part of the year. This has led to a reduction in the amount of available surface water for infiltration at piezometer 11 and thus lowered the buffer capacity of this lake for the groundwater reservoir after 2014. As a result, groundwater level at piezometer 11 lowered after 2014, which means net desiccation compared to 2007-2012 (fig. 5.7).

Lastly, piezometers 14 and 16 show both desiccation and rewetting (fig. 5.8). Groundwater at the location near piezometer 14 is influenced by the reduction of surface water drainage through Witte Loop and Rielloop, such as relevant for piezometers 3 and 4. The groundwater level at this location is likely to be higher during spring and summer due to the increased water holding capacity of surface water in this channel, as discussed before. Further, the changed surface water drainage from Peelrijt/Witte Loop towards Marijke Ven has decreased the amount of surface water that infiltrates at piezometer 14 in autumn and winter. This led to net desiccation at piezometer 14 for autumn and winter. In conclusion, piezometer 14 is situated downstream from piezometer 3 and 4, that are supposed to be influenced by a changed water drainage pattern through Witte Loop. Therefore the behaviour of the effect of the measures on the groundwater level, defined for piezometer 14, is quite similar to the behaviour defined for piezometer 3 and 4 (fig. 5.5; 5.8). Desiccation defined for the location at piezometer 16 is unexpected. There seems no direct cause for the represented desiccation, part of the year (fig. 5.8). However, according to waterboard De Dommel, the operation of the nature restoration measures near piezometer 16 might be slightly different from the locations of these measures as defined on the map (Appendix 1). In addition, creeks East of piezometer 14 are obstructed by dams and ‘elevating bottom of streams’ is not necessarily performed in all creeks, as defined on the nature restoration map (Appendix 1). In other words, the adequately implementation of the nature restoration measures near piezometer 16 might deviate (slightly) from the measures on the map. This deviation can have caused less rewetting than should have been expected based on the nature restoration map and can thus be an explanation for the unexpected result, considering the groundwater level at piezometer 16 (fig. 5.8).

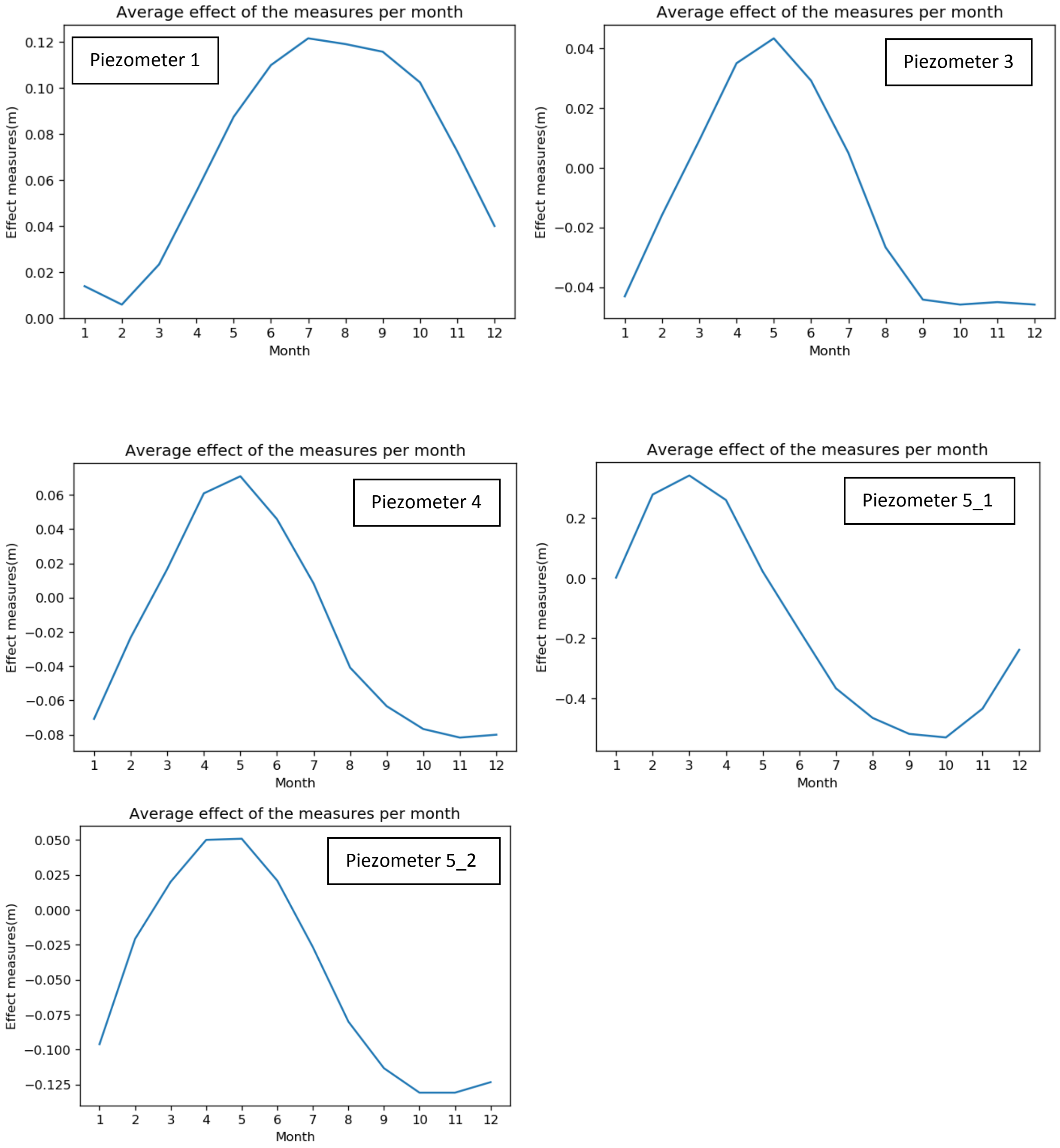

Figure 5.5: averaged monthly effect of the measures on the groundwater level, measured by the different piezometer. These piezometers are situated along a line (fig. 5.2; section 3.2.3; Appendix 5).

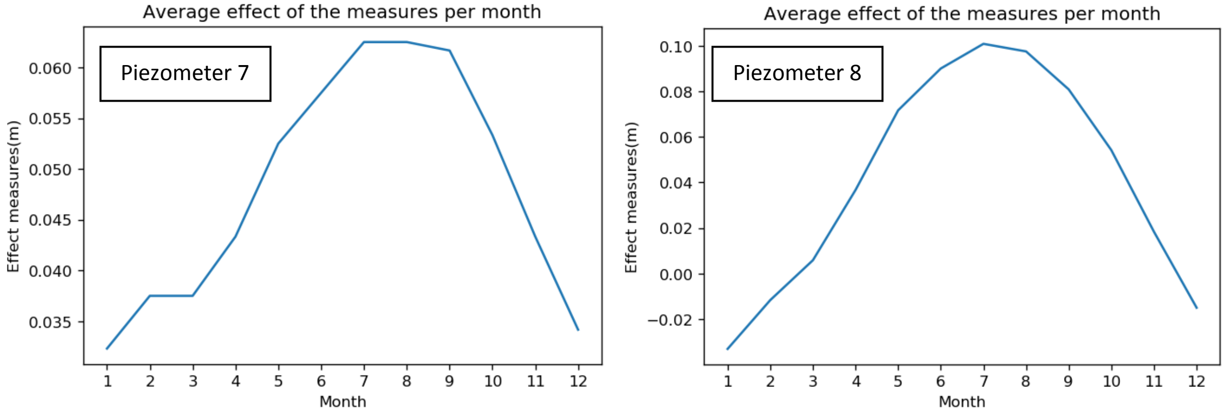

Figure 5.6: averaged monthly effect of the measures on the groundwater level, measured by the different piezometer. These piezometers in the same area close to surface water body Marijke Ven (fig. 5.2; section 3.2.3; Appendix 5).

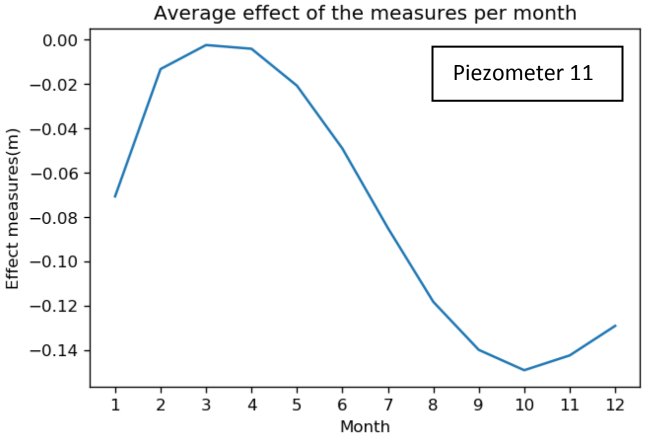

Figure 5.7: averaged monthly effect of the measures on the groundwater level, measured by the piezometer 11. This piezometer is situated apart from the others, nearby Wachsven (fig. 5.2; section 3.2.3; Appendix 5).

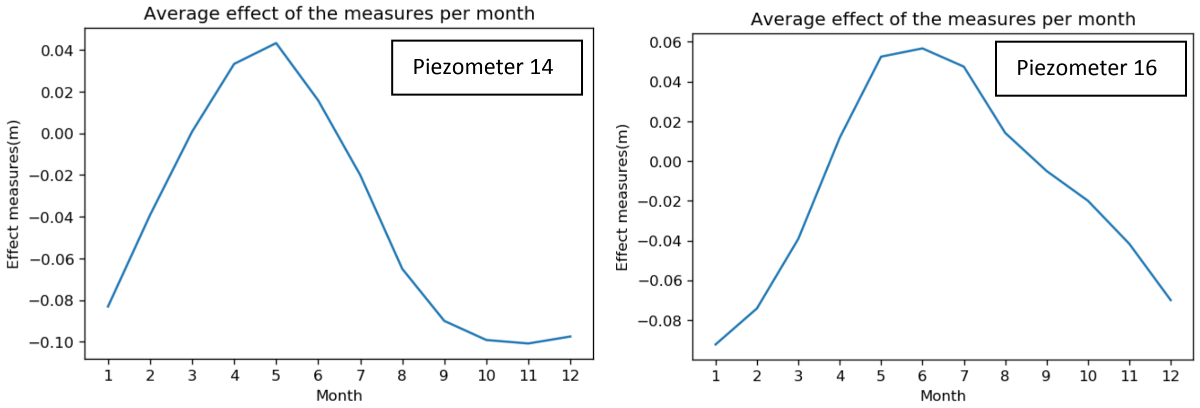

Figure 5.8: averaged monthly effect of the measures on the groundwater level, measured by the different piezometers. These piezometers are situated South from Witte Loop/Rielloop (fig. 1.3; fig. 5.2; section 3.2.3; Appendix 5).

The results showed that rewetting is dominantly present in spring and summer, whereas desiccation is mainly present in autumn and winter. Waterboard De Dommel has placed piezometers 1, 3, 4 and 5 in line to verify the theory that the influence of the measures decreases with increasing distance from the measures. Unfortunately, piezometer 5 gave unreliable results. In addition, piezometer 1 is located close to the measure 'landcover change from pine forest to heathlands', which is likely to be the major reason for rewetting at piezometer 1. Piezometers 3 and 4 show behaviors that are quite similar and are thus likely to be affected by similar hydrological influences. From these two piezometers, the results for piezometer 4 show the largest effect of the measures on the groundwater level (fig. 5.5). Although there is a severely limited amount of results available to test this theory, based on the results of these two piezometers the expected theory is verified.

Around 40 to 50% of the total nature reserve Strabrechtse Heide was expected to encounter a rise in groundwater level of at least 5 centimeters (Muilwijk, 2013; Vermue, 2012; section 2.4). According to the reports that were written during the preparation phase before the actual implementation of the measures, the measures would increase the AHG, ALG or ASG up to 50 centimeters, where the largest rise would have been expected close to Witte Loop and Rielloop (section 2.4; Muilwijk, 2013: Vermue, 2012). Based on the final results, most plots show a rise in groundwater level of at least 5 centimeter which confirms part of the expectations, but the rise in groundwater level is never more than 12 centimeters (fig. 5.5 – 5.8; Appendix 5). In addition, most plots show besides the rise in groundwater level also groundwater depletion and thus desiccation (fig. 5.5 – 5.8). In other words, the expectations such as discussed in section 2.4 are not fully realized at the locations of the studied piezometers at this moment.

5.3 Did the measures have an effect?

According to the hypothesis, the nature restoration measures were supposed to result in a reduction of the desiccation and a rise in groundwater level in the study site (section 1.2). The discussion of the results defined that only piezometers 1 and 7, from the 9 studied piezometers, show persistent rewetting (section 5.2). The other 8 piezometers show also desiccation, dominantly for autumn and winter. In other words, groundwater levels are not only risen, but also lowered. In conclusion, the hypothesis has to be rejected.

The main research question was: *how are groundwater levels in nature reserve Strabrechtse Heide affected by measures taken by waterboard 'De Dommel' for nature restoration?* The nature restoration measures were implemented in order to rewet the Strabrechtse Heide, which is essential for the occurrence of the (rarely) protected native species, such as *Lobelia Dortmanna.* The results show overall rewetting in spring and summer, but indicate desiccation at several locations, mainly for autumn and winter. However, since rewetting of the subsoil is extensively present in the drier spring and summer months, the nature restoration measures might have had a relatively positive effect on the persistence of the natural ecosystem and biodiversity. If the groundwater levels were situated some meters beneath the surface level before 2013, a raise of maximum 12 centimetres, as result of the rewetting activities (Appendix 5), would not have had any desirable effect on the flora, since groundwater levels would have been still far beneath the root zone. However, groundwater levels, defined for the locations at the studied piezometers, were not far beneath surface level before 2013 (Appendix 2). Therefore, the defined rewetting, mainly for spring and summer, is likely to be beneficial for the persistence of the native species.

According to the Pastas time series analysis that is performed in this study, the study site does not exclusively experience rewetting. The nature restoration measures were implemented to prevent further desiccation. Therefore, the desired effect, is not realized completely at this moment. The answer to the main research question is dominantly based on the simulated groundwater levels, based on fit-period 2007-2012 and 2014-2019 (Appendix 4; 5; section 3.2.3; chapter 4). Regarding 2014-2019, there are at least two extreme years present in a period of 5 years. 2016 was exceptional wet, whereas 2018 was exceptional warm and dry (Huiskamp, 2019; section 2.3). The occurrence of extreme weather increases the non-linear behaviour between precipitation, evaporation and the groundwater level. As a result, simulation of the virtual groundwater behaviours by Pastas, based on the fit-period of 5 years that includes two extreme years, is supposed to include a significant deviation compared to the reality. Taking a longer fit-period, with those 2 extreme years included, might lower the substantial influence of the deviation between the measured time series and the simulated time series on the final results, dependent on the frequency of present extreme years.

The nature restoration measures that were implemented in 2013-2014 had major impact on the landscape and changed the hydrological setting in the study site. Changing vegetation, cutting forest and constructing artificial (regulated) structures have affected and altered the landscape and the local ecosystem severely. Consequently, there is time needed to stabilise the system and ecosystem again after the human interventions were done. That stabilisation process might take years, which means that the new balance is not reached yet and that the influence of the rewetting measures on the hydrology in Strabrechtse Heide might still change towards a more consistent contribution (Fuller, 2017; Ruprecht, 2006). In addition, several piezometers that are used in this study are placed in order to monitor the effect of the restoration measures on the groundwater level. Although waterboard De Dommel has placed these piezometers based on extensive research and discussion among experts, some piezometers such as 3, 4, 5 and 14 are not placed at a logical location to measure the desired rewetting. Rewetting is likely to be significantly more present slightly upstream from a dam where water is retained than slightly downstream from a dam, which is relevant for 3, 4, 5 and 14.

The critical thoughts about the used methods clarify that it would be helpful to analyse the effect of the measures on Strabrechtse Heide again in several years from now. The study site will be fully recovered from the interruption caused by the implementation of the nature restoration measures and there will be reached a new natural balance between the system variables. In addition, the fit-period after the implementation of the measures can be extended, which lowers the influence of the deviation among the measured groundwater levels and simulated groundwater levels, mainly caused by the presence of the two extreme years after 2014. Critical note: it cannot be guaranteed that extreme dry or wet years will not occur in the near future, which might reject the attempt to lower the influence of deviation among modelled and measured time series. If the fit-period after the implementation of the measures is extended, one can extend the fit-period before the implementation of the measures as well to maintain equal fit-periods. Equal fit-periods cause equal contribution of seasonal- and year-variability regarding weather to the two simulated groundwater time series (section 3.2.3; Appendix 4). Groundwater data, precipitation data and evaporation data before 2007, are available and thus this fit-period is easy to extend. In addition, the essential Python scripts are written and saved, thus available for waterboard De Dommel. In a quick and simple analysis, one need to assign the directories where the input variables (precipitation, evaporation, groundwater data) are saved and the Python will run new models and show new results, based on the new input data. For the proposed analysis of the effect of the measures on the groundwater level in the future, it might be helpful to consider some piezometers which are situated outside the specific study site, but still in Strabrechtse Heide (fig. 2.2). The results showed variable and slightly inconsistent behaviours of the groundwater levels closely to the implemented measures (section 5.2). The measures were conducted to rewet the entire nature reserve and thus it is supposed that rewetting might also be visible beyond the borders of the specific study site. In addition, net groundwater flow is North-West and thus increased groundwater levels in the South is supposed to influence the groundwater level in the North of Strabrechtse Heide (fig. 2.3). Including some piezometers that are situated North from the specific study site, but still in Strabrechtse Heide is a good suggestion for future research to see whether there is any desirable effect for the persistence of the native species quite some distance from the implemented nature restoration measures.

6. Conclusion

The Strabrechtse Heide is a nature reserve which is characterized by an alteration between relatively dry areas, which form dominantly dry heathlands and lower situated wet areas, that form wet heathlands and marshes. This nature reserve functions as habitat for several rare and native flora and fauna species, such as *Lobelia Dortmanna.* Continuous desiccation caused by climate change has created a severe threat for the protected and native species which mainly rely on relatively wet conditions. Therefore, waterboard De Dommel implemented nature restoration measures between 2013 and 2014 to improve the hydrological circumstances, which had as main purpose to rewet the nature reserve to counteract biodiversity loss.

