Rewetting the Peelhorst

Monitoring the hydrological and ecological effects of restoration measures in *wijstgebieden*

Internship report

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Abstract

'Waterschap Aa en Maas' is restoring wet nature areas with the hydrological phenomenon *wijstwater*, where seepage water from deeper layers flows upward along the fault lines to the surface. The high groundwater levels and nutrient-poor and iron-rich conditions of the *wijstwater* lead to the flourishing of rare flora and fauna. Restoration projects have been carried out in five different *wijstgebieden* (areas with *wijstwater*). In this internship the changes achieved by the taken measures were investigated in terms of groundwater levels, groundwater quality and ecology. First an inventory was made to explore and bundle the existing information on the projects and the *wijstgebieden*. With the available data a variety of analyses was conducted. For the groundwater levels a time series analysis was done in the model PASTAS, where corrections for fluctuations in weather were carried out to isolate the effect of the measures on the groundwater level. For the groundwater quality far less data was available, especially on a temporal scale. Van Wirdum diagrams and stiff-diagrams show the origin of the sampled water, time series show the changing iron concentration and boxplots and t-tests show the seasonal groundwater temperature fluctuation (which is supposedly lower for seepage water than for rainwater). The ecological analysis entailed counting the number of present *wijst*-indicator species (flora and fauna) before and after the measures were taken. The main conclusion from this internship is that too little data is available to properly monitor the changes that the measures have achieved. The data is often too sparse or does not date back to before the measures were taken, so no baseline situation is known. In the analyses it could be inferred that the reaction of the groundwater levels is heterogeneous: for Geeneneind the conditions became wetter, at St Annabos small changes in both directions were found and at Venloop the conditions became drier. However, these changes are small and there is no certainty that they were caused by the taken measures. The groundwater quality analyses were done with few measurements, perhaps not enough to properly formulate conclusions based on the groundwater quality analyses. The results from these analyses could very well be the result of changing weather or noise in the measuring methods. The number of species present in the project areas increased, whether this is due to the taken measures is hard to say. The part of the project areas destined for nature also often increased, perhaps being a more plausible reason for increasing species richness than the taken measures. The lessons learned from this research are used to formulate recommendations for future monitoring of *wijst*-restoration measures.

1 Introduction

1.1 Wijstwater, a unique hydrological phenomenon to be restored

In the south of the Netherlands a unique hydrological phenomenon can be found, iron rich seepage water called *wijstwater* flows up to the surface creating wet conditions on the higher ground (Fig. 1.1). This *wijstwater* is related to the Peel Boundary Fault Zone, a northwest-southeast oriented active fault zone in the southeast of the Netherlands. The faults have created barriers for horizontal groundwater flow due to smearing of clay along the faults and precipitation of iron oxides close to the surface (Lapperre et al., 2019). The phenomenon is enforced by fine sands from the Miocene that act as a resisting layer and form the hydrological base ensuring that the groundwater can only move upward (van Balen, 2009) (Fig. 1.2). Due to the upward seepage on the horst (the area moving upward along the fault; the 'Peelhorst') these locations, situated higher in the landscape, have more shallow groundwater tables than the lower located graben (the area moving downward along the fault; the 'Roerdalslenk') (Lapperre et al., 2019; van Balen, 2009). This upward seepage consists of nutrient-poor and iron-rich groundwater (*wijstwater*) coming from deeper layers in the soil (Bonte et al., 2007). The groundwater is not sensitive to seasonal fluctuations and therefore has a stable temperature, warmer than the surface water in winter and colder in summer. The high groundwater levels combined with the iron-rich, nutrient poor and constant temperature conditions lead to the flourishing of rare vegetation (van Balen, 2009).

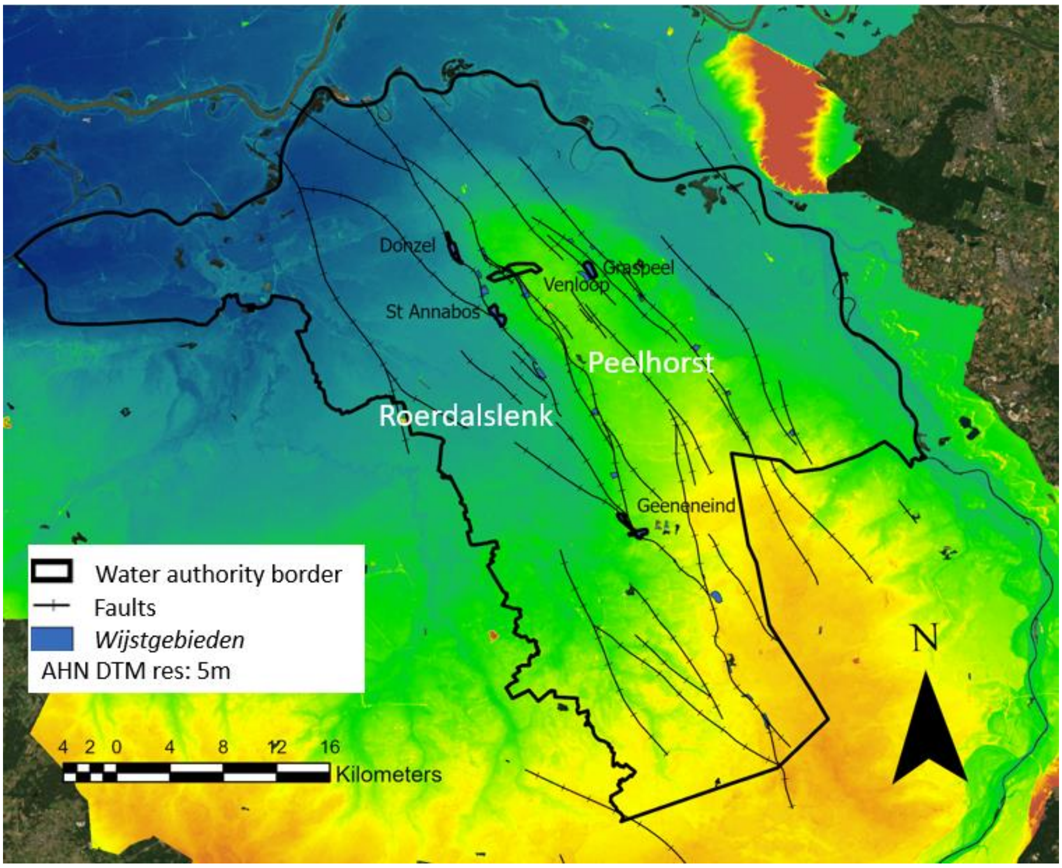


Figure 1.1. Elevation map (AHN4) of the management area of the water authority Aa en Maas. An elevated land tongue can be seen in the same direction as the faults and the blue areas where seepage water comes up are all located next to these fault zones.