This study focussed on the effect of the nature restoration measures on the groundwater level and showed that the measures have resulted in rewetting of the study site, but also have enhanced desiccation part of the year. Based on this, one can argue that implementation of the measures has not fulfilled the objective to rewet Strabrechtse Heide. However, the measures have increased the water holding capacity of the nature reserve and the opportunity to artificially regulate surface water drainage in the area. Nevertheless, surface water drainage, which dominantly occurs via Peelrijt/Witte Loop/Rielloop, is changed. Before 2013, water flew from Peelrijt/upstream Witte Loop further downstream towards Rielloop, via which it was drained out of the nature reserve. Since 2014, water flows dominantly from Peelrijt/upstream Witte Loop to Marijke Ven via a drainage channel, which was part of the nature restoration measures. This change in surface water drainage lowered the water presence in Witte Loop and Rielloop, which is with the current knowledge likely to have caused a reduction in infiltration surrounding these channels, especially for autumn and winter. As a result, desiccation is present part of the year. However, for spring and summer, drainage from Peelrijt/upstream Witte Loop further downstream used to be minimal before 2013, since the water level in this channel was low during these frequently dry seasons. As a consequence, there is no significant change in surface water drainage during spring and summer compared to these seasons before the implementation of the measures, but the capacity to (artificially) retain water in Witte Loop increased after 2014, resulting in an increased amount of water that is retained in this channel during these dry seasons. This excess in water has probably enhanced infiltration, dominantly for spring and summer, and caused therefore net rewetting in spring and summer surrounding Witte Loop and Rielloop.

Although the nature restoration measures have increased rewetting in the study site, dominantly for the spring- and summer months, there is still desiccation present, especially for fall and winter. The measures had drastic impact on the landscape and changed the hydrological circumstances, such as surface water drainage, in the study area. This leads to a changed infiltration pattern throughout the nature reserve, compared to the initial situation before 2013. The system might still be changing towards a new balance in which the contribution of the measures to the ecosystem, and thus the hydrology, is stabilised. Further, the Pastas time series analysis might deviate substantially from reality due to the presence of at least 2 extreme years within the fit-period of 5 years for the groundwater simulation based on 2014-2019. In other words, it would be useful to run the relevant Python scripts in several years from now, with longer fit-periods and other piezometers that are situated further North from the specific study site, but still in Strabrechtse Heide.

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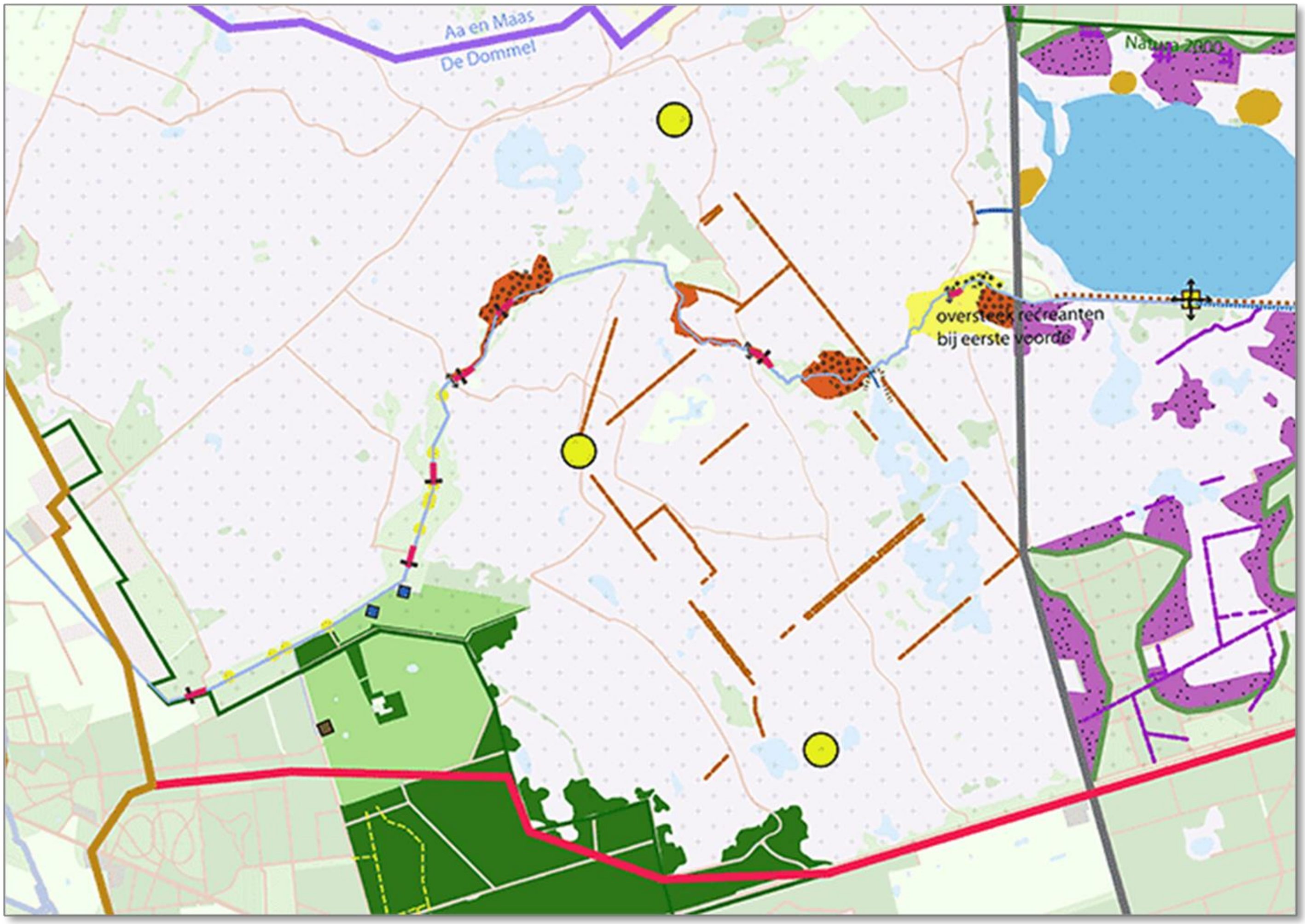
Vermue, H., Royal Haskoning DHV, (2012), GGOR Strabrechtse Heide en Sang en Goorkens

Appendix 1

Nature restoration measures, taken by waterboard De Dommel, in the study site (Strabrechtse Heide) (Muilwijk, 2013)



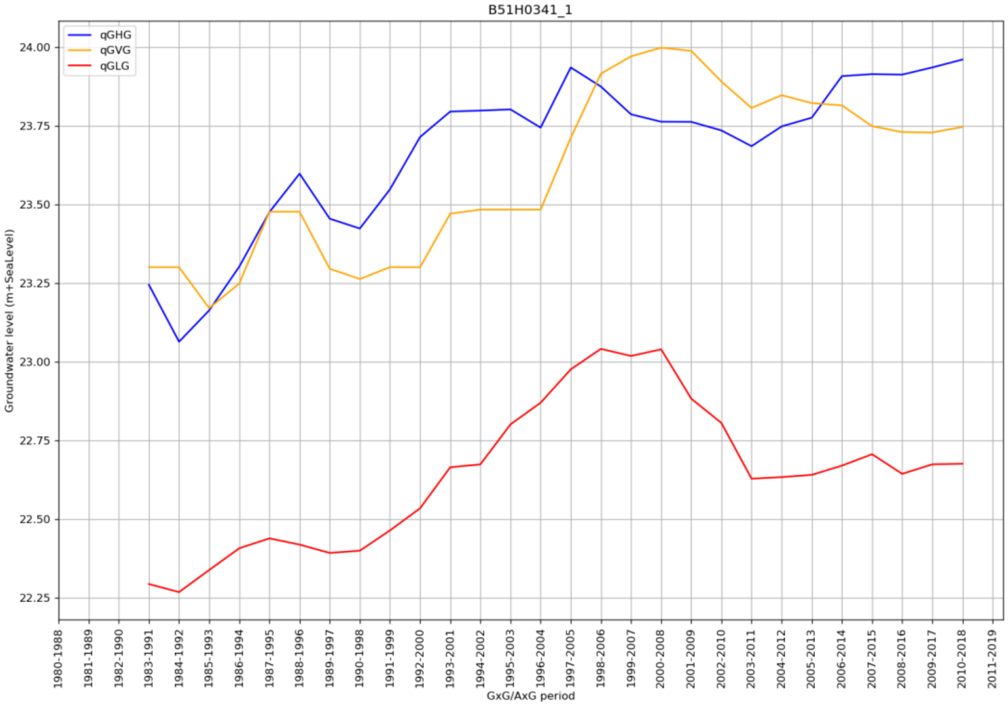
Legend nature restoration measures

🟪	Landcover change from pine forest to heathland (municipality Someren);
□	Developing transition zone between forest and heathlands, several shrubs types are dominantly used (municipality Someren);
━	Developing a natural drainage channel;
┅	Elevating the shore that is situated around Beuven (new elevation: 23.70m above sealevel);
✥	Changing settings artificial water spreader;
🟨	Developing searching area for zone where shoreweed flourishes;
╲	Lowering road
	Reducing drainage in the stream Witte Loop:
▮	- Existing dams (maintaining
━	- Elevating bottom of creeks upstream from waterspashes and dams (30cm)
┈	- Elevating bottom of the stream Peelrijt (22.50m above sealevel)
⤡	- Construction of new watersplashes
●	- Construction of local sand replenishments in stream Witte Loop
	Restore wet depressions in the area surround the stream Witte Loop:
🟧	- Removing the upper 25cm of the topsoil
🟨	- Removing the upper 15cm of the topsoi
▩	- Maintaining forest/shrubs in current conditions
	Rewetting forestlands and adjacent grasslands:
🟩	- Forest
🟩	- Grasslands
▤	- Closing streams
🟦	- New manually controlled dams
🟫	- Changing existing dams
	Drainage network Strabrechtse Heide:
╌	- Closing streams
╌	- Elevating bottom of streams (30cm)
○	- Maintaining construction that divides stream areas
◆	Automatizing existing dams
↖	Restoring natural drainage of Grafven

Appendix 2

GHG/AHG, GLG/ALG and GVG/ASG determined according to the ‘kwantiel methode’ for the piezometers that are situated at the 9 locations in the specific study site.

1



Location of B51H0341_1

X-coordinate = 172620.0

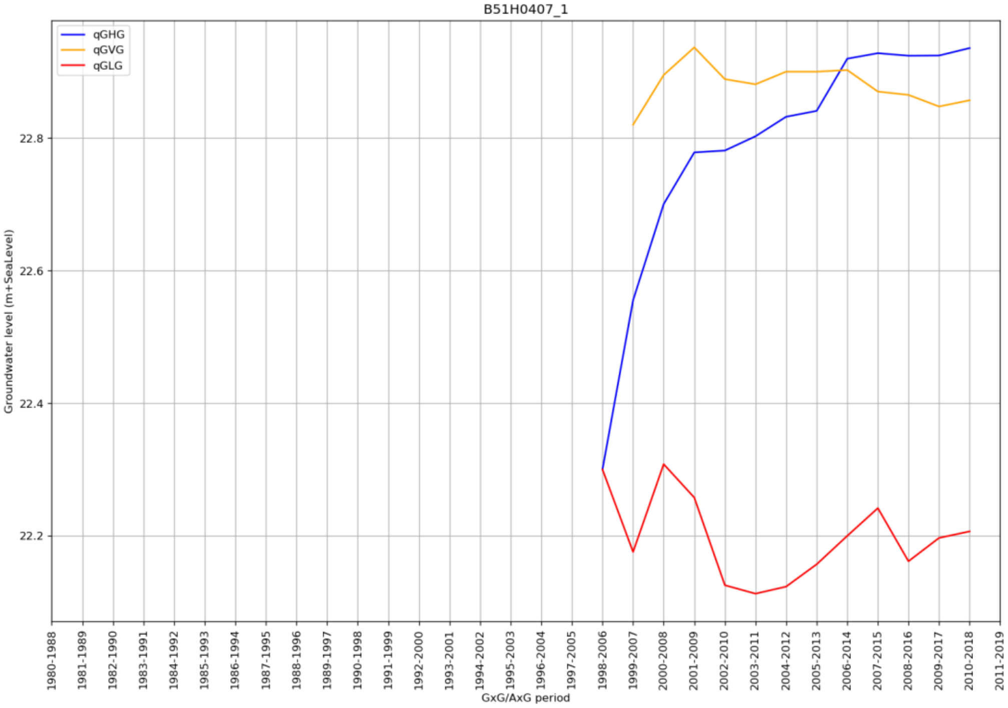
Y-coordinate = 377370.0

Surface level = 24.05m+SeaLevel

Start measuring (Dutch date): 01-12-1989

End measuring (Dutch date): 26-04-2019

3



Location of B51H0407_1

X-coordinate = 172370.0

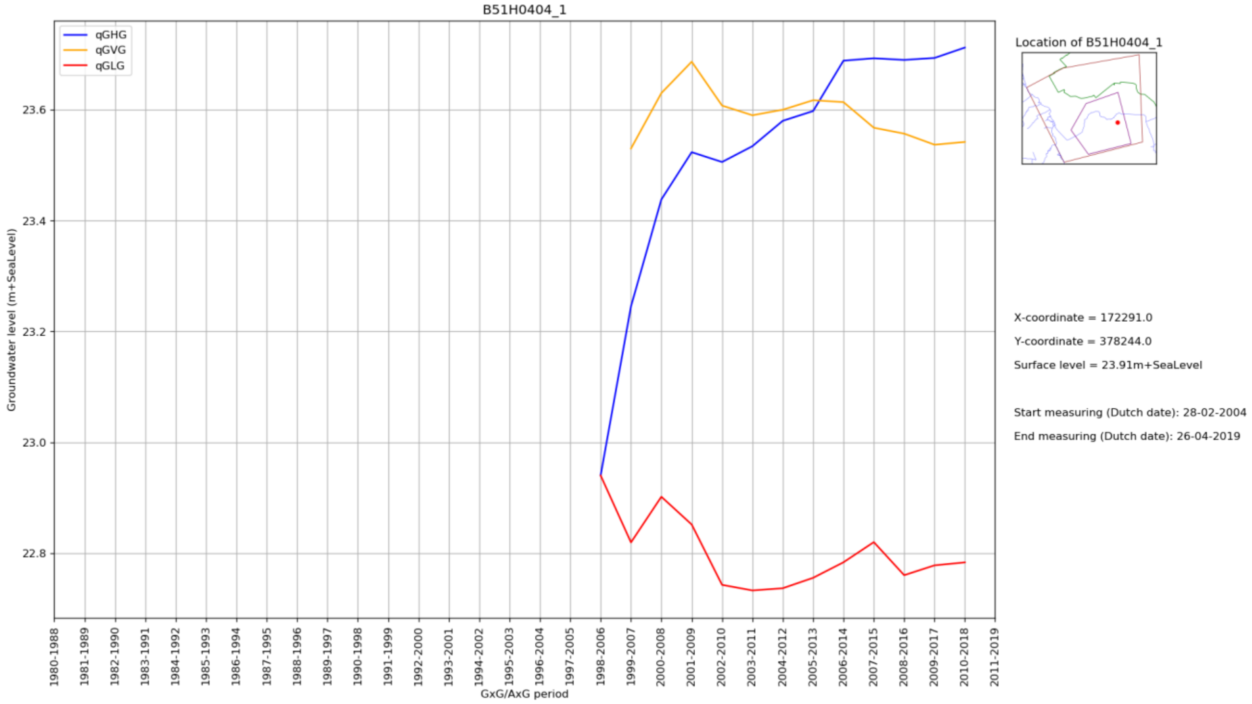
Y-coordinate = 377981.0

Surface level = 23.05m+SeaLevel

Start measuring (Dutch date): 28-02-2004

End measuring (Dutch date): 26-04-2019

4



X-coordinate = 172291.0

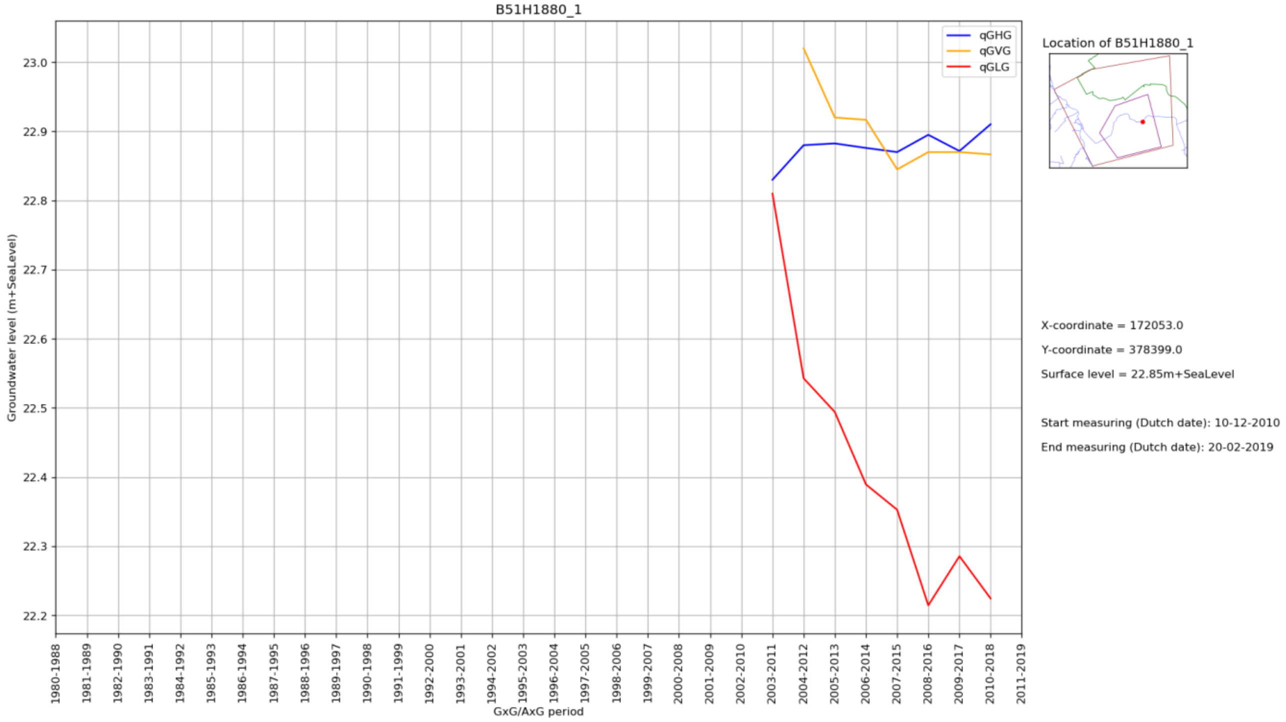
Y-coordinate = 378244.0

Surface level = 23.91m+SeaLevel

Start measuring (Dutch date): 28-02-2004

End measuring (Dutch date): 26-04-2019

5 (filter number 1)



X-coordinate = 172053.0

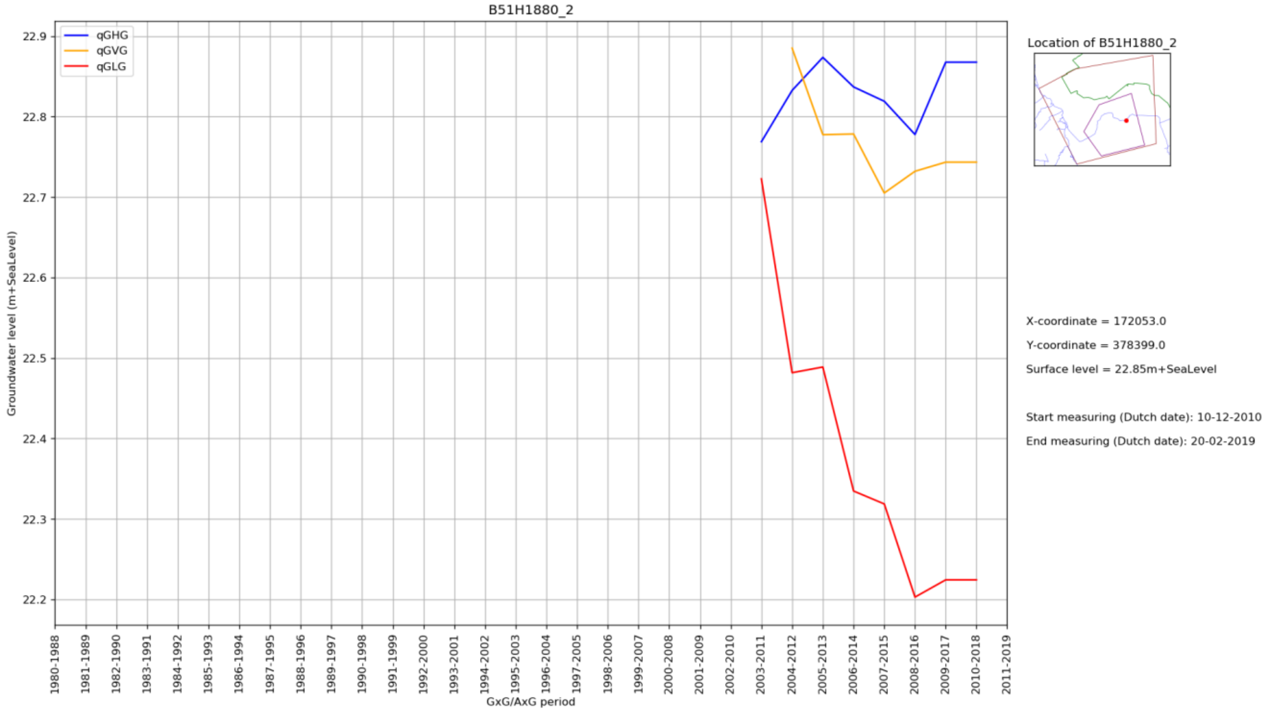
Y-coordinate = 378399.0

Surface level = 22.85m+SeaLevel

Start measuring (Dutch date): 10-12-2010

End measuring (Dutch date): 20-02-2019

5 (filter number 2)



X-coordinate = 172053.0

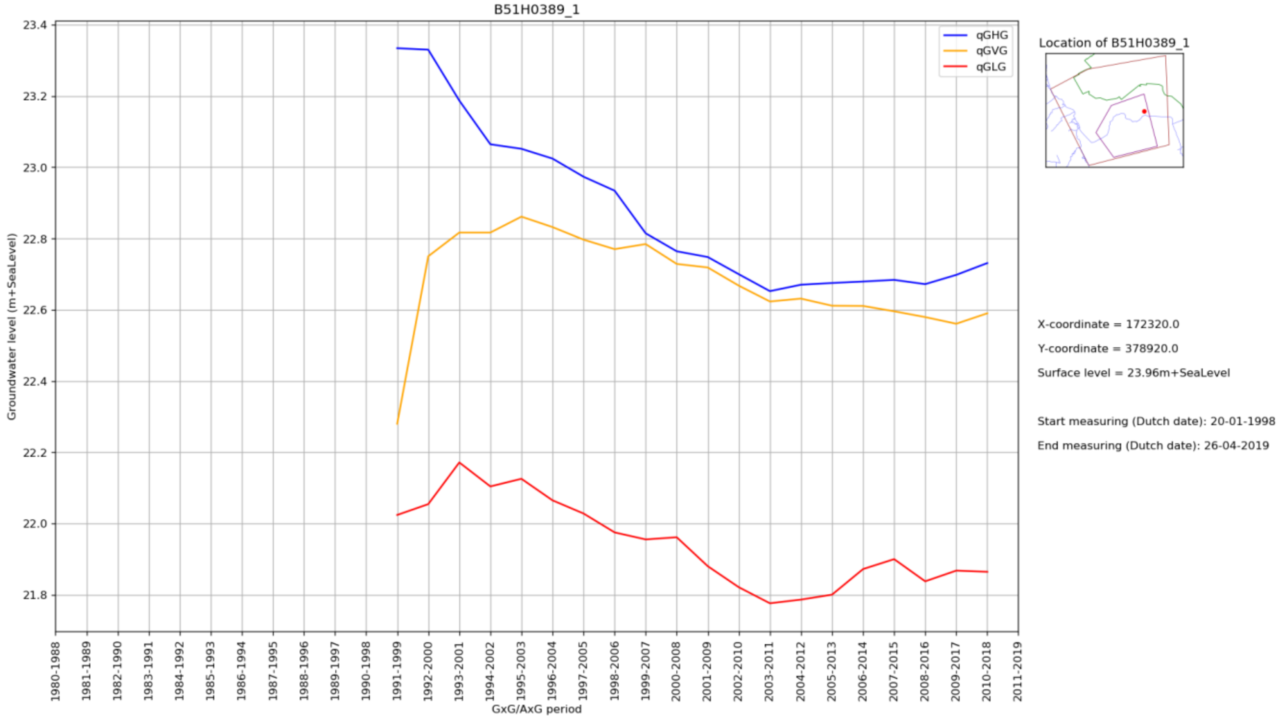
Y-coordinate = 378399.0

Surface level = 22.85m+SeaLevel

Start measuring (Dutch date): 10-12-2010

End measuring (Dutch date): 20-02-2019

7



X-coordinate = 172320.0

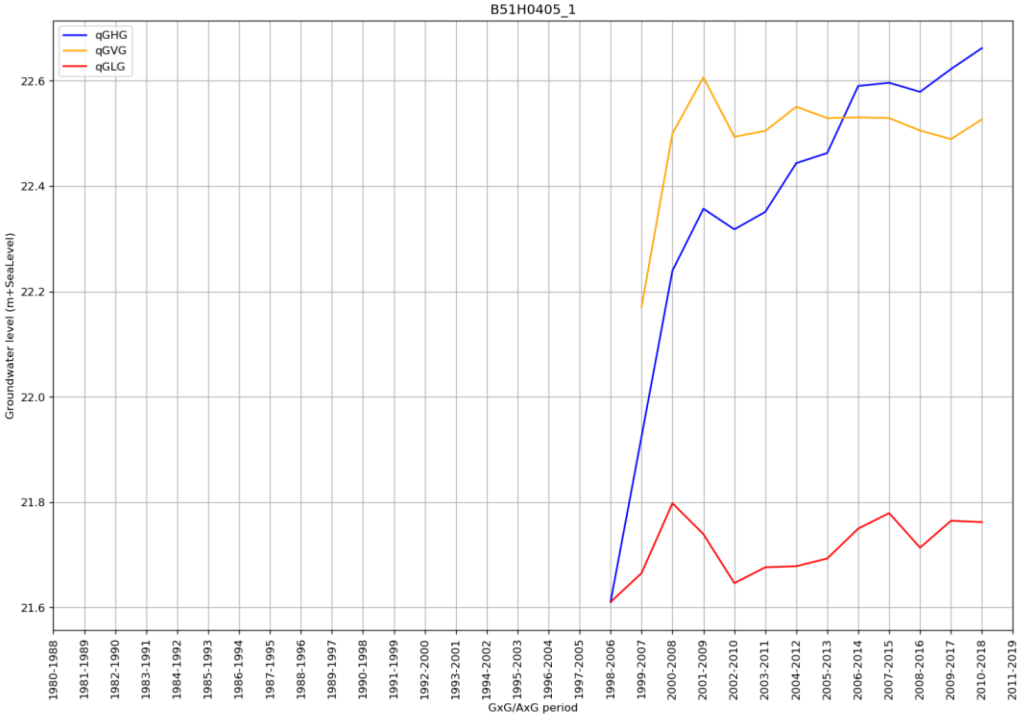
Y-coordinate = 378920.0

Surface level = 23.96m+SeaLevel

Start measuring (Dutch date): 20-01-1998

End measuring (Dutch date): 26-04-2019

8



Location of B51H0405_1

X-coordinate = 172137.0

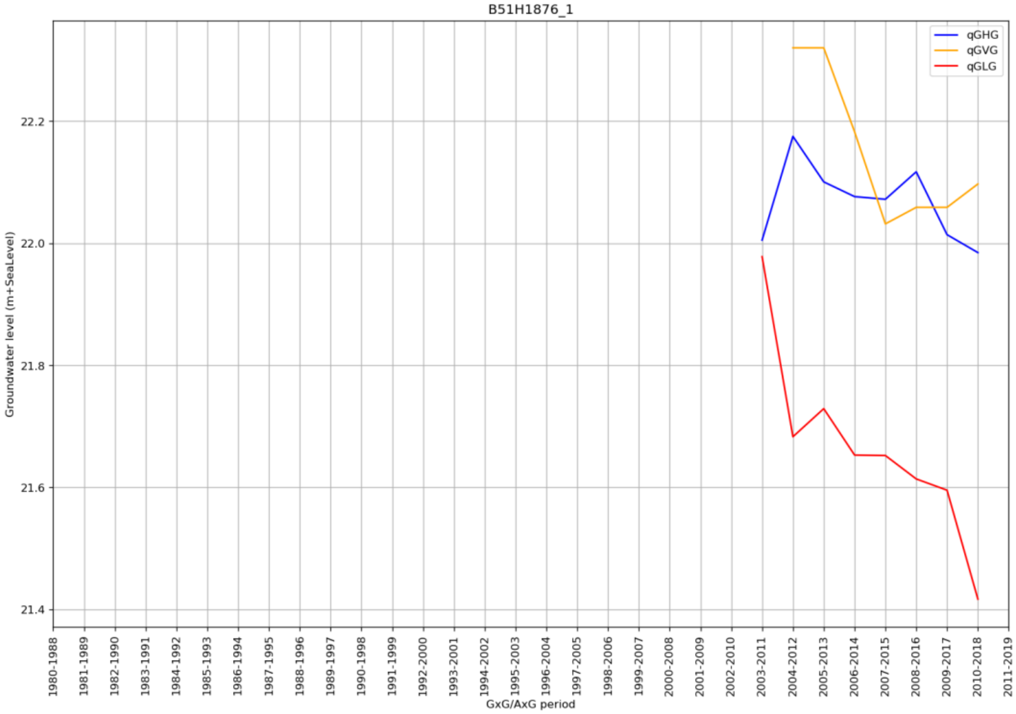
Y-coordinate = 379285.0

Surface level = 23.9m+SeaLevel

Start measuring (Dutch date): 28-02-2004

End measuring (Dutch date): 26-04-2019

11



Location of B51H1876_1

X-coordinate = 170894.0

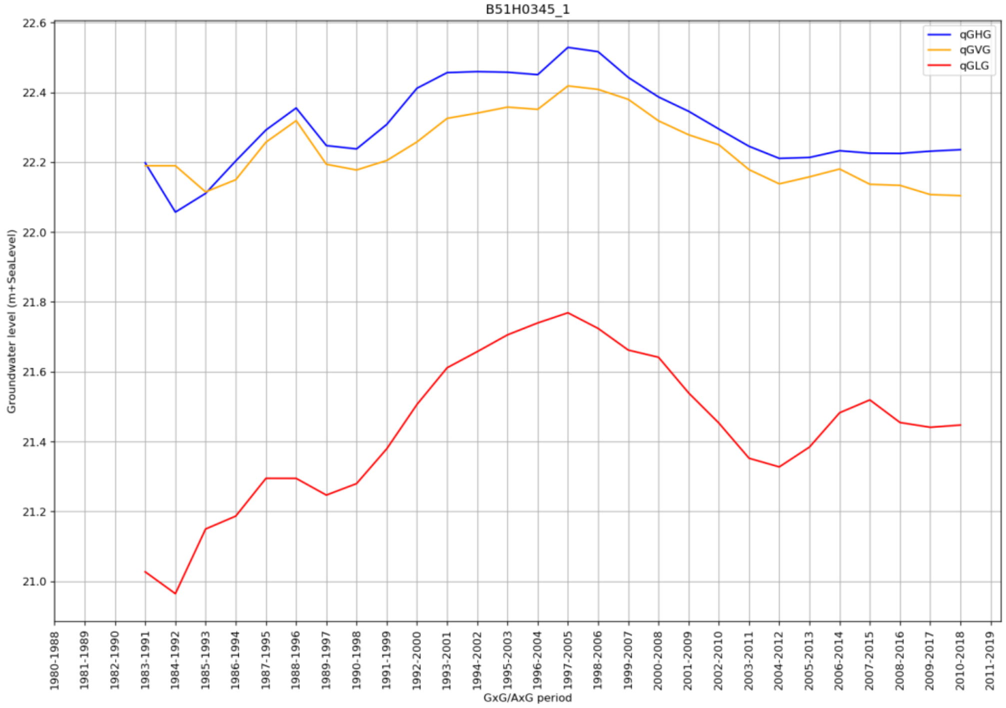
Y-coordinate = 379237.0

Surface level = 21.89m+SeaLevel

Start measuring (Dutch date): 21-12-2010

End measuring (Dutch date): 22-02-2019

14



Location of B51H0345_1

X-coordinate = 171175.0

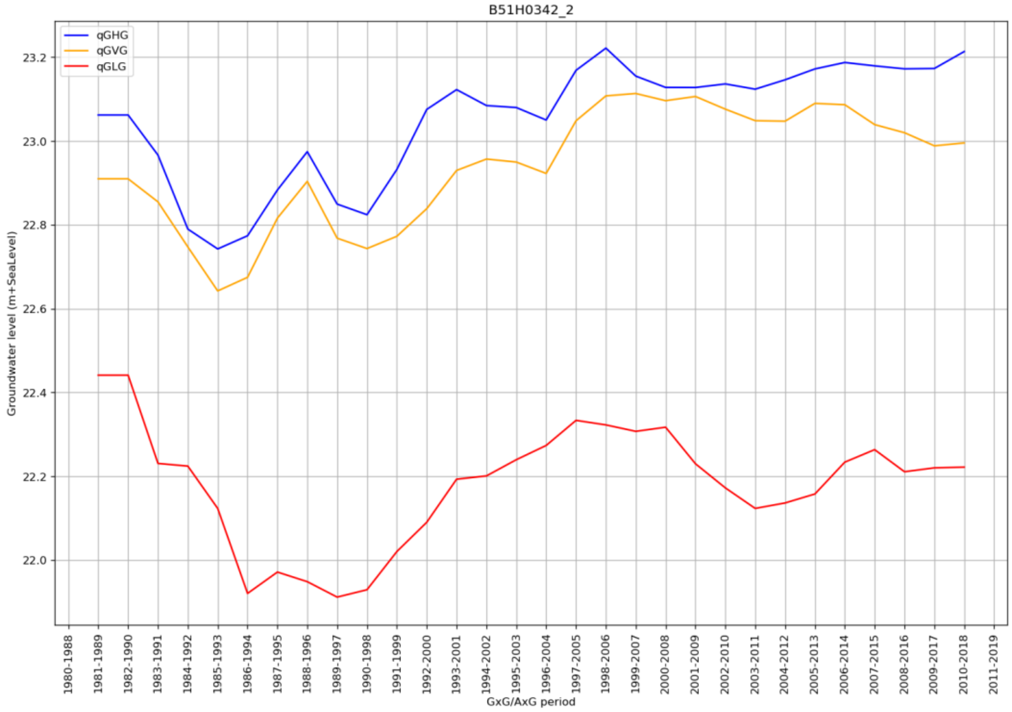
Y-coordinate = 378745.0

Surface level = 22.37m+SeaLevel

Start measuring (Dutch date): 01-12-1989

End measuring (Dutch date): 26-04-2019

16



Location of B51H0342_2

X-coordinate = 171100.0

Y-coordinate = 377590.0

Surface level = 23.62m+SeaLevel

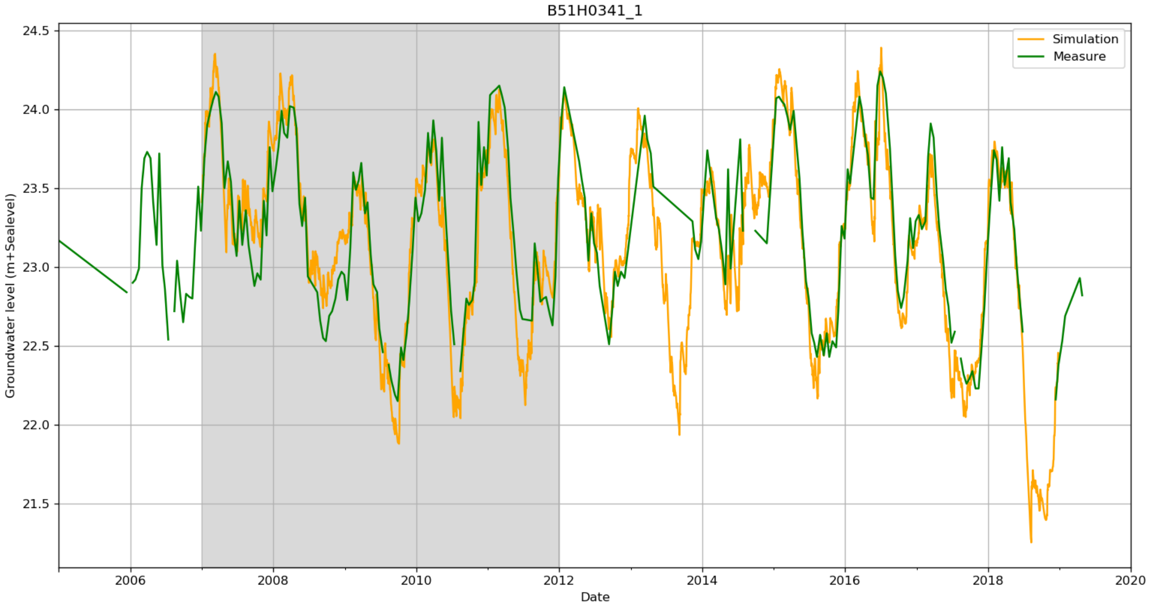
Start measuring (Dutch date): 03-03-1983

End measuring (Dutch date): 26-04-2019

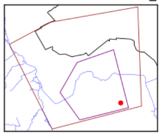
Appendix 3

The simulated groundwater level (yellow) based on the measured groundwater level (green), the precipitation and evaporation for the selected piezometers. The simulation is based on fit period 2007-2012. The EVP is defined in the bottom right of each plot and is expressed in percentage with an optimum of 100%, meaning that the simulation matches the measured time series perfectly.