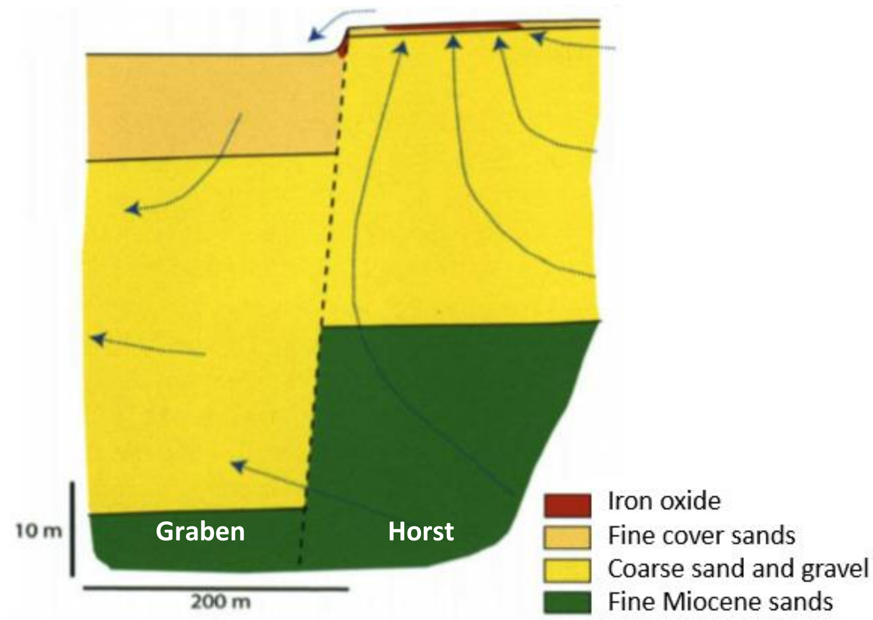


Figure 1.2. Schematic visualisation of the fault zone and the groundwater flow (Van Balen, 2009).

Due to the high groundwater levels the horst area (*Peelhorst*) originally consisted of peat bogs and swamps (Bonte & Witjes, 2007). However, from 1850 onward agriculture gained terrain and the area was drained (Bonte & Witjes, n.d.). As a result, the iron-rich seepage no longer reached the surface and the ecological values of the horst largely disappeared (Bonte & Witjes, n.d.; van Balen, 2009). In addition, the hydrological sponge-function of the *Peelhorst* largely disappeared (Verbeek, n.d.). Abundant water was no longer stored in the peat areas. Instead, it was discharged quickly by the growing network of ditches and canals. Therefore, the water was not available anymore in dry periods, resulting in drought related issues. Furthermore, climate change is bringing prolonged and more frequent dry periods (Spinoni et al., 2018). Especially the areas of the Netherlands situated on the cover sands in both the east and the south of the country are struggling with water shortages (Van den Eertwegh et al., 2019). Therefore restoring the high groundwater levels has a twofold positive effect: 1) bringing back the biodiversity of the wet ecosystems; 2) storing water which can be used in drier periods.

'Waterschap Aa en Maas' is trying to recover the original biodiversity and ecological values of the *wijstgebieden* by restoring the upward seepage and high groundwater levels. In recent years, several *wijstgebieden* have undergone measures aiming at rewetting the project areas and restoring their original hydrological system (*Projectenboek Benutten En Herstellen Wijst*, 2020). Measures include: raising surface water levels with weirs, removing ditches by filling them up, recovering the upper part of the fault (that can be ploughed away by farmers) and excavating the nutrient-rich top soil of former agricultural fields (Bonte & Witjes, 2007).

Although this sounds promising, it is not sure yet whether these restoration projects have the desired effect. After a project is executed the chances of it being forgotten and not monitored are high (Reeze & Lenssen, 2015).

1.2 Aim and Research questions

The main goal of this internship research is to investigate the effect of *wijst*-restoration measures at the *Peelhorst*. This internship research will inventorise if existing monitoring networks provide enough data to assess the effect of *wijst*-mitigation measures. The available data is used to analyse the hydrological and ecological effects of the taken measures to restore the *wijstgebieden*. In addition an advice will be given on how to continue improving future monitoring of the *wijstgebieden* based on the experience gathered in this research. This leads to the following research questions:

1. Inventory: Which *wijst*-restoration projects have been carried out so far and are they described and monitored well enough to assess their effect?
2. Effect: What changes did the previously taken *wijst*-restoration measures achieve?
    a. Groundwater levels: What changes can be seen regarding the groundwater levels?
    b. Groundwater quality: What changes can be seen regarding the water quality (temperature, iron concentration, nutrient concentration)?
    c. Ecology: What changes can be seen regarding the occurring flora and fauna species?
3. Future outlook: What is needed to better monitor the effects of *wijst*-restoration projects in the future?

1.3 Research approach

Firstly, we inventorise all the *wijstgebieden* of 'Aa en Maas'. This inventory will focus on: which *wijstgebieden* restoration measures have been taken; when were these carried out; what type of *wijst*-restoration measures have been taken; are they well documented; and what measurements are available for data analysis to assess their effects. For available measurement data the focus is on groundwater levels, groundwater quality and ecological data, ranging from local project-measurements to data from more regional or national monitoring networks. An important aspect of the available data is that it has to be a sufficiently long time series to contain measurements before and after the taken measures. Secondly, we selected the *wijst*-restoration projects with sufficient data to analyse the restoration effects in time and space. There are five *wijstgebieden*, where the taken measures are well documented, not all project areas have measurements on all three categories, therefore not all project areas will have all types of analyses carried out. Thirdly, the lessons learned from this research are summarized into recommendations for future monitoring of *wijst*-restoration measures.

2 Methods

2.1 Inventory

In the *Aa en Maas* management area about 40 locations along the fault have (potential) presence of *wijst.* All of these areas are located on the Peelhorst, where the seepage comes up. From all these locations five were chosen for this monitoring network. Available information on all these five project areas has been assembled in an overview (Tab. 2.1) (Appendix A). The most important source of information for the inventory was an overview of projects in the management area from the water authority (*Projectenboek Benutten En Herstellen Wijst*, 2020) and the research on potential *wijstgebieden* in the area by consultancy company Witteveen+Bos (Bonte & Witjes, 2007). Information on the performed measures were often found in layout plans or monitoring plans (R. Lappere & Blok, 2012; R. E. Lappere, 2016; *Projectplan Maatregelen Wijstherstel Donzel En Graspeel Fase 1*, 2015; van Rens, 2009) and personal communication. The land use has also been incorporated in the inventory for before and after the measures (tab 2.1)

Table 2.1. Simplified overview of the wijst-restoration projects chosen in this research (Appendix A for more information)

nr	Project area	Size (ha)	Status			Year of execution	Nature area (%)	Agricultural area (%)	Availability data		
			Executed	In progress	Planned		After measures (before measures)	After measures (before measures)	Ecology	Groundwater quality	Groundwater quantity
1	St Annabos	77.3	x	x		2008-2011	35 (20)	65 (80)	x	x	x
2	Geeneneind	90	x	x		2014/2015	8 (8)	92 (92)		x	x
3	Donzel	14.5	x	x		2016	0 (0)	100 (100)			x
4	Graspeel	5.7	x	x		2005 + 2016	0 (0)	93 (93)			
5	Venloop	215	x			2016	61 (57)	39 (43)	x		x

Data availability is one of the most important criteria, since no analysis is possible without it. Groundwater levels are measured in piezometers, these measurement devices are installed in boreholes where a filter lets the groundwater penetrate and the groundwater is often measured automatically with a constant time interval. Piezometers throughout the area measure the groundwater heads, both the water authority and the province of Brabant have installed piezometers that can be used for this research. The measurement networks are designed to cover the management area as efficiently as possible. However, because the *wijstgebieden* are fairly small (often only a couple hundred meters from the fault) it is not uncommon for a *wijstgebied* to not even contain a single piezometer. Furthermore, some of the *wijstgebieden* have a monitoring network designed to be able to track the hydrological conditions at that project area. This is the case at both St Annabos and Geeneneind. All of these piezometer locations and a time series of the measurements can be found in the program Delft-FEWS, where the data from the water authority's own piezometers as well as the piezometers of DINOloket are stored. Piezometers from both of these sources will be used in this research.

The installed piezometers can also be used to gather groundwater samples for qualitative measurements. This is not done at all piezometers and often it is not done frequently. Therefore the only time series of qualitative measurements that span across the time of recovery measures taken is at St Annabos. St Annabos is marked as a "*Natte Natuurparel*", a special appointed title for wet nature areas, because of which the water authority has these useful groundwater quality measurements for this research. At Geeneneind only data from the monitoring plan from 2015 is available. Extensive measurements were done for 6 months in a row, from July to December, however these measurements were discontinued.

The ecological measurements within the project area have been gathered from NDFF ('Nationale Database Flora en Fauna'). Indicator species of *wijst* have been determined in earlier research (Ettema, 2010). Observations of these indicator species were exported with data ranging from 2000 till 2021. The NDFF is an assembled database where measurements executed by a variety of organisations is gathered (NDFF, 2021). This database is therefore the most extensive database for ecological observations in the Netherlands.

2.2 Project area selection

The suitability for analysis in this research was tested based on several criteria (Tab. 1.2). This selection was made before the start of assembling the inventory data. These criteria were selected to have the most useful data analysis. The larger sized areas are expected to show more effect of the measures, a focus on nature is important to be able to do an ecological analysis and the availability of data is necessary to perform the analysis. The other two criteria: time of measures performed and type of measures preformed were included to be able to conclude on the lag time from measures to effects and on the difference in effects between different types of measures. However, only a limited number of the *wijstgebieden* in the management area of the water authority had undergone measures before and also had some data availability in the form of monitoring networks or the water authority wide network.

Table 2.2. Basic information that needs to be gathered for all project areas in order to decide what monitoring can be done.

Criterium	Reason	Decision
Size	This varies largely, with some areas being smaller than 1 ha. These small areas might have a higher influence from their surroundings, which can interfere with the results.	Choose a relatively larger area
Time of measures performed	Some of the measures were only installed and performed recently, this makes it harder to conclude if the measures did not have the desirable effect or whether it has simply not been long enough for the new conditions to settle in.	Choose a variety of different time periods
Type of measures	In the introduction different types of measures are mentioned. Not all measures might have the same effects, therefore being aware of the measures before choosing an area is important.	Choose a variety of types of measures
Availability of data	The monitoring networks do not cover all project areas. If data is not available field work will have to be done and baseline measurements will have to be found.	Choose if data is available

From the inventory described above five project areas (Fig. 2.1) were selected to investigate in this internship research. Not all criteria as described above were met when choosing the project areas. This was due to the fact that only at five *wijstgebieden* measures have been taken already. As a result of not having abundant options to choose from not all project areas are nature areas and therefore the ecological analysis will not be carried out for all of these areas (Tab. 2.3). Aside from this, also the hydrological data availability at some of the chosen areas is not optimal. At Donzel and Graspeel only one piezometer is present and at Donzel, Graspeel and Venloop no water quality measurements were found (Tab. 2.3). The one piezometer found at both Donzel and Graspeel was also not located within the project area, but seemed close enough that further inspection of the data of that piezometer might be fruitful. Therefore, these agricultural area was included in the research, but the results and conclusions on those areas will be highly limited compared to the results and conclusions that are expected from St Annabos, Geeneneind and Venloop. At Graspeel the one available piezometer ended up not having measurements before the recovery measures were taken here, therefore no monitoring analyses have been done for this project area in the end.

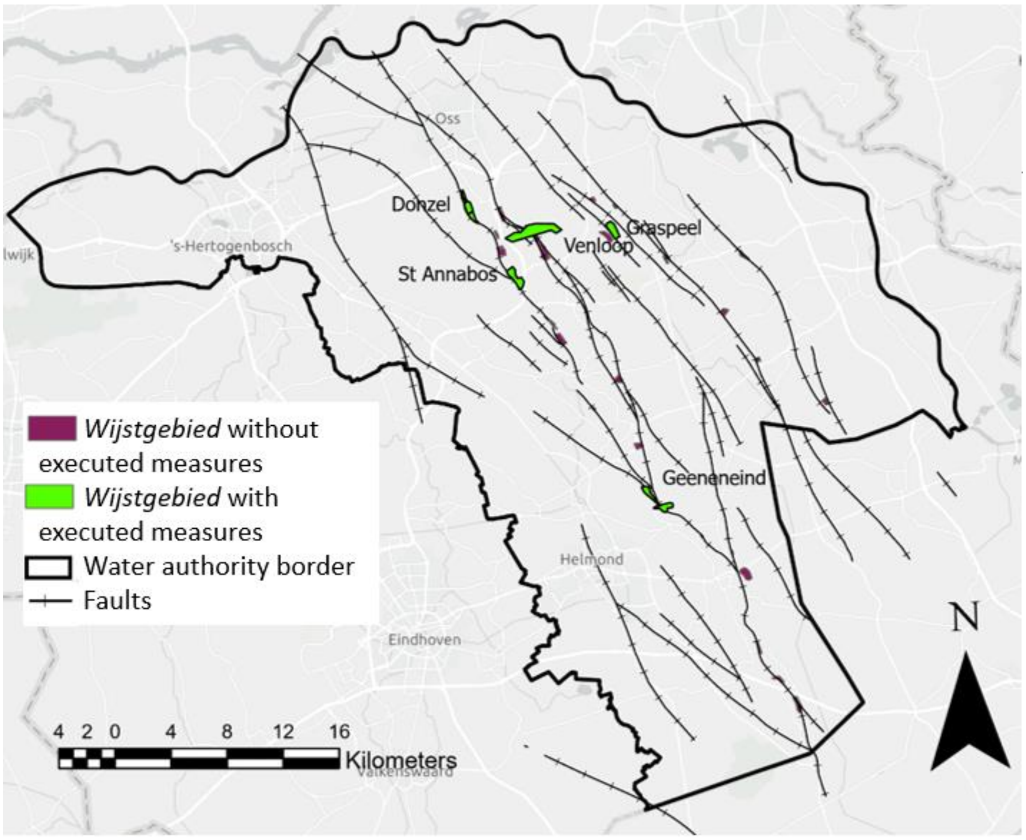


Figure 2.1. Locations of the selected project areas, where measures to restored wijst *have been executed in the past and other areas with potential* wijst *that has not been restored yet* (Bonte & Witjes, 2007)*.*

Table 2.3. Availability of data at the five project areas

Project area	Number of piezometers	Number of water quality measurement locations	Ecological data availability
St Annabos	30 (22 used)	10	Yes
Geeneneind	22	3	Yes
Venloop	15	0	Yes
Donzel	1	0	No
Graspeel	1 (0 used)	0	No

2.3 Study area background

The different *wijstgebieden* can be categorised by a system as found in Meuwissen & Van den Brand, 2003. Categories are formed looking at two variables: the visibility of the fault zone in the landscape and the level of seepage, this can be used to differentiate between the project areas. The way these variables are used to classify the categories can be seen in table 2.4. In figure 2.2 a map visualizing the different categories for each of the selected project areas is shown. A project area with the value A1 has the strongest characteristics of a *wijstgebied*, while C1 is weaker in terms of these characteristics. In figure 2.2 it can be seen that St Annabos and a part of Geeneneind are categorised as strong *wijstgebieden*, these two project areas also have the most present data and seem to be prioritised for recovery projects.