1



Location of B51H0341_1



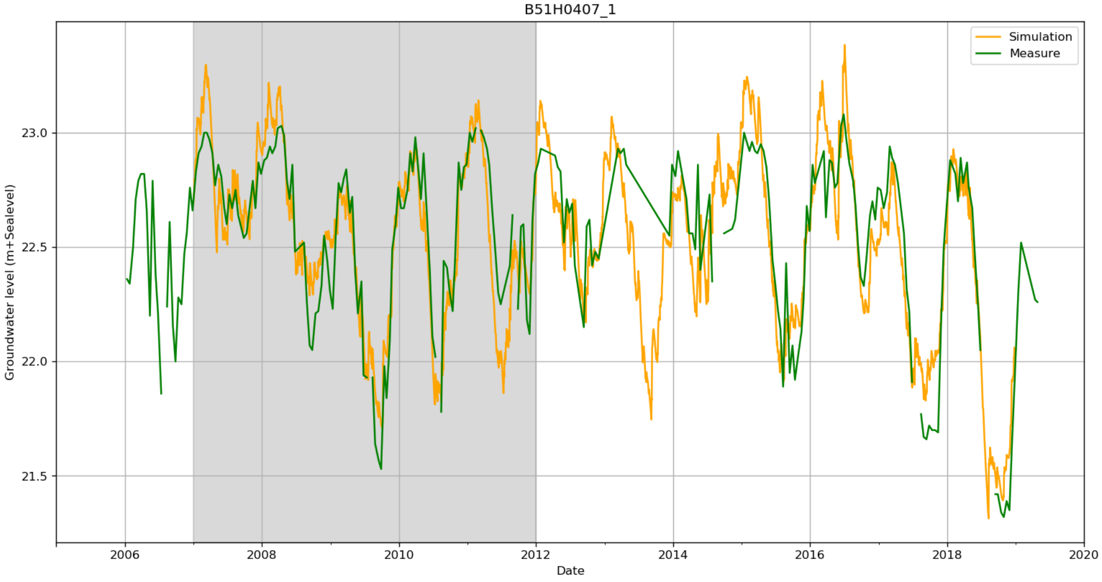
X = 172620.0
Y = 377370.0
Surface level = 24.05 m+Sealevel

Start measuring (Dutch date): 01-12-1989
End measuring (Dutch date): 26-04-2019

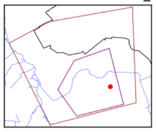
Simulation fit on period (Dutch date):
1-1-2007 - 1-1-2012
(grey surface area in the plot)

EVP = 87.89

3



Location of B51H0407_1



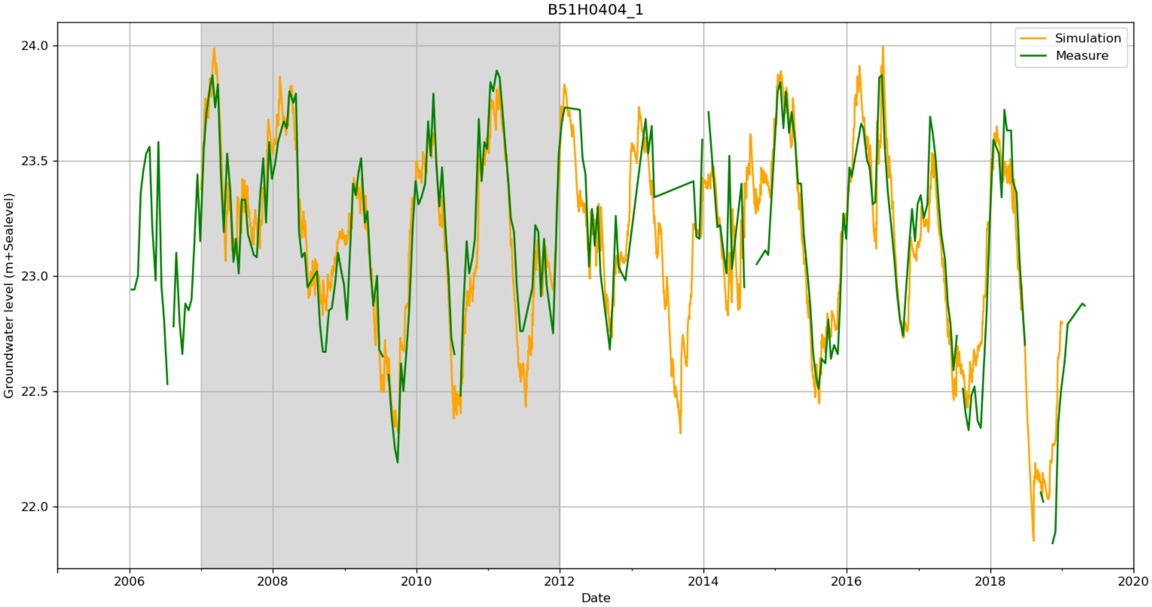
X = 172370.0
Y = 377981.0
Surface level = 23.05 m+Sealevel

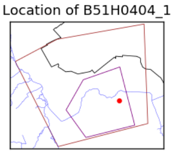
Start measuring (Dutch date): 28-02-2004
End measuring (Dutch date): 26-04-2019

Simulation fit on (Dutch date):
1-1-2007 - 1-1-2012
(grey surface area in the plot)

EVP = 83.91

4





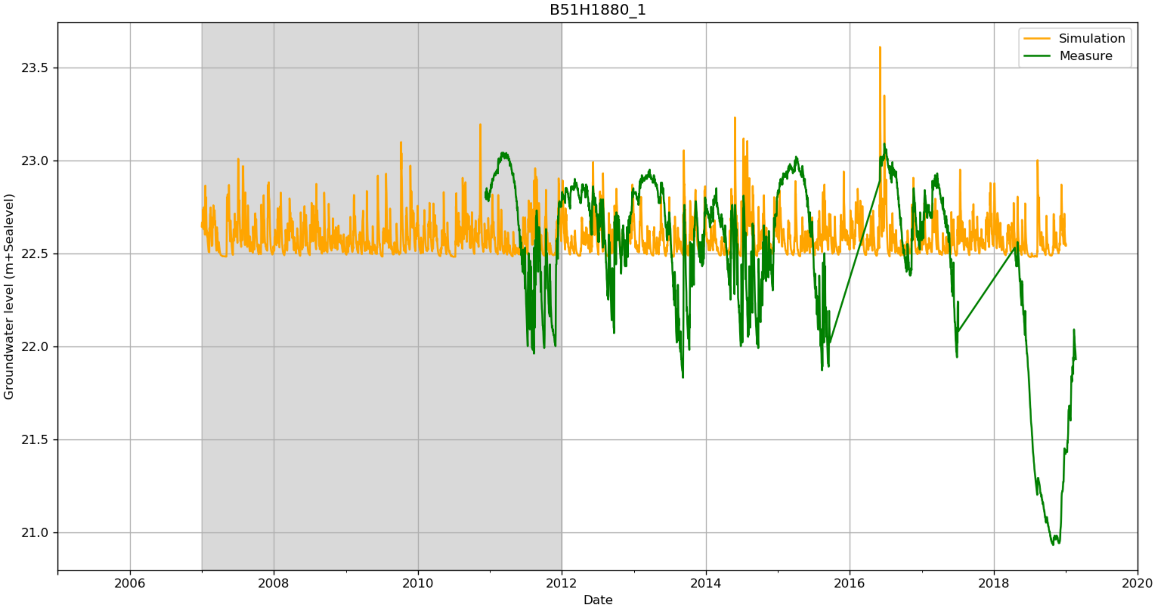
X = 172291.0
Y = 378244.0
Surface level = 23.91 m+Sealevel

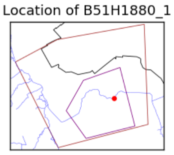
Start measuring (Dutch date): 28-02-2004
End measuring (Dutch date): 26-04-2019

Simulation fit on (Dutch date):
1-1-2007 - 1-1-2012
(grey surface area in the plot)

EVP = 89.24

5 (filter number 1)





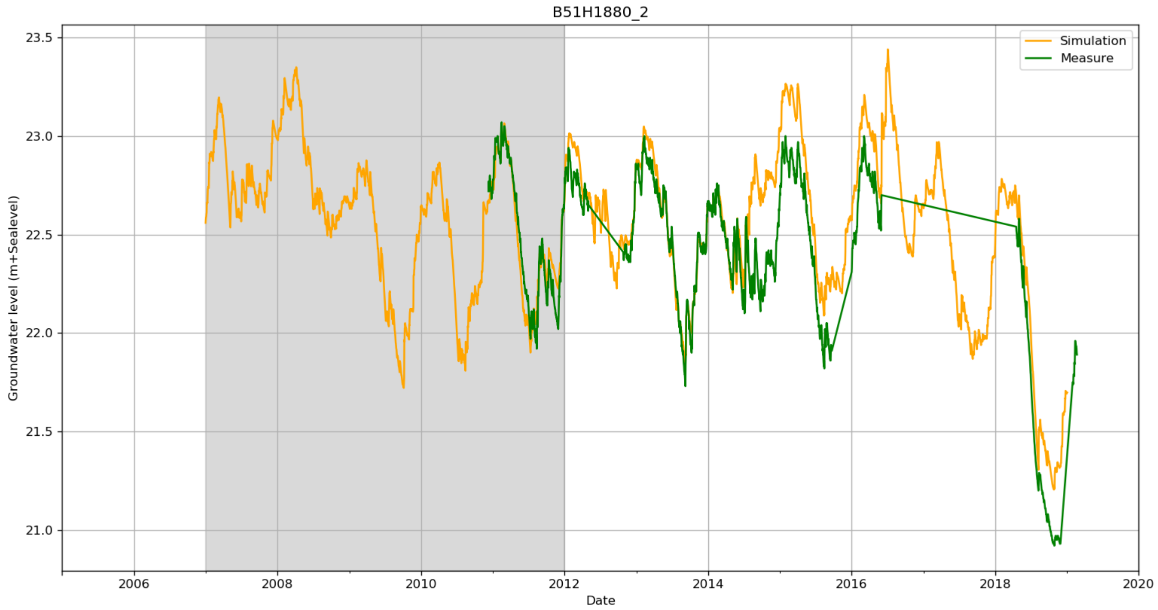
X = 172053.0
Y = 378399.0
Surface level = 22.85 m+Sealevel

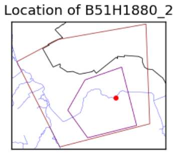
Start measuring (Dutch date): 10-12-2010
End measuring (Dutch date): 20-02-2019

Simulation fit on (Dutch date):
1-1-2007 - 1-1-2012
(grey surface area in the plot)

EVP = 0.0

5 (filter number 2)





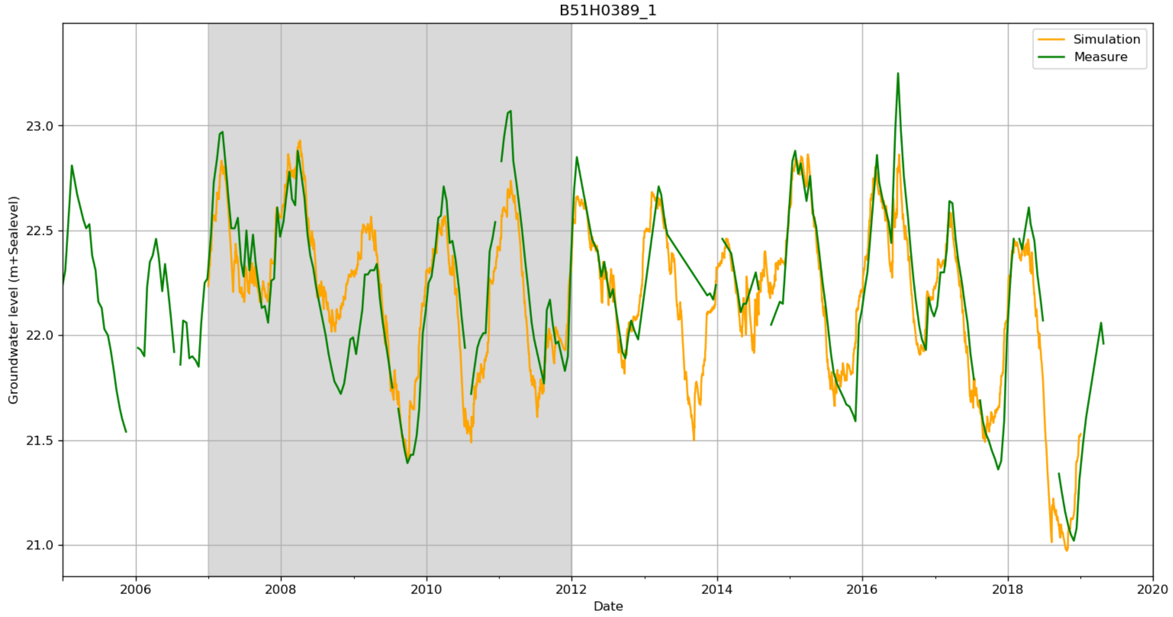
X = 172053.0
Y = 378399.0
Surface level = 22.85 m+Sealevel

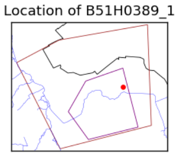
Start measuring (Dutch date): 10-12-2010
End measuring (Dutch date): 20-02-2019

Simulation fit on (Dutch date):
1-1-2007 - 1-1-2012
(grey surface area in the plot)

EVP = 92.65

7





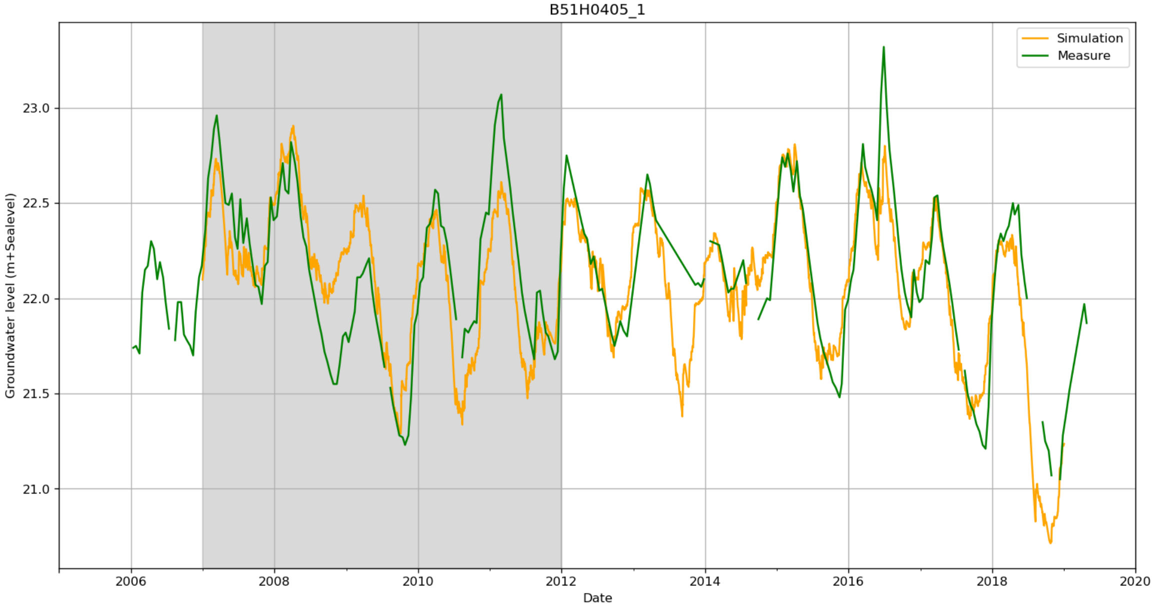
X = 172320.0
Y = 378920.0
Surface level = 23.96 m+Sealevel

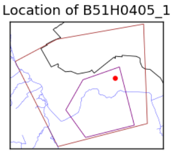
Start measuring (Dutch date): 20-01-1998
End measuring (Dutch date): 26-04-2019

Simulation fit on (Dutch date):
1-1-2007 - 1-1-2012
(grey surface area in the plot)