Table 2.4. Categories of wijstgebieden based on the visibility of the fault zone and the level of seepage (translated from Meuwissen & Van den Brand, 2003).

Visibility of the fault zone	**Seepage up to surface level**	**Seepage to ditches**
Visible elevation difference	A1	A2
Drifting dunes on fault	Non-existent	B
Not visible	C1	C2
Not visible due to buildings	D	D

Figure 2.2. Categories of wijstgebied as explained in table 3 for each of the chosen project areas.

2.3.1 St Annabos

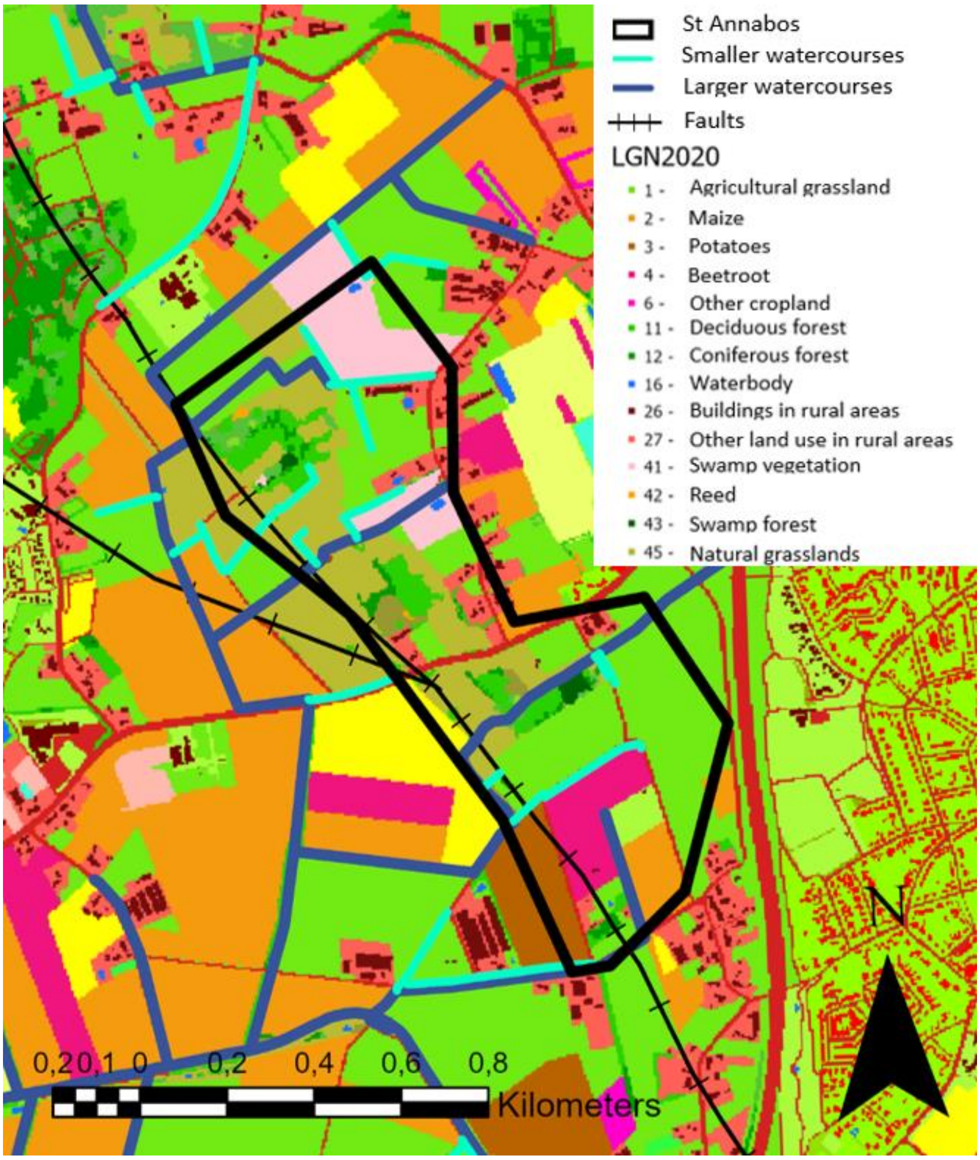


Figure 2.3. Land use at project area St Annabos. Also showing watercourses and faults.

St Annabos is located next to Uden and is situated at the east-side of the *Peelrandbreuk* (Fig. 2.1). St Annabos is a type A1 *wijstgebied*, meaning it has a visible elevation in the landscape where the fault is present and the seepage comes up to the surface level (Tab. 2.4). At St Annabos a variety of croplands can be found next to the wet vegetation that is representing the seepage rich environment (Fig. 2.3). An Alder swamp wood is naturally present in the centre of St Annabos, showing the potential for wet vegetation in the area (van Rens, 2009). St Annabos has also been designated as part of the ecological structure (*Ecologische Hoofdstructuur, EHS*) connecting nature areas in the Netherlands. The goal for St Annabos is wet vegetation in the centre of the area surrounded by wet and flowery grasslands. To ensure the safety of the ecosystem at St Annabos a protection zone of 500 m are marked, meaning that no sudden interferences, such as new groundwater abstractions, are allowed in that zone (van Rens, 2009). For the different zones of vegetation at St Annabos different groundwater levels are desired. The swamp and Alder swamp wood need the highest groundwater levels, 3 cm and 9 cm below surface, the wet grasslands need the groundwater at 25 cm below surface and the flowery grassland at 42 cm below surface (van Rens, 2009).

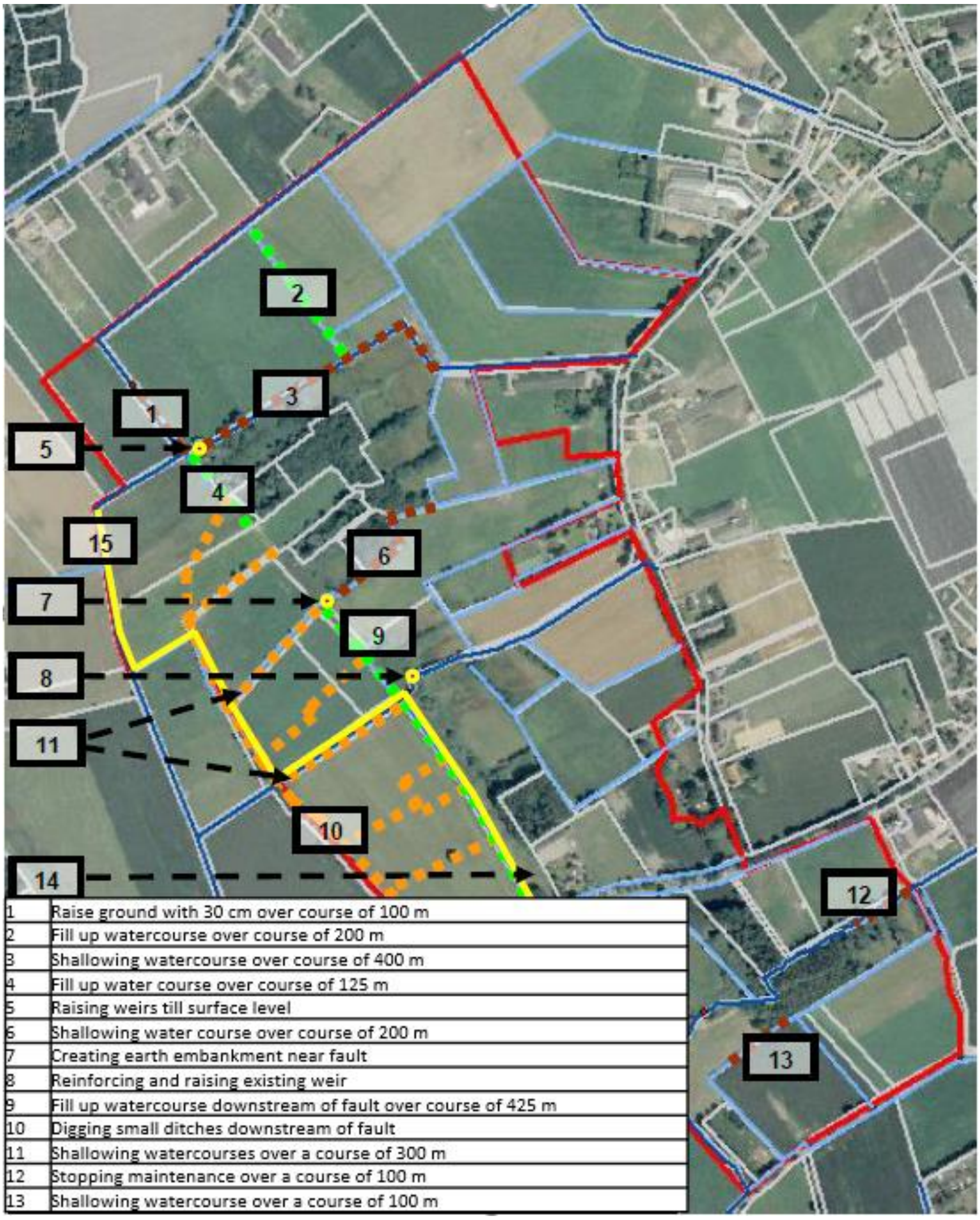


Figure 2.4. Map indicating the taken measures at project area St Annabos. (adapted from van Rens, 2009)

St Annabos, located next to Uden, is one of the most far-advanced recovery projects for *wijstgebieden* at the *Peelhorst*. The measures taken that will be monitored in this project date back to 2009, therefore a considerable amount of years and progress can be researched. The project serves as a role-model. Therefore, a considerable amount of measurement data is available and a considerable amount of measures have been taken (Fig. 2.4).

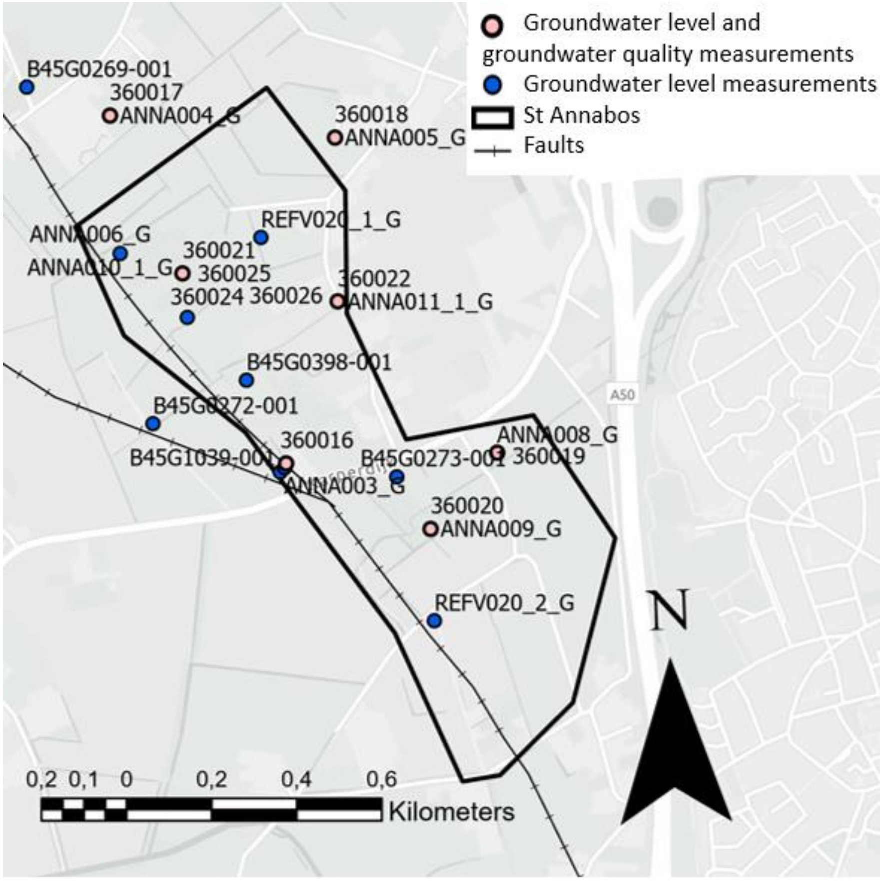


Figure 2.5. Project area St Annabos and the available piezometers there for both groundwater level analysis and groundwater quality analysis.

Figure 2.5 shows the availability of groundwater data at St Annabos. The groundwater levels are measured at all of these points, these measurement points indicate piezometers in the area where groundwater measurements can be taken. The measurement codes only consisting of numbers indicate the groundwater quality points and the codes consisting of letters and numbers indicate a groundwater level measurement point. All the measurement points with the code starting with 'ANNA' have a measurement period starting in 2008 and continuing up to the present. The groundwater measurement points B45G0269-001, B45G0272-001 and B45G0273-001 have time series starting in 1982. The 'ANNA' measurements points' time series consists of hourly data, for the longer time series this is not the case, these started with a measurement approximately every two months, going to daily measurements from 1995 to 2010 and changing to hourly measurements from 2010 until present. The filters of the piezometers, where the measurements are taken, are all located between 2 and 5 meters deep. ANNA010_G and ANNA011_G have multiple filter depths, these go as deep as 20 meters. Other piezometers in the area lacked sufficiently long time series, therefore eight of these were discarded in this research. Two of the piezometers are just outside the project area, but these measurement points are very interesting because they enable possible conclusions about the lag time or attenuation of effects further away from the taken measures.

Most groundwater quality measurement points overlap with the groundwater level measurement points, because the groundwater samples for the qualitative measurements are taken from existing piezometers. At all the groundwater quality measurement points at least two measurements are taken, one in July of 2009 and one in December of 2009. For two piezometers, indicated with codes 360018 and 360025, measurements continued until after the measures were done, yearly measurements were also taken here in 2015, 2016, 2017 and 2018. These two time series will be used for temporal analysis on the groundwater quality measurements.