EVP = 76.35

8





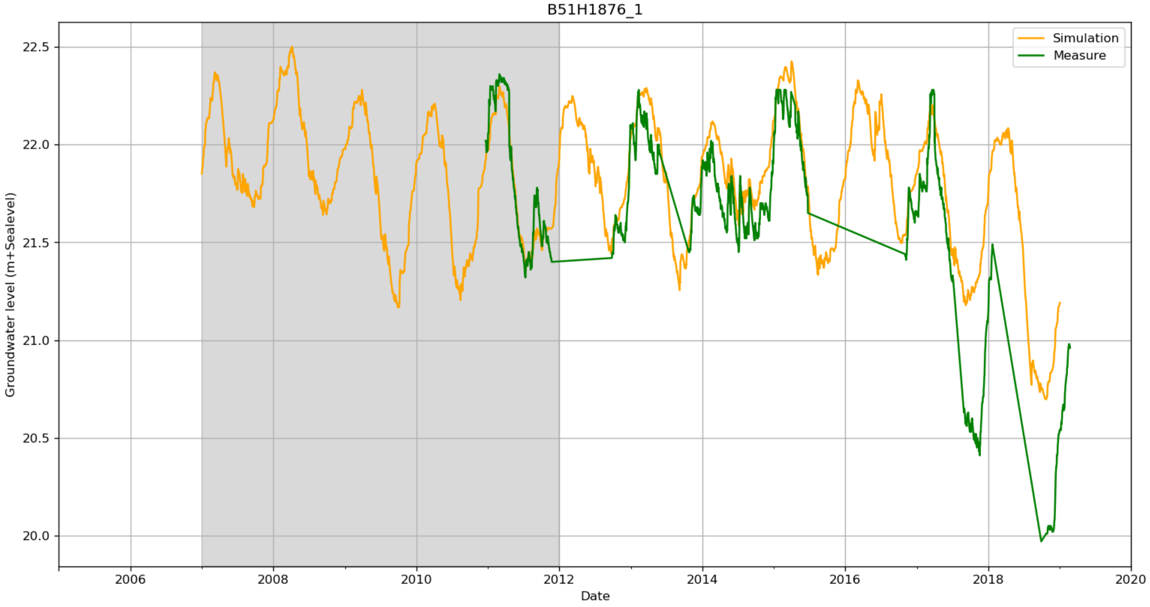
X = 172137.0
Y = 379285.0
Surface level = 23.9 m+Sealevel

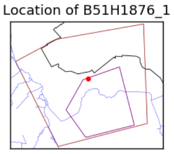
Start measuring (Dutch date): 28-02-2004
End measuring (Dutch date): 26-04-2019

Simulation fit on (Dutch date):
1-1-2007 - 1-1-2012
(grey surface area in the plot)

EVP = 63.1

11





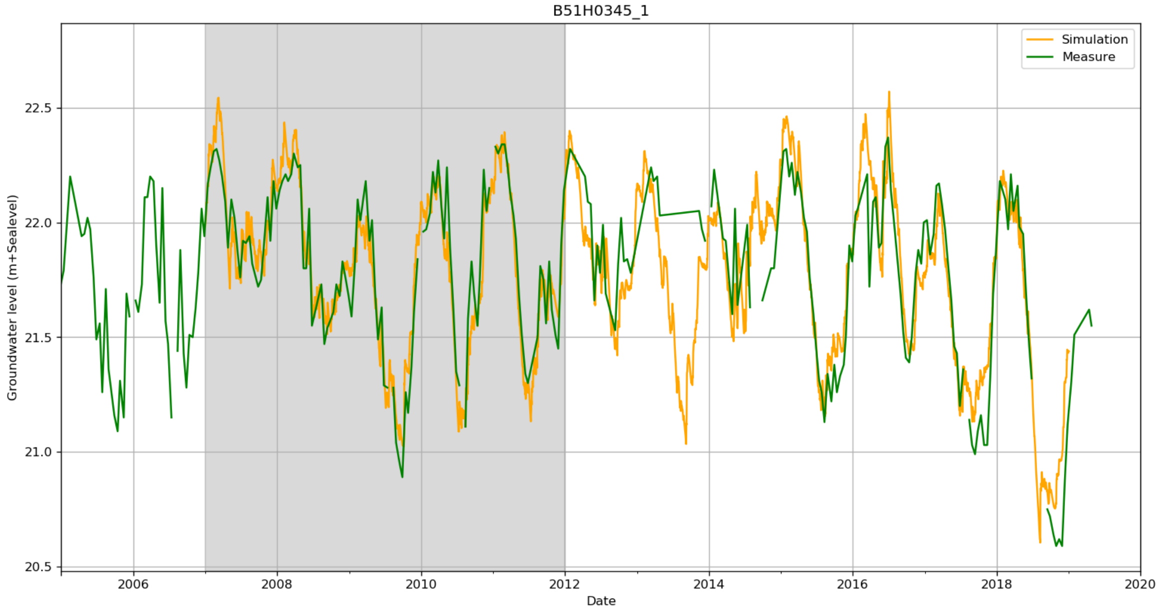
X = 170894.0
Y = 379237.0
Surface level = 21.89 m+Sealevel

Start measuring (Dutch date): 21-12-2010
End measuring (Dutch date): 22-02-2019

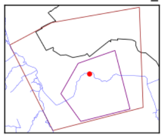
Simulation fit on (Dutch date):
1-1-2007 - 1-1-2012
(grey surface area in the plot)

EVP = 94.4

14



Location of B51H0345_1



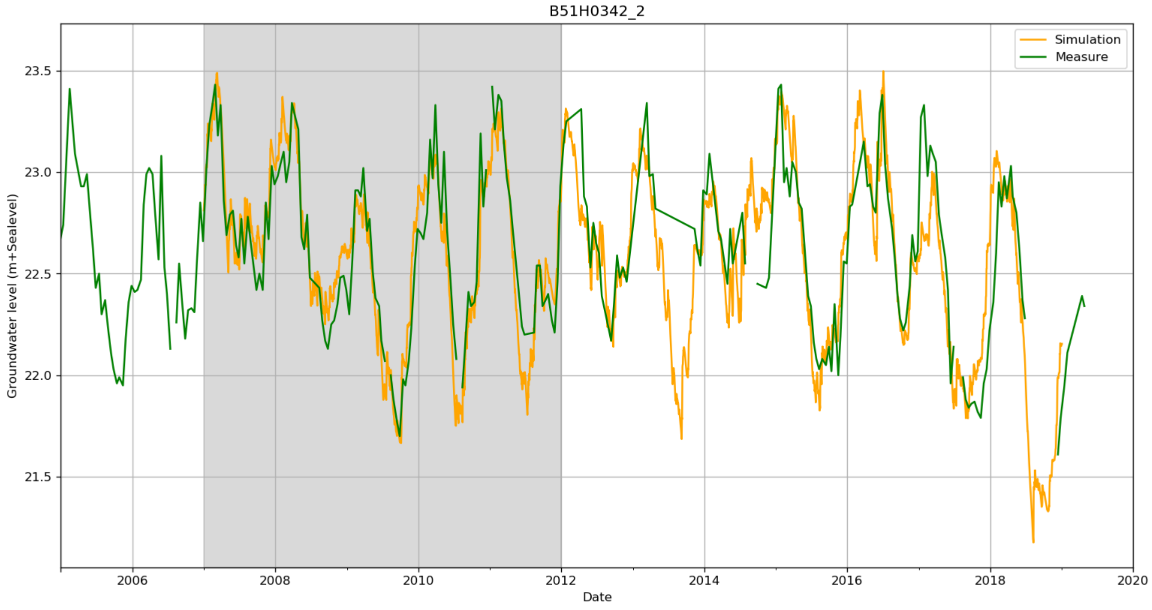
X = 171175.0
Y = 378745.0
Surface level = 22.37 m+Sealevel

Start measuring (Dutch date): 01-12-1989
End measuring (Dutch date): 26-04-2019

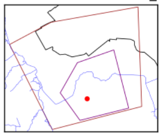
Simulation fit on (Dutch date):
1-1-2007 - 1-1-2012
(grey surface area in the plot)

EVP = 90.46

16



Location of B51H0342_2



X = 171100.0
Y = 377590.0
Surface level = 23.62 m+Sealevel

Start measuring (Dutch date): 03-03-1983
End measuring (Dutch date): 26-04-2019

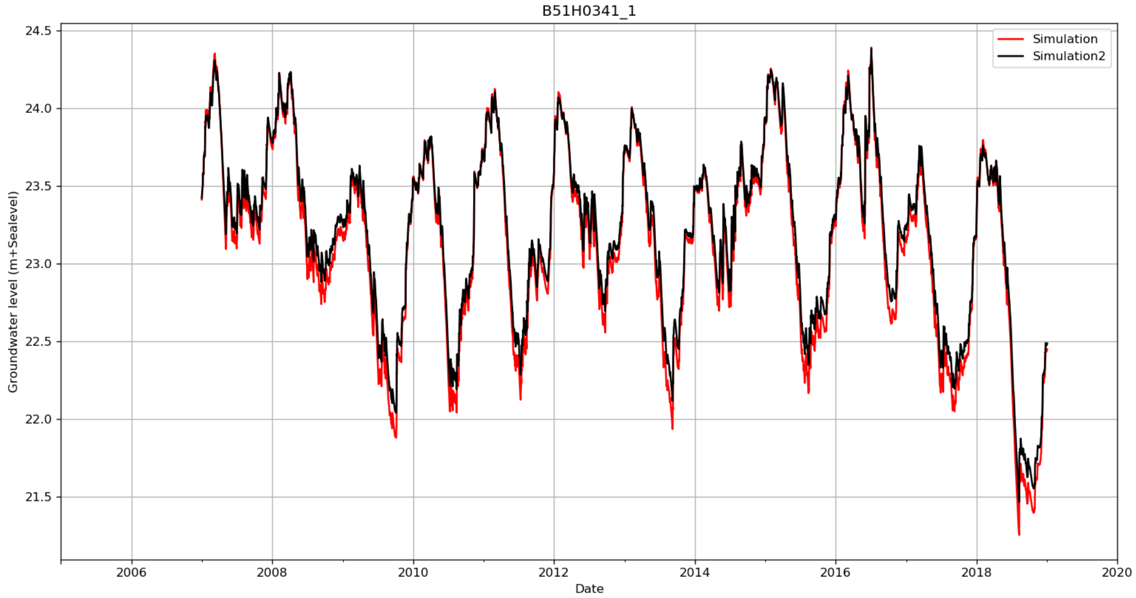
Simulation fit on (Dutch date):
1-1-2007 - 1-1-2012
(grey surface area in the plot)

EVP = 89.16

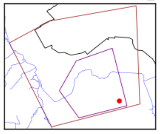
Appendix 4

The simulated groundwater level (yellow) based on the measured groundwater level (green), the precipitation and evaporation for the selected piezometers. Simulation2 (black) is based on fit period 2014-2019. Simulation (red) is based on fit period 2007-2012.

1



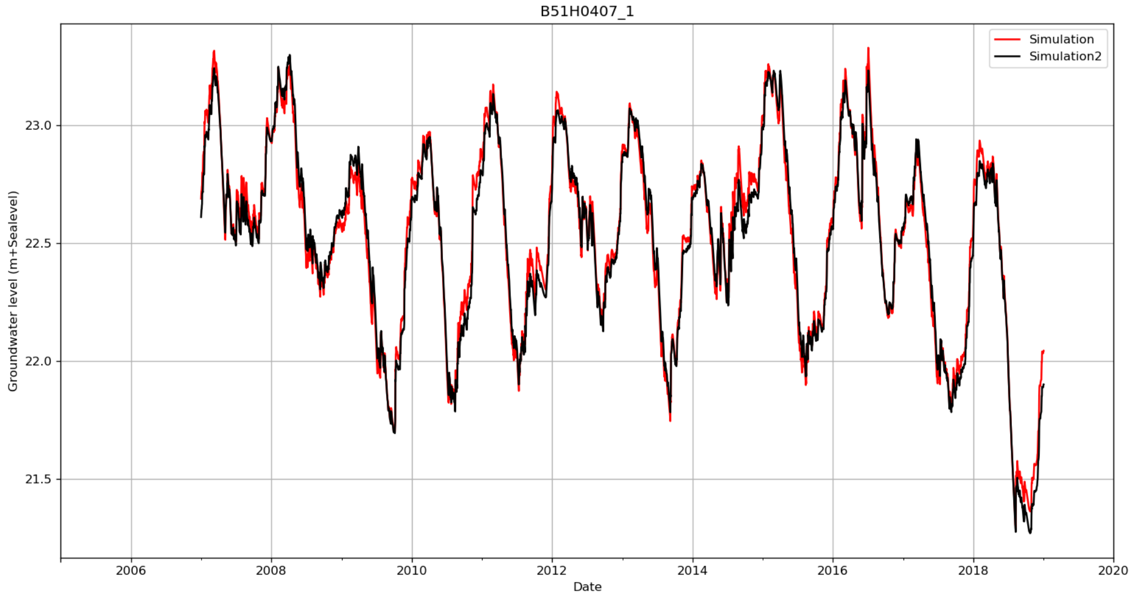
Location of B51H0341_1



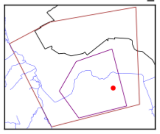
X = 172620.0
Y = 377370.0
Surface level = 24.05 m+Sealevel

Start measuring (Dutch date): 01-12-1989
End measuring (Dutch date): 26-04-2019

3



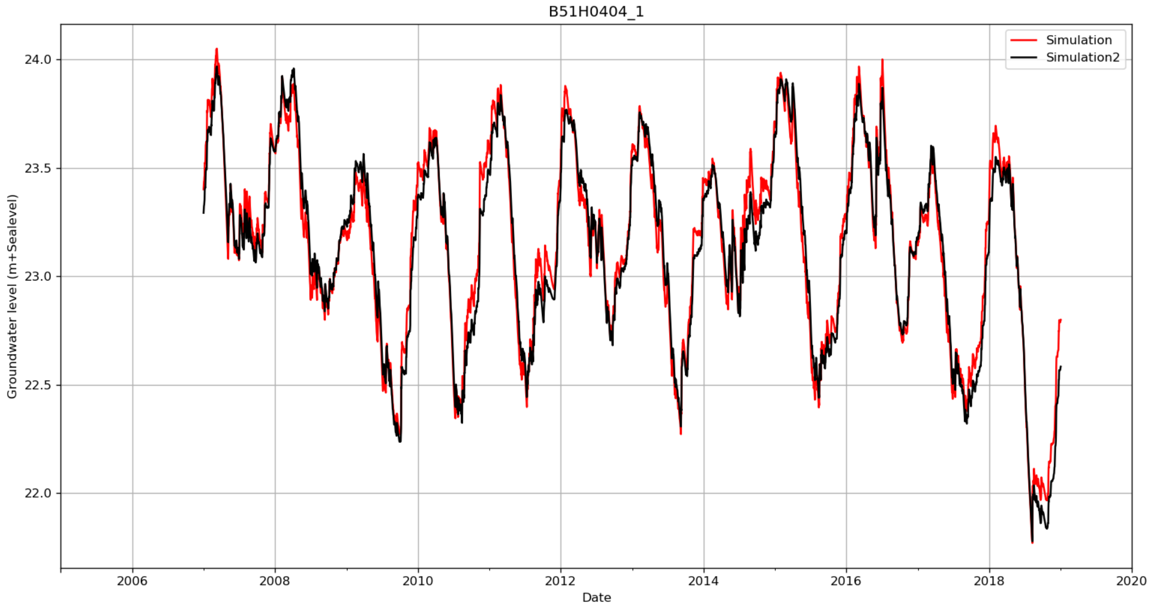
Location of B51H0407_1

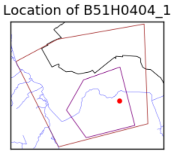


X = 172370.0
Y = 377981.0
Surface level = 23.05 m+Sealevel

Start measuring (Dutch date): 28-02-2004
End measuring (Dutch date): 26-04-2019

4

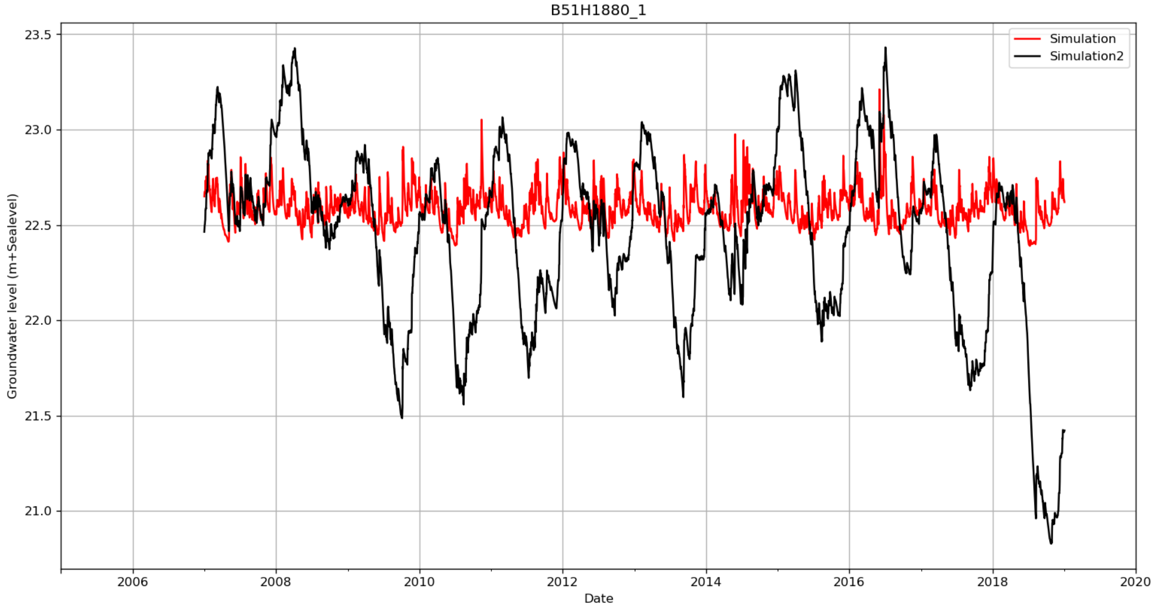


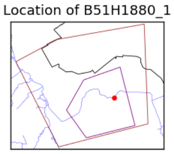


X = 172291.0
Y = 378244.0
Surface level = 23.91 m+Sealevel

Start measuring (Dutch date): 28-02-2004
End measuring (Dutch date): 26-04-2019

5 (filter number 1)