2.3.2 Geeneneind

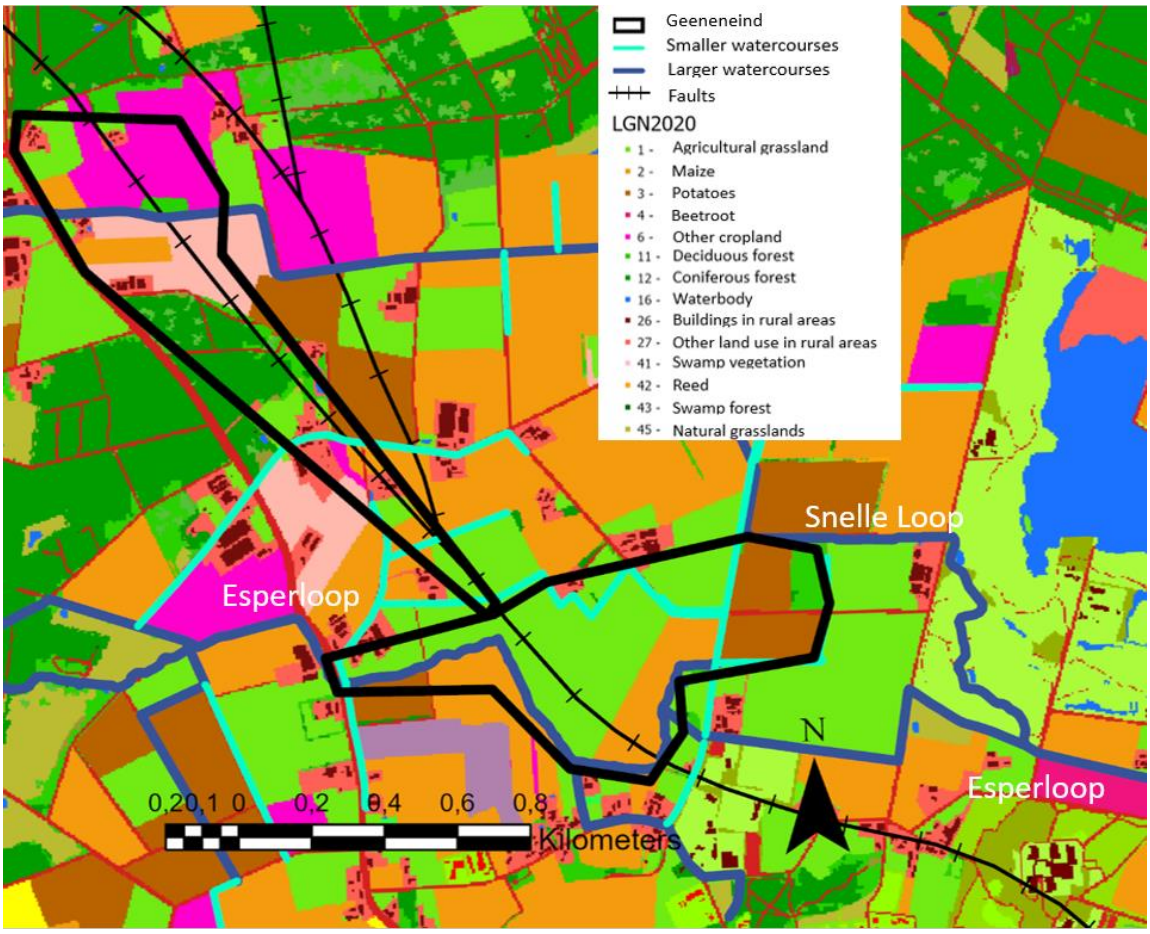
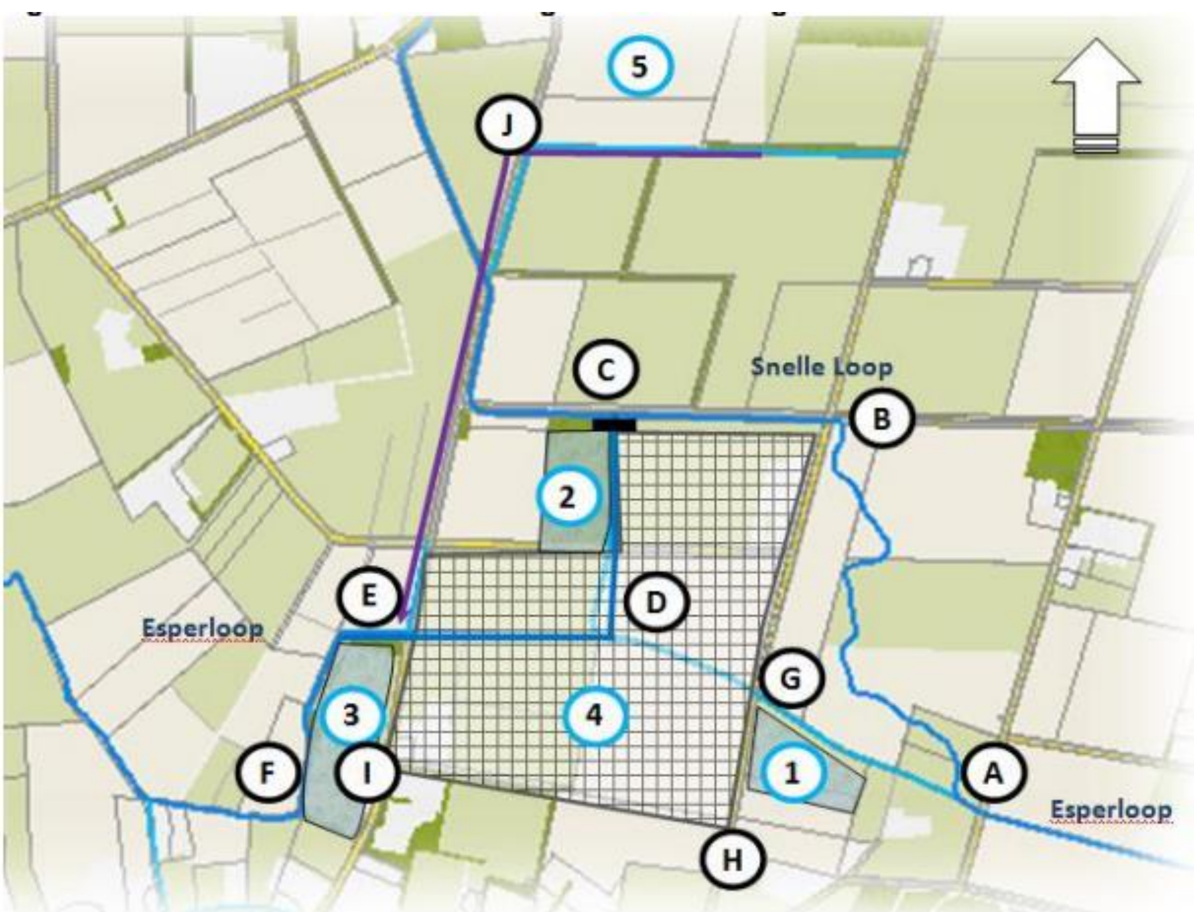


Figure 2.6. Land use at project area Geeneneind. Also showing watercourses and faults.

The project area Geeneneind is situated in the municipality Gemert-Bakel. The project area of Geeneneind has been assigned to two different categories of *wijst*, the northern part is C1 and the southern part A1 (Tab. 2.2). This means that the southern part has a more visible elevation step, but the two areas both have seepage up until the surface level. Geeneneind is a more agricultural area where a variety of crops is being cultivated (Fig. 2.6). Forested nature areas can be found both to the west and the east. The Esperloop is a small brook streaming from east to west through Geeneneind. The Snelle Loop is another watercourse in the area, this watercourse will drain the agricultural water coming in from the east and redirect it around the project area. During summer the Snelle loop also discharges water that is let in from the Meuse (Lappere, 2016). Rare and endangered species use the special conditions of a *wijstwater*-fed brook as their habitat, such as the *Cordulegaster boltonii* (Dutch: *Bronlibel*, English: Golden-ringed dragonfly) (Termaat & Groenendijk, 2005).