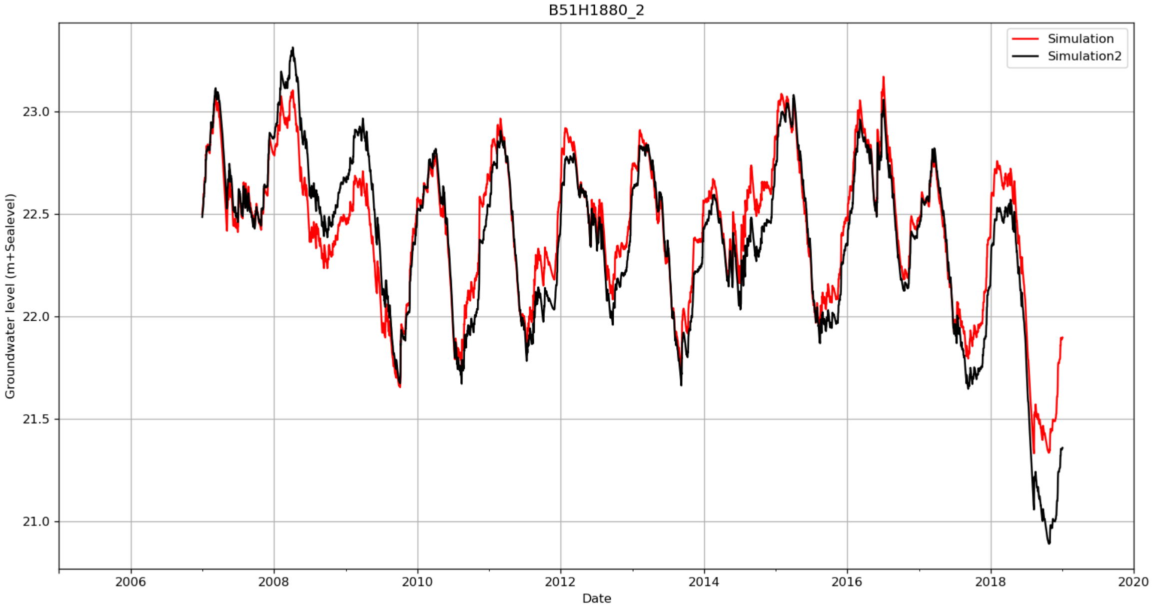


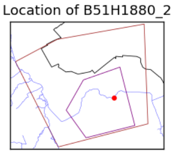


X = 172053.0
Y = 378399.0
Surface level = 22.85 m+Sealevel

Start measuring (Dutch date): 10-12-2010
End measuring (Dutch date): 20-02-2019

5 (filter number 2)

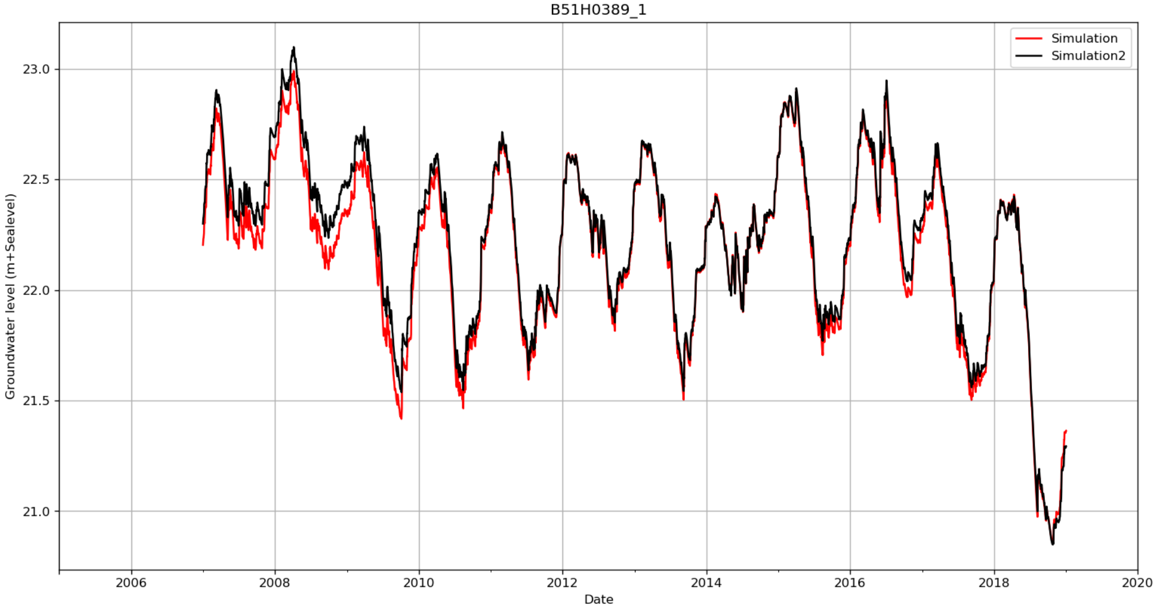


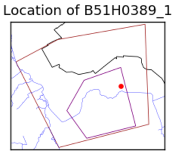


X = 172053.0
Y = 378399.0
Surface level = 22.85 m+Sealevel

Start measuring (Dutch date): 10-12-2010
End measuring (Dutch date): 20-02-2019

7

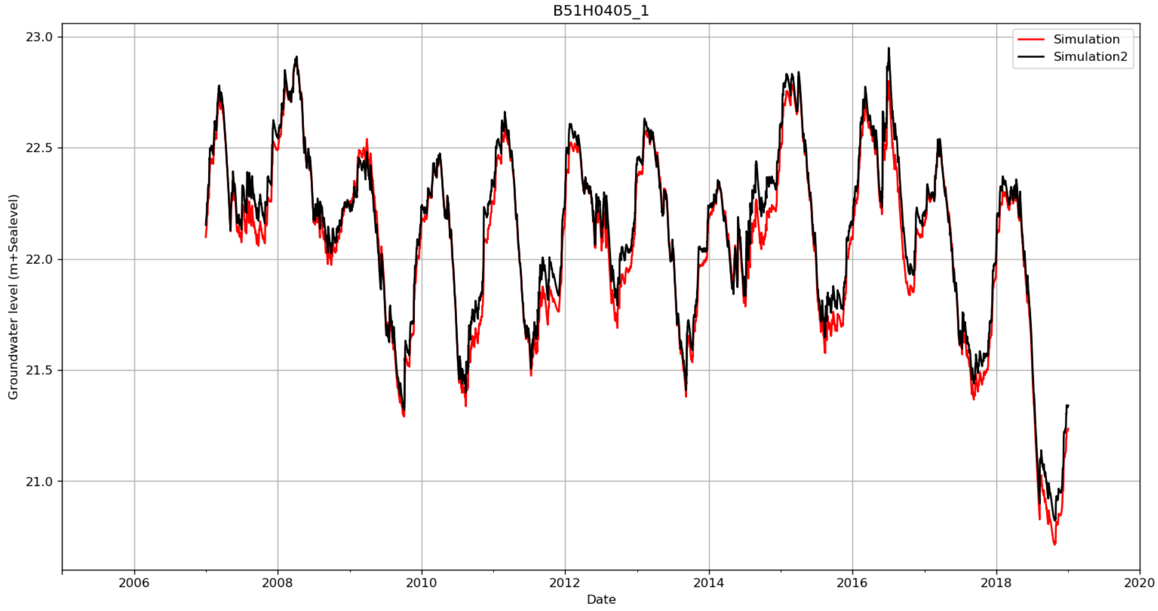


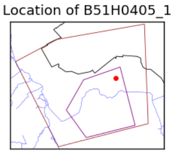


X = 172320.0
Y = 378920.0
Surface level = 23.96 m+Sealevel

Start measuring (Dutch date): 20-01-1998
End measuring (Dutch date): 26-04-2019

8

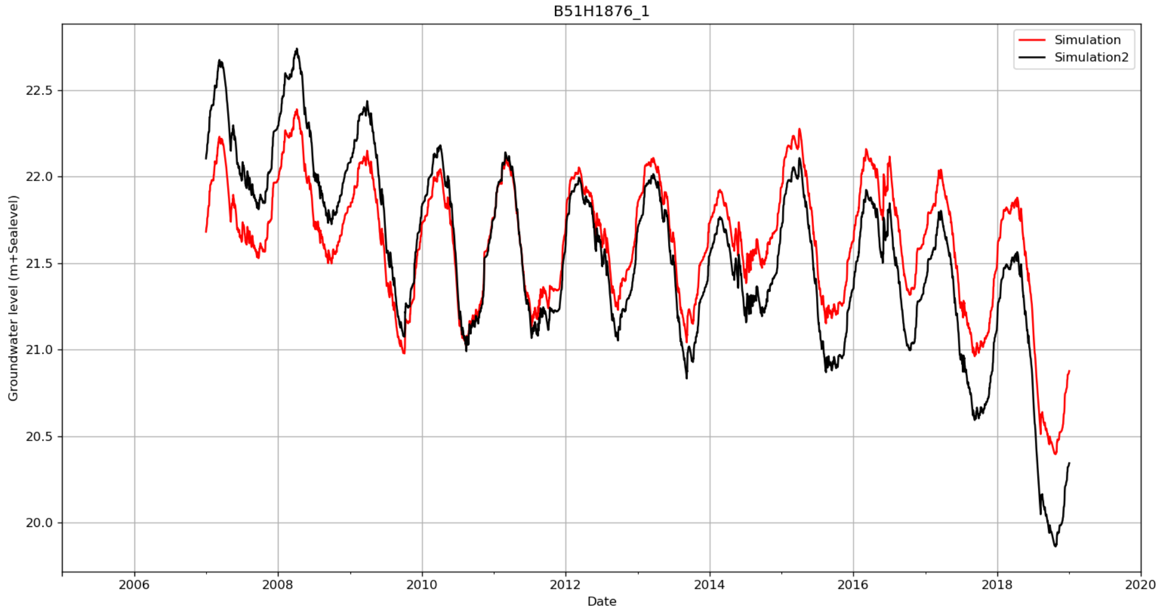


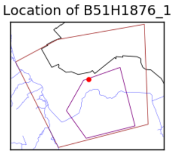


X = 172137.0
Y = 379285.0
Surface level = 23.9 m+Sealevel

Start measuring (Dutch date): 28-02-2004
End measuring (Dutch date): 26-04-2019

11

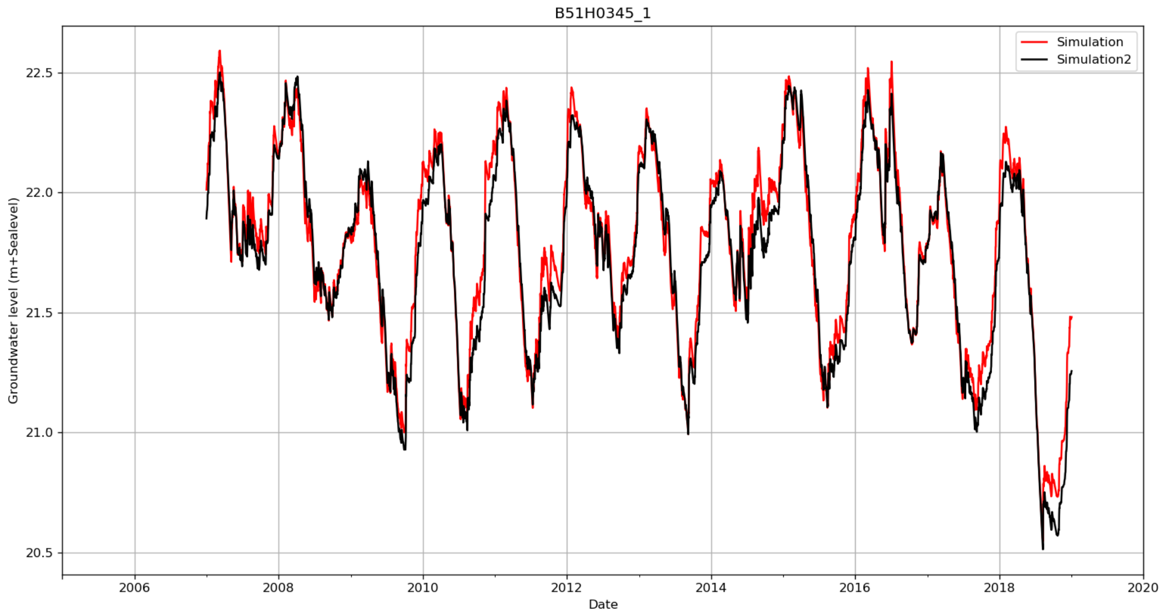




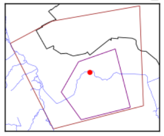
X = 170894.0
Y = 379237.0
Surface level = 21.89 m+Sealevel

Start measuring (Dutch date): 21-12-2010
End measuring (Dutch date): 22-02-2019

14


B51H0345_1

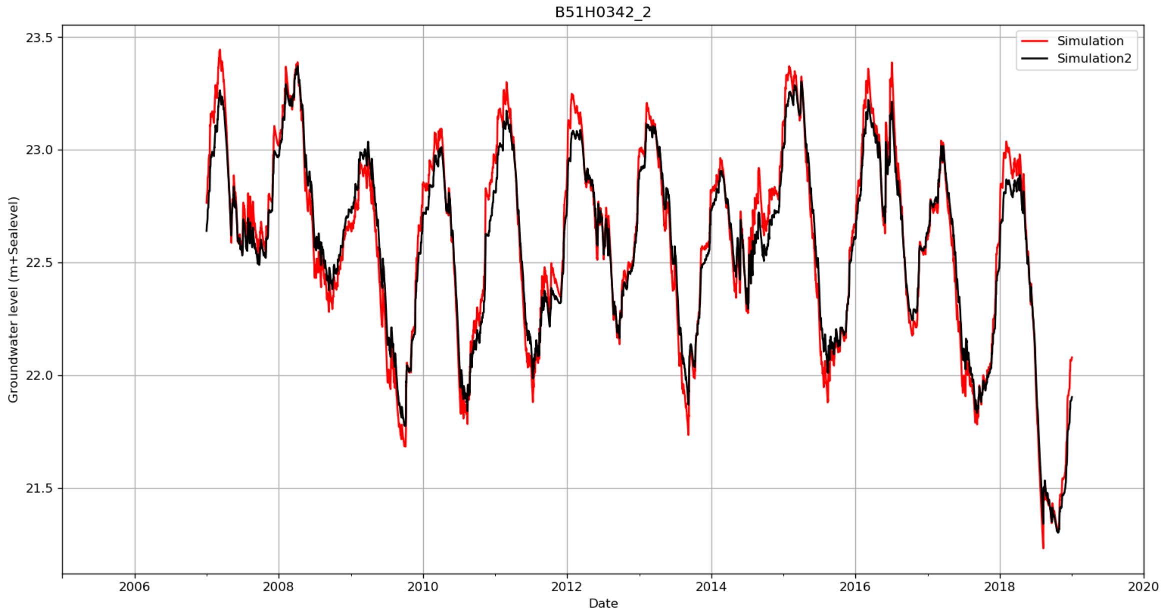
Location of B51H0345_1



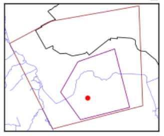
X = 171175.0
Y = 378745.0
Surface level = 22.37 m+Sealevel

Start measuring (Dutch date): 01-12-1989
End measuring (Dutch date): 26-04-2019

16


B51H0342_2

Location of B51H0342_2



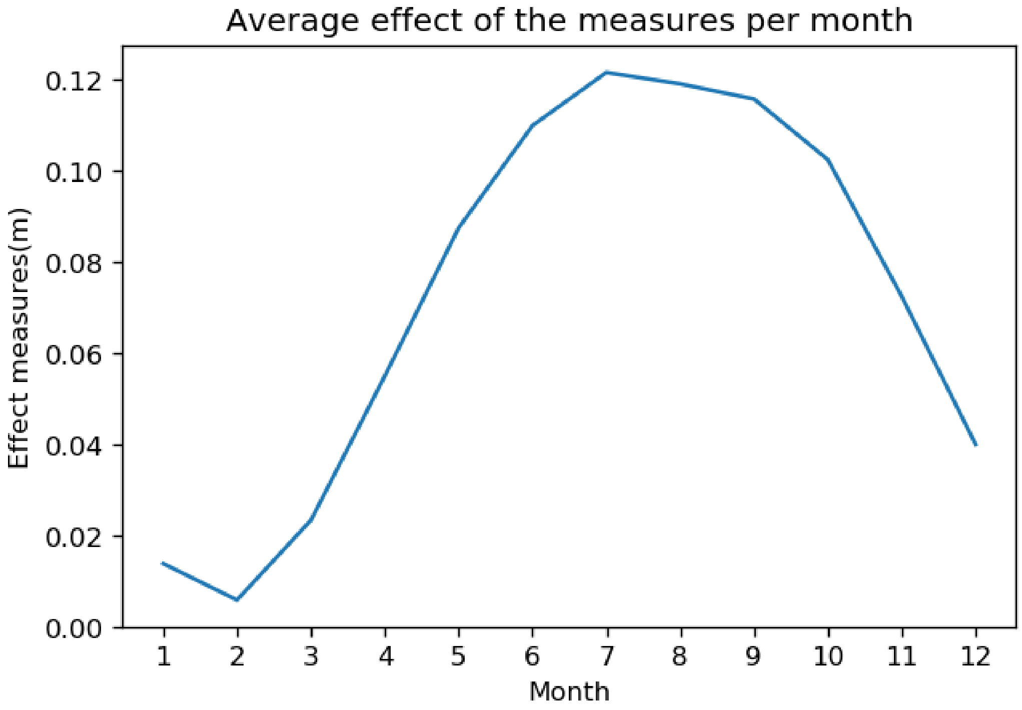
X = 171100.0
Y = 377590.0
Surface level = 23.62 m+Sealevel

Start measuring (Dutch date): 03-03-1983
End measuring (Dutch date): 26-04-2019

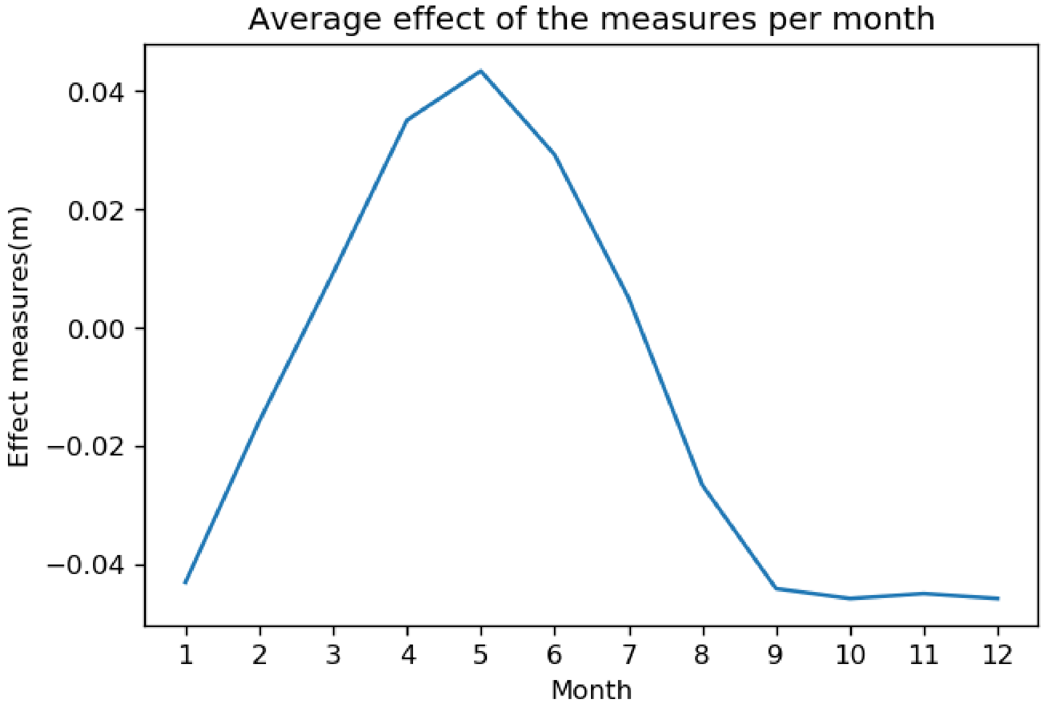
Appendix 5

'Simulated2-Simulated' (Appendix 4), entire solve period 2007-2019 averaged and defined per year to show the average effect of the measures per season.