A-B-C-D	Redirects the agricultural water from upstream around the source area of the Esperloop
D-G	Filling up of the ditch
E-F	Recovery of the natural water course
G-H	Drainage of agricultural water
1 & 3	Arrangements to visualise the *wijstwater*
1, 2 & 3	Install natural ponds
4	Install smart drainage systems with the farmers
5	Redirect ditches towards Esperloop

Figure 2.7. Measures taken at project area Geeneneind. (adapted from Lappere & Blok, 2012)

At Geeneneind a large variety of measures has been conducted (Fig. 2.7) between 2014 and 2015. In 2021 there is also a project further restoring the natural course of the Esperloop further downstream from point F in figure 2.7. The measures taken here are not only focussed on the re-wetting of the project area, but also on the recovery of the water quality and the ecology. Geeneneind is also a part of the ecological structure (*Ecologische Hoofdstructuur, EHS*) connecting nature areas in the Netherlands. One of the recovery measures taken here is ensuring that the Esperloop is solely discharging *wijstwater* and no agricultural drainage water (Fig. 2.7), in order to get the right water quality in this brook. To do so, the far upstream part of the Esperloop (the east part) is disconnected from the more downstream part (at point A in Fig. 2.7), such that all the upstream agricultural water ends up in the Snelle Loop. These measures are taken in the southern part of the project area, where the *wijst* is more dominantly present as the type assigned here is A1 (Tab. 2.4).

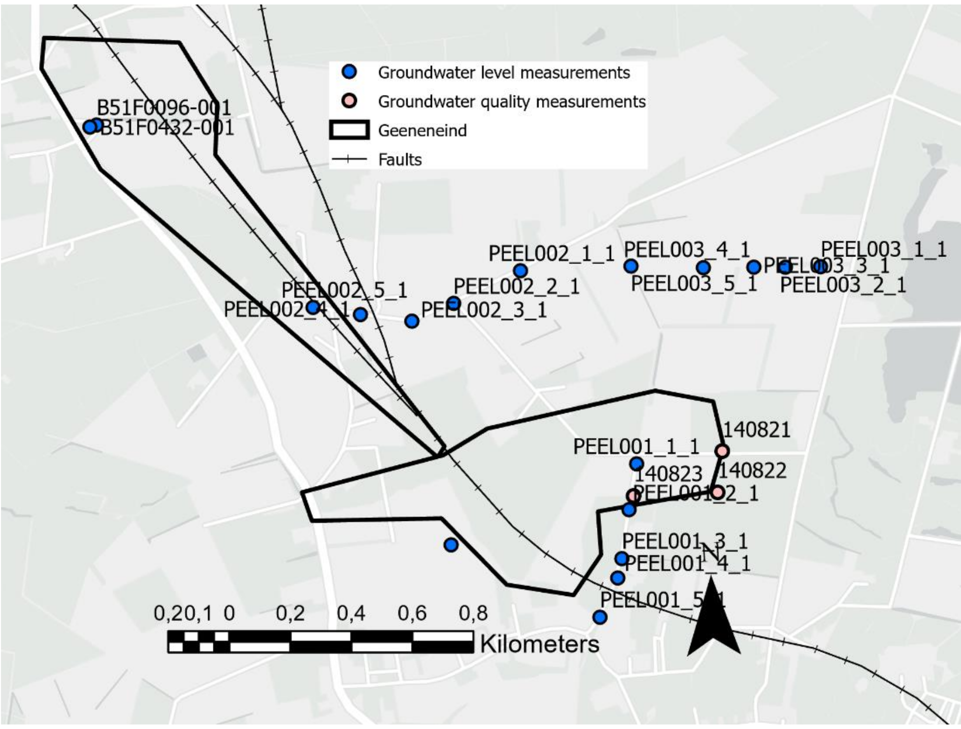


Figure 2.8. Project area Geeneneind and the available piezometers there for both groundwater level analysis and groundwater quality analysis

The measurement periods differ greatly at Geeneneind, with starting dates going back to 1966 (B51F0432) or 2010 (all codes starting with 'PEEL'), the measurement periods of the piezometers with a code starting with 'PEEL' discontinued in 2020 and therefore miss one year of measurements and likely more in the future. Almost all groundwater level measurements are taken hourly, however, for the long time series such as B51F0432 starting in 1966 this is not the case. The measurements in the beginning are taken inconsistently with up to multiple months in between measurements. Measurements at B51F0432 are approximately biweekly from 2003 to 2007, daily from 2007 to 2017 and become hourly after that until present. The filter depths of the piezometers at Geeneneind vary between 2 and 4 meters deep.

The groundwater quality samples at Geeneneind were taken in the south-east corner of the project area (Fig. 2.8). Measurements were taken every month for this half year (Lappere, 2016), therefore also capturing the seasonal fluctuation of the groundwater quality parameters. However, these measurements were not continued after 2015 and are therefore not useful for monitoring the effects of the taken measures.

2.3.3 Venloop

The project area Venloop is the only project area chosen for this internship research that was not marked as a current *wijstgebied* in the Witteveen+Bos inventory (Bonte & Witjes, 2007). This project was also marked as a potential project in the manual used by the water authority (*Projectenboek Benutten En Herstellen Wijst*, 2020). However, after a field visit and personal communication with Nico Ettema, Anton Sijbers and Theo van de Mortel this was identified as a current and interesting project area. The project area as shown in figure 2.9 was created after an example from the project manual, where Venloop is mentioned as a potential project area (*Projectenboek Benutten En Herstellen Wijst*, 2020). Witteveen+Bos has identified *wijstgebied* Slabroek, however, since the measures investigated in this internship research do not fall into this area the decision was made to use the project area Venloop instead.

The Venloop is situated to the south-east of the village of Nistelrode. The project area Venloop is a suitable addition to this internship research because it is one of the few *wijstgebieden* where some nature areas can be found. Because of this an ecological analysis can also be performed next to a hydrological analysis. The Venloop is the third project area to also be an ecological structure (*Ecologische Hoofdstructuur, EHS*) connecting nature areas in the Netherlands (*Streefbeeld Venloop*, 2004). As can be seen in figure 2.9 the area is mostly natural grasslands, but also forest and swamp vegetation can be found. The measures as shown in figure 2.10 are performed in between the faults of the area along a small part of the Venloop. The logs installed on the streambed and ditches filled up there are supposed to generate higher water levels upstream in the project area (Witjes et al., 2016) and therefore serve as re-wetting measures of the project area. All of these measures were taken in 2016.