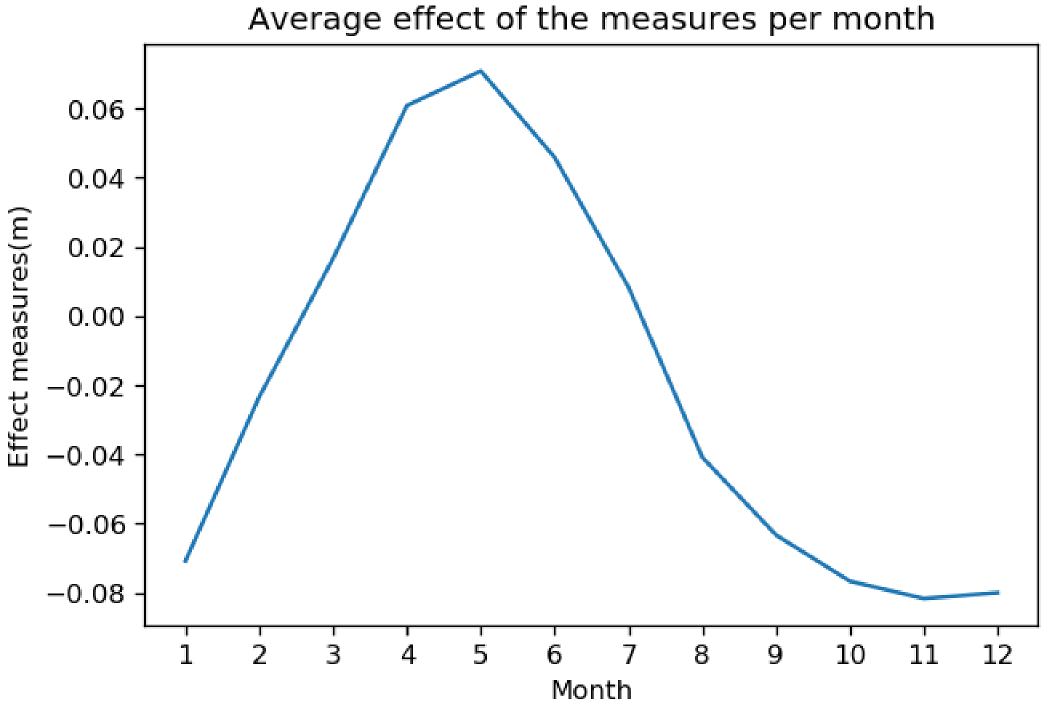
1



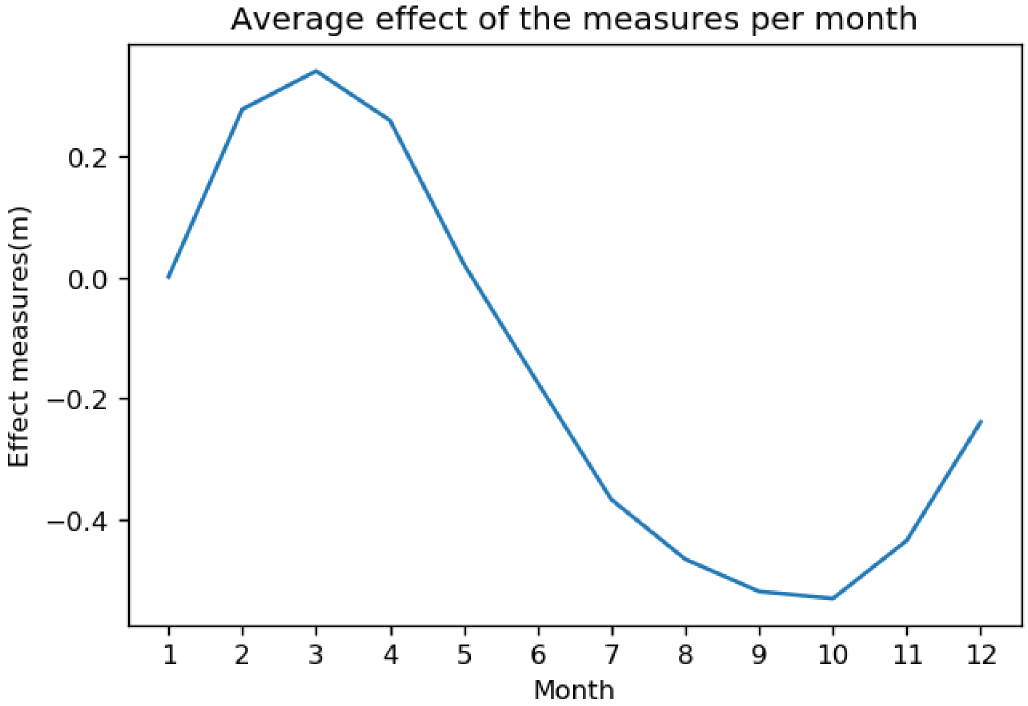
3


Average effect of the measures per month
Effect measures(m)
0.04
0.02
0.00
−0.02
−0.04
1
2
3
4
5
6
7
8
9
10
11
12
Month

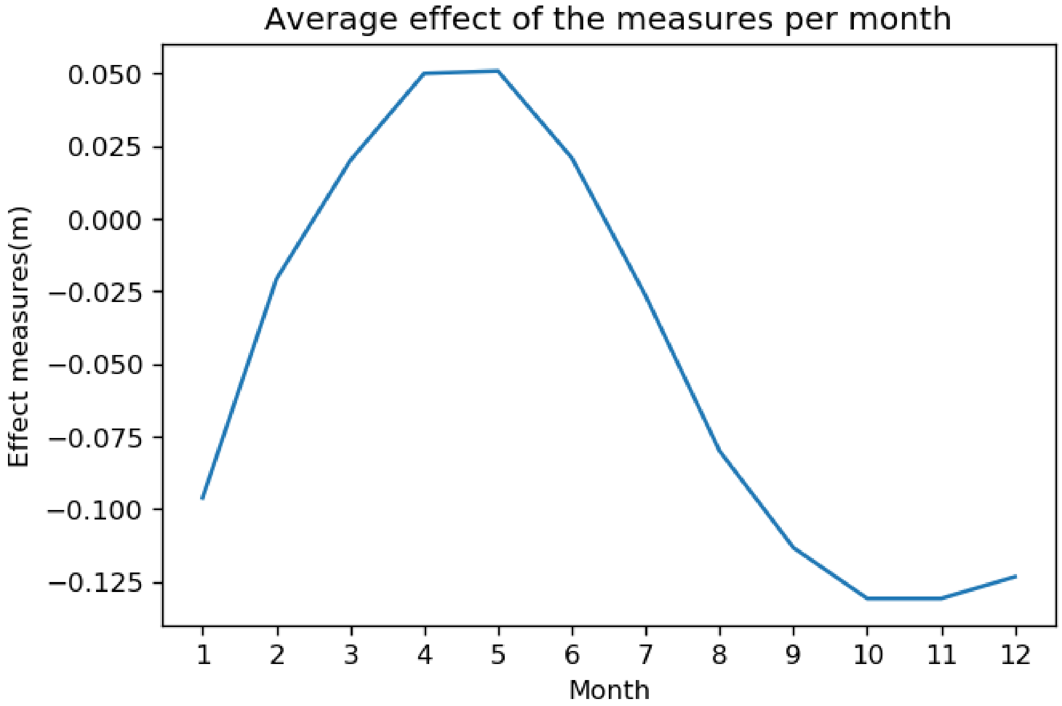
4


Average effect of the measures per month
Effect measures(m)
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
1
2
3
4
5
6
7
8
9
10
11
12
Month

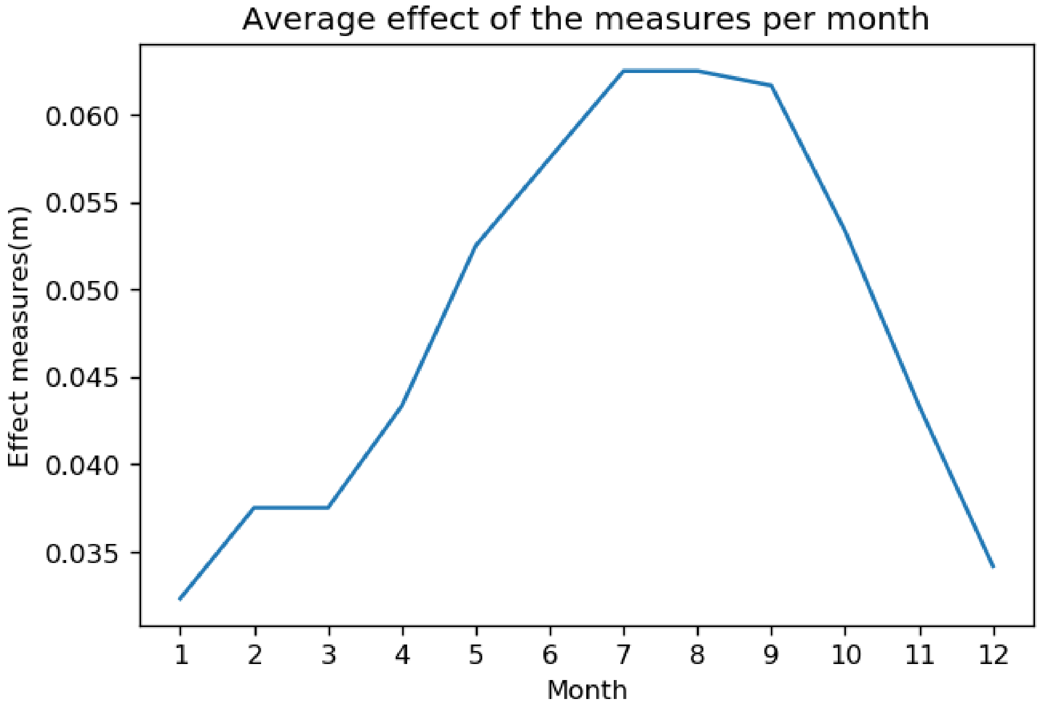
5 (filter number 1)



5 (filter number 2)

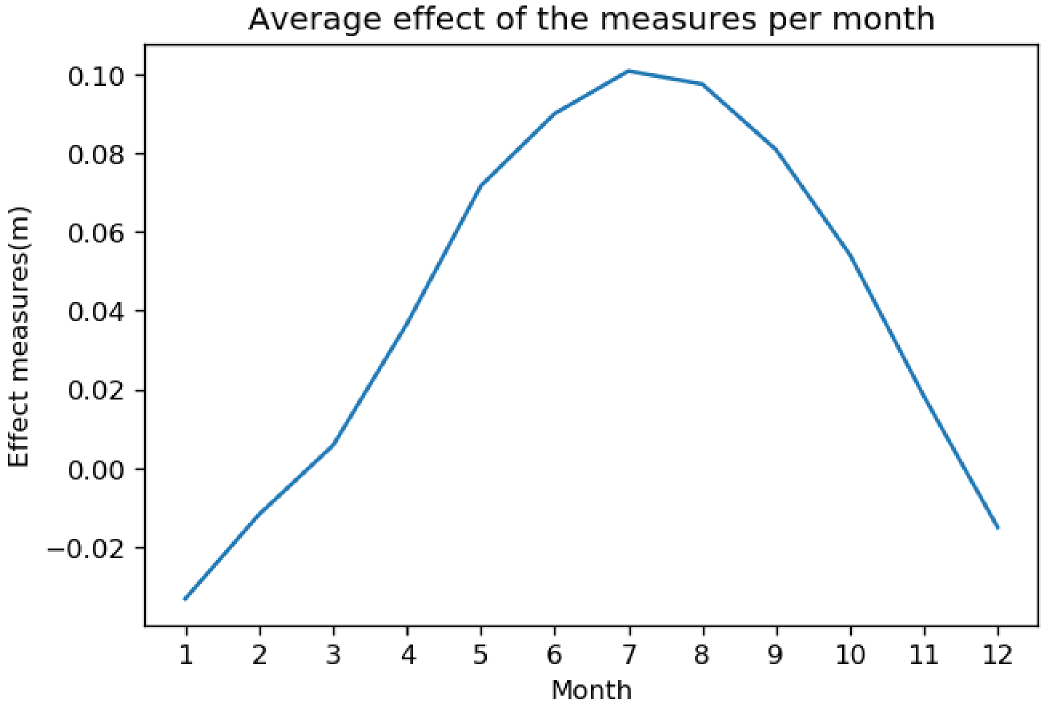


7



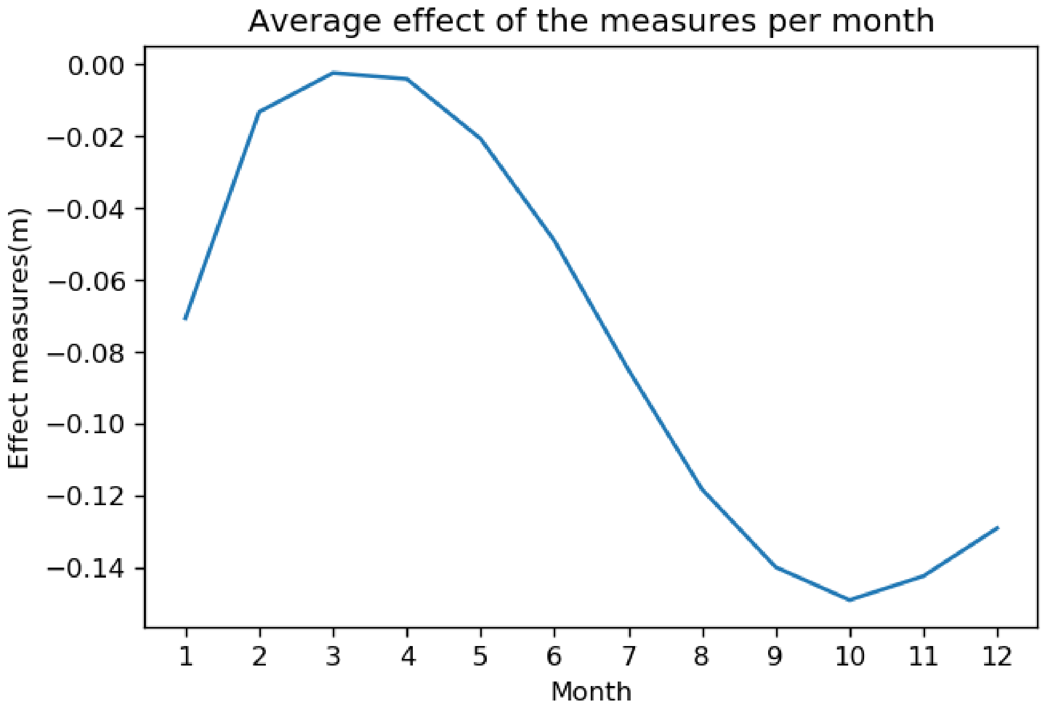
Average effect of the measures per month
Effect measures(m)
0.060
0.055
0.050
0.045
0.040
0.035
1
2
3
4
5
6
7
8
9
10
11
12
Month

8

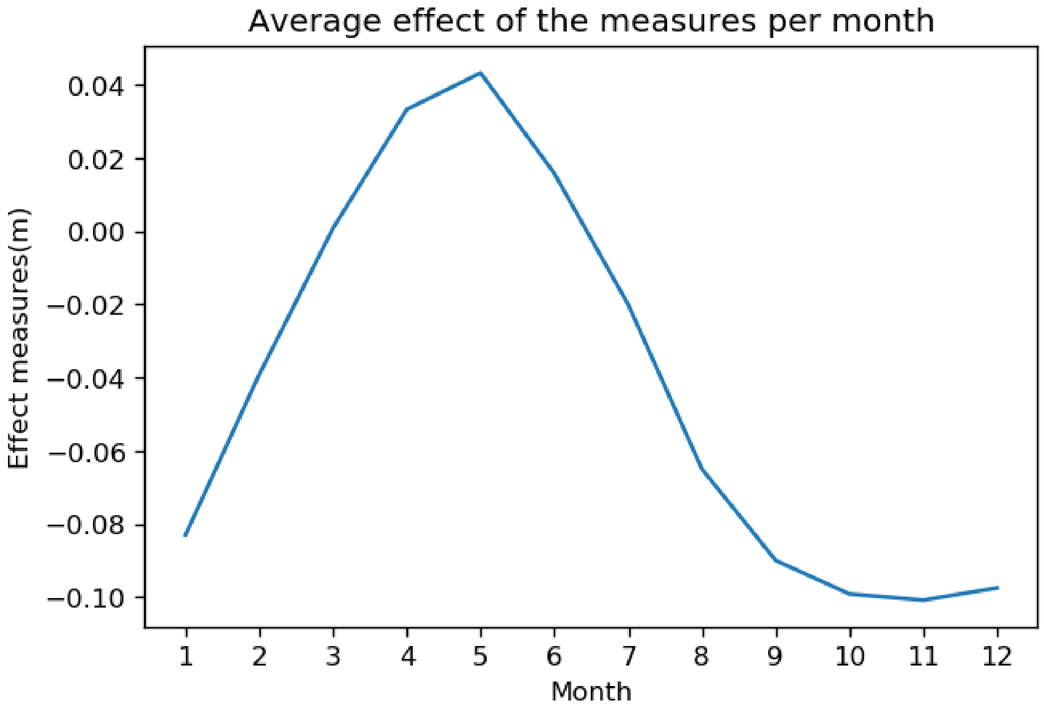


Average effect of the measures per month
Effect measures(m)
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
1
2
3
4
5
6
7
8
9
10
11
12
Month

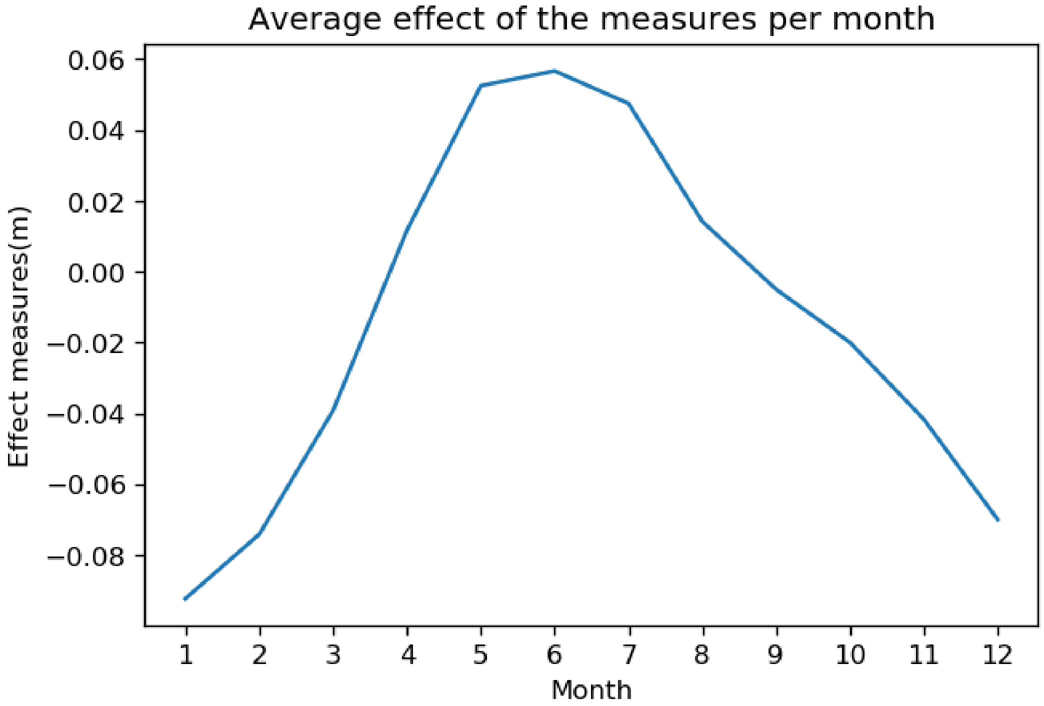
11


Average effect of the measures per month
Effect measures(m)
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
−0.12
−0.14
1
2
3
4
5
6
7
8
9
10
11
12
Month

14

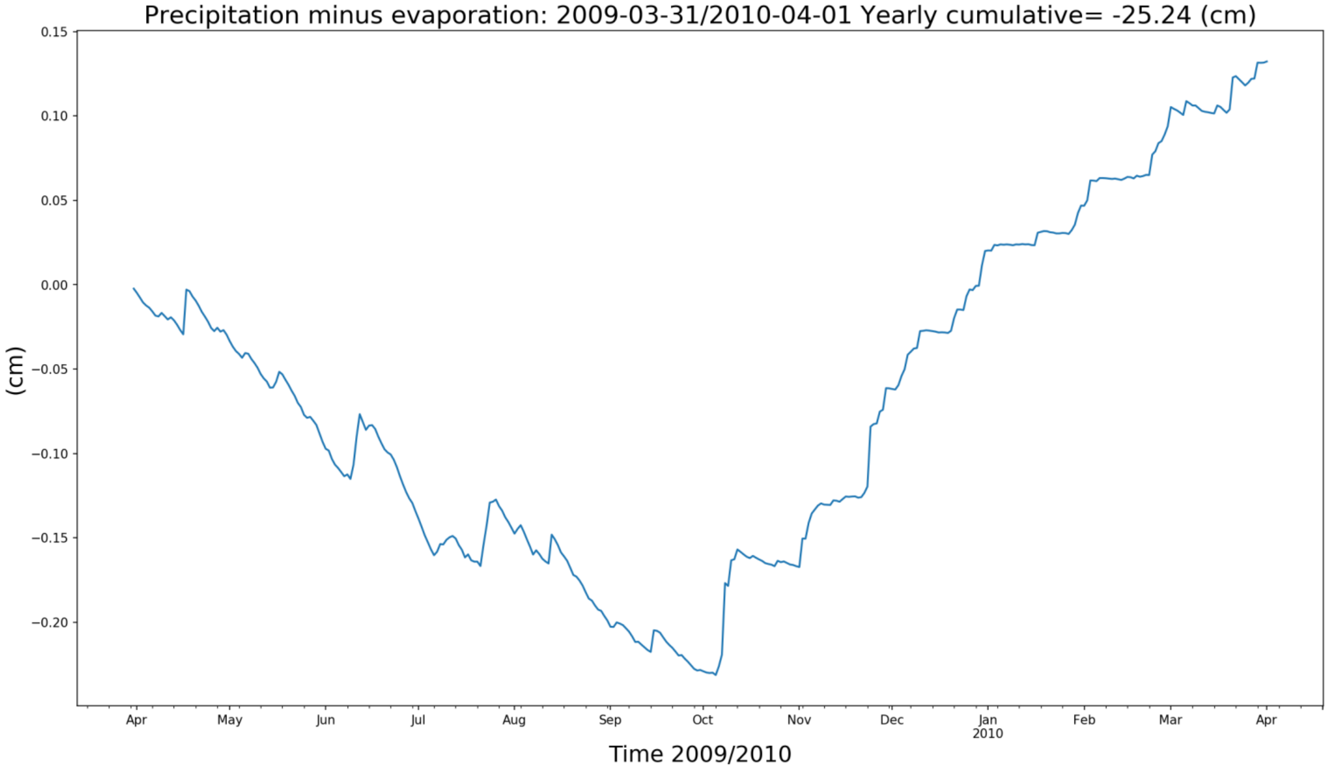

Average effect of the measures per month
Effect measures(m)
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
1
2
3
4
5
6
7
8
9
10
11
12
Month

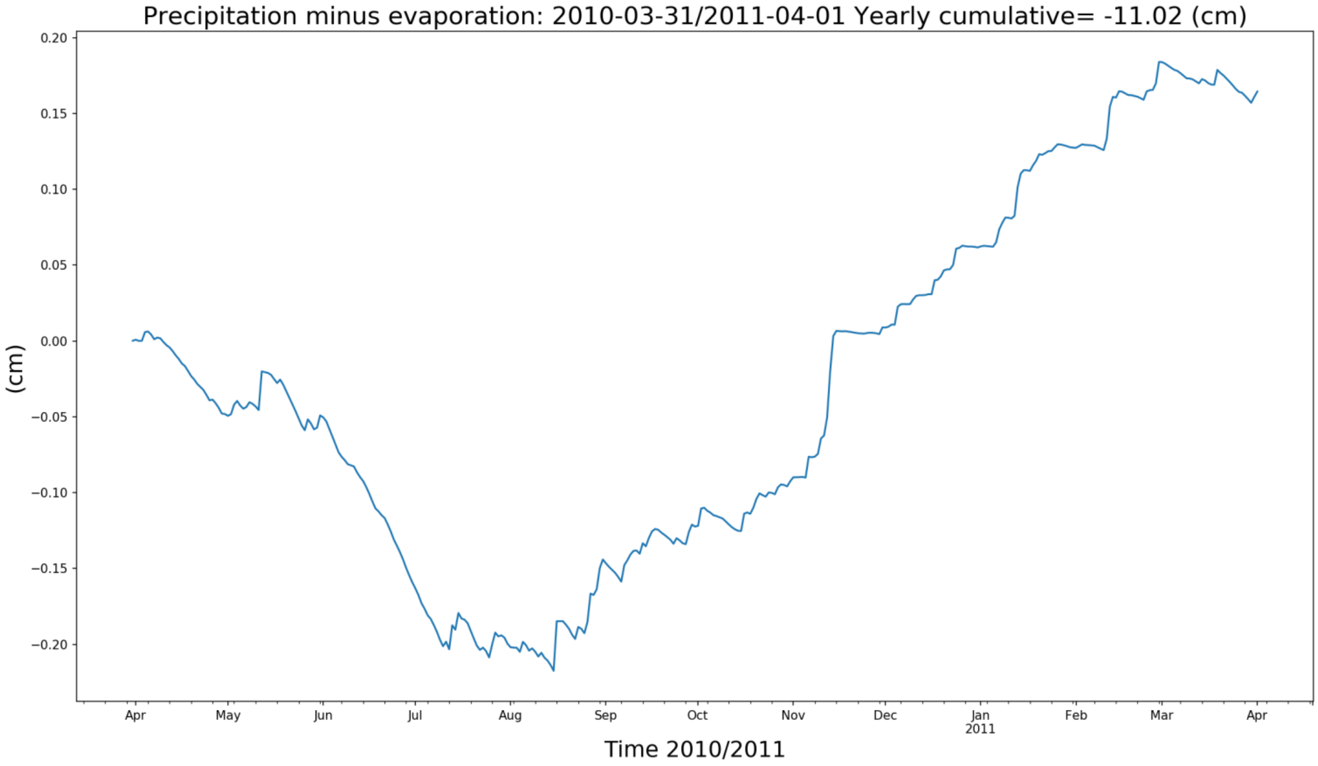
16

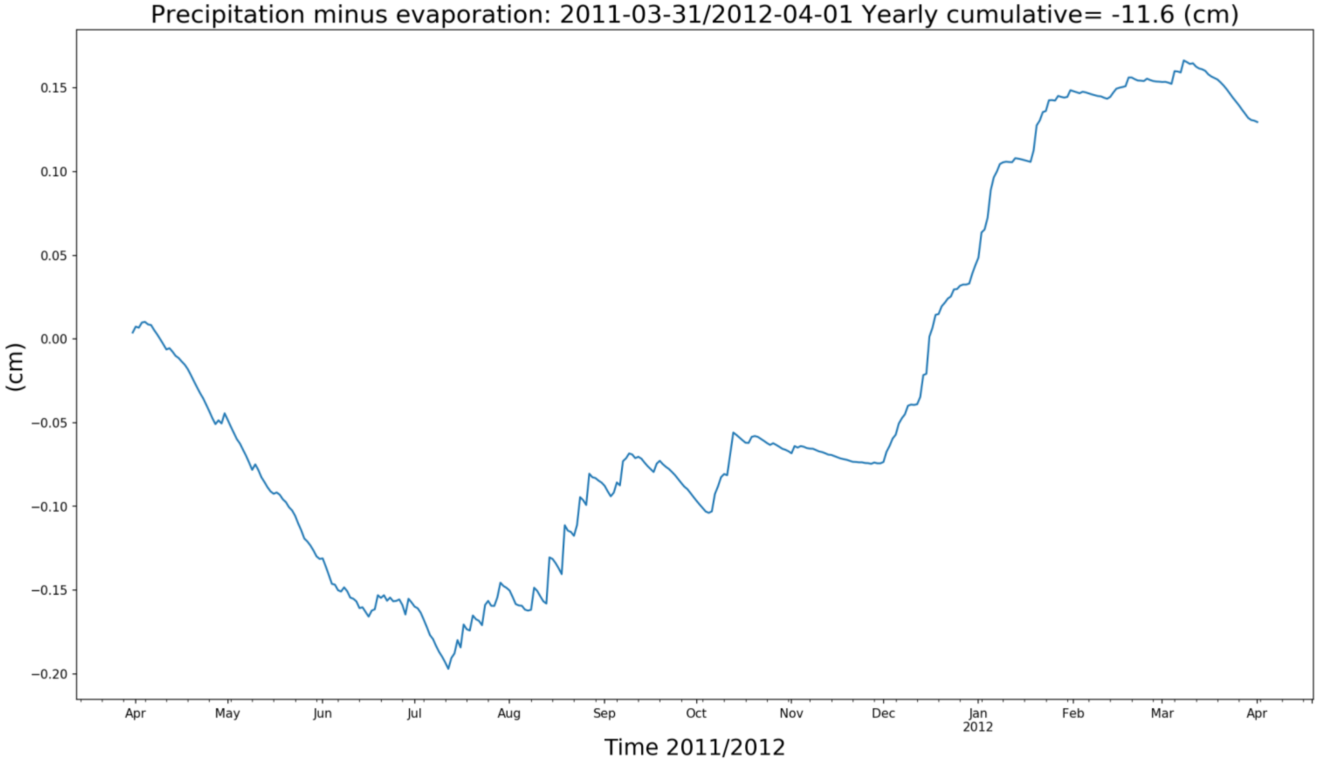

Average effect of the measures per month
Effect measures(m)
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
1
2
3
4
5
6
7
8
9
10
11
12
Month

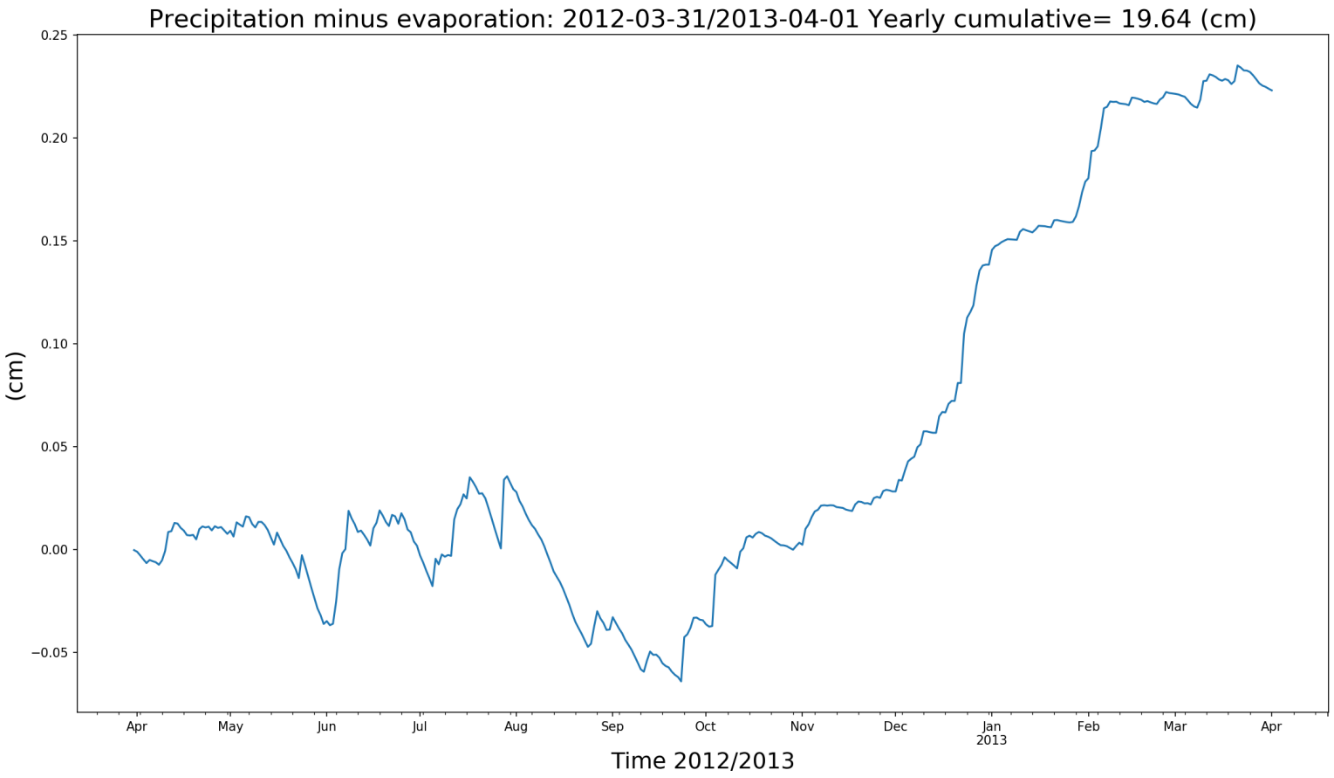
Appendix 6

Yearly cumulative ('precipitation – evaporation'), showed for period April 2009 to April 2013 (according to hydrological years). These figures show that the relationship between precipitation, evaporation and groundwater levels for piezometers 5 and 11, based on 1-1.5 year groundwater data, is calculated for a period that is characterized by deficient precipitation. Graphs are made in Python and based on the used precipitation and evaporation datasets from the KNMI weather stations (respectively Someren and Eindhoven).




Precipitation minus evaporation: 2010-03-31/2011-04-01 Yearly cumulative= -11.02 (cm)
(cm)
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
2011
Feb
Mar
Apr
Time 2010/2011


Precipitation minus evaporation: 2011-03-31/2012-04-01 Yearly cumulative= -11.6 (cm)
(cm)
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
2012
Feb
Mar
Apr
Time 2011/2012


Precipitation minus evaporation: 2012-03-31/2013-04-01 Yearly cumulative= 19.64 (cm)
(cm)
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
2013
Feb
Mar
Apr
Time 2012/2013