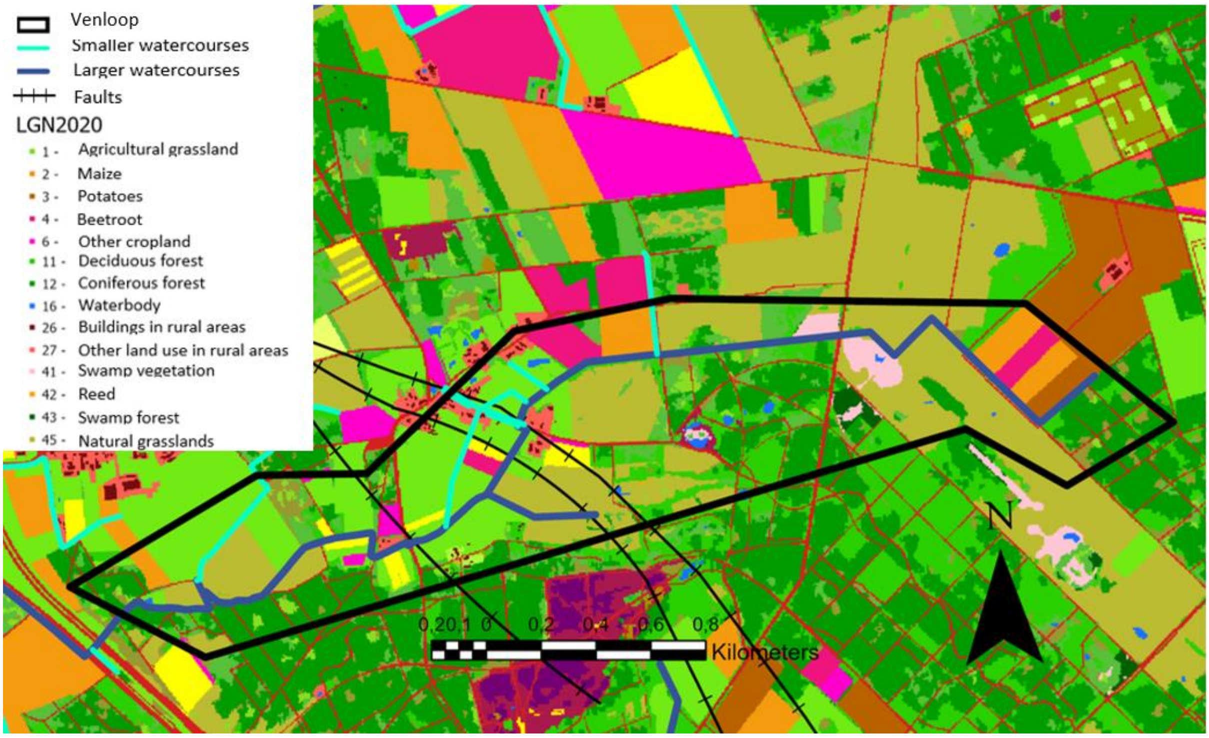


Figure 2.9. Map showing the land use at project area Venloop. Also showing the watercourses and fault.

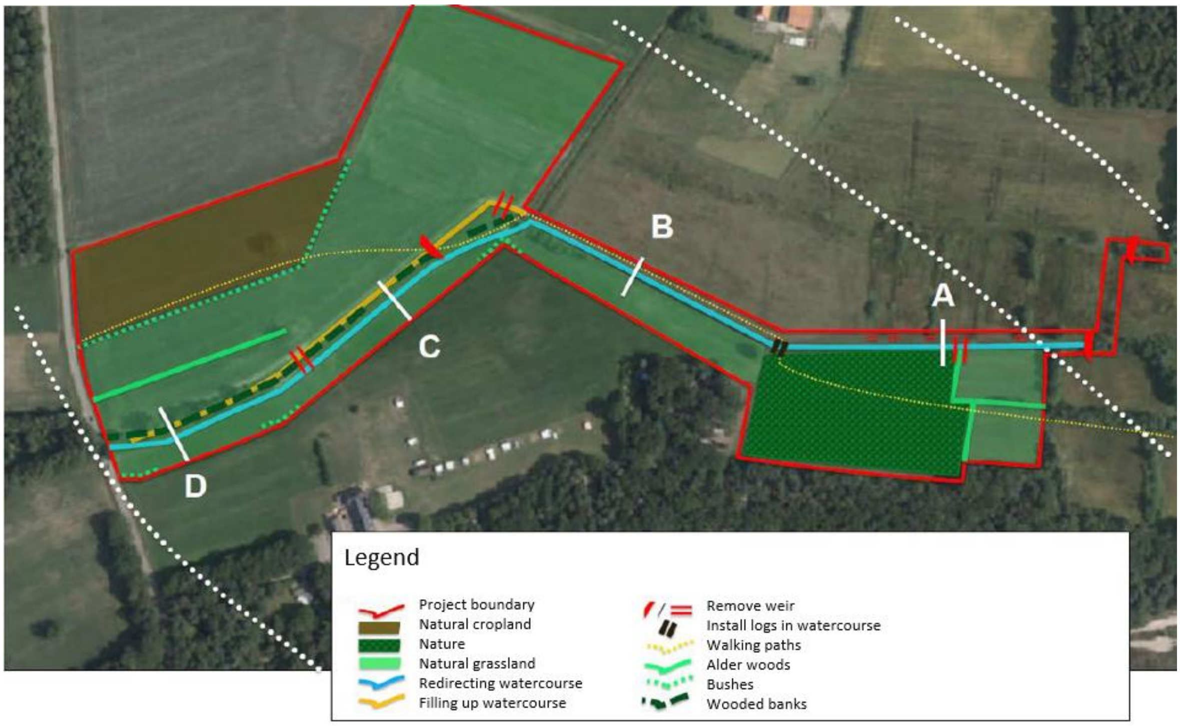


Figure 2.10. Measures taken at project area Venloop in 2016 (adapted from Witjes et al., 2016).

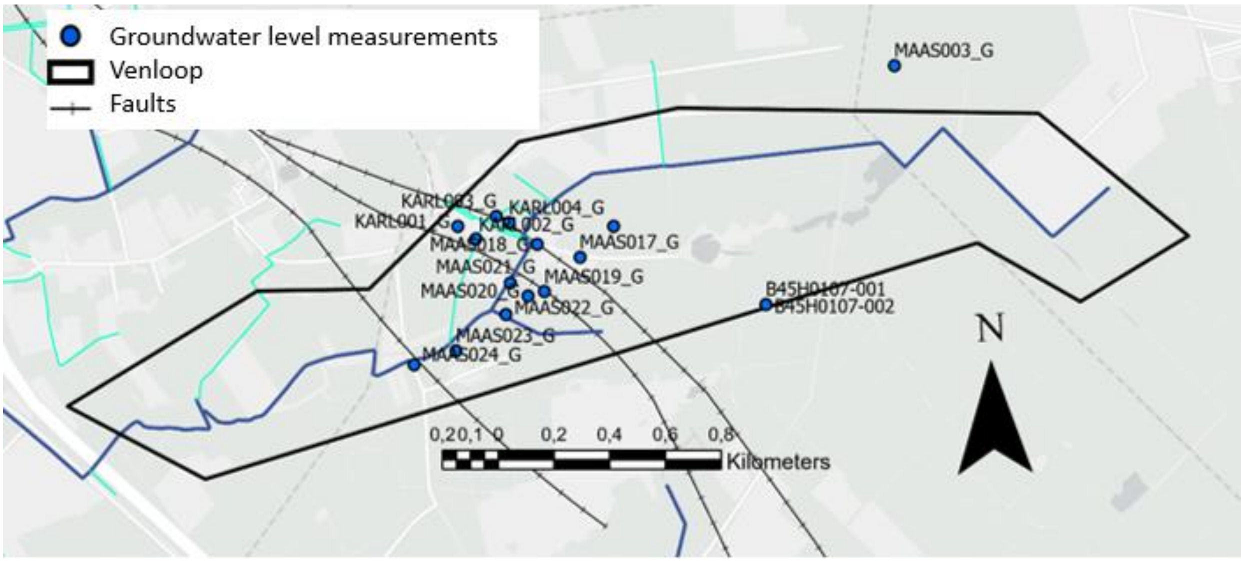


Figure 2.11 Project area Venloop and the available piezometers there for groundwater level measurements.

At Venloop 15 groundwater level measurement points are present and no groundwater quality points. The measurement periods of these piezometers started between 2003, 2009 or 2014. The piezometers starting with code 'KARL' started in 2014 and have also stopped in 2020, therefore only containing 6 years of data. At all groundwater level measurement points the measurements are taken hourly. The filter depth of the piezometers, where the measurements are taken, is situated between 2 and 4.5 meters depth.

2.3.4 Donzel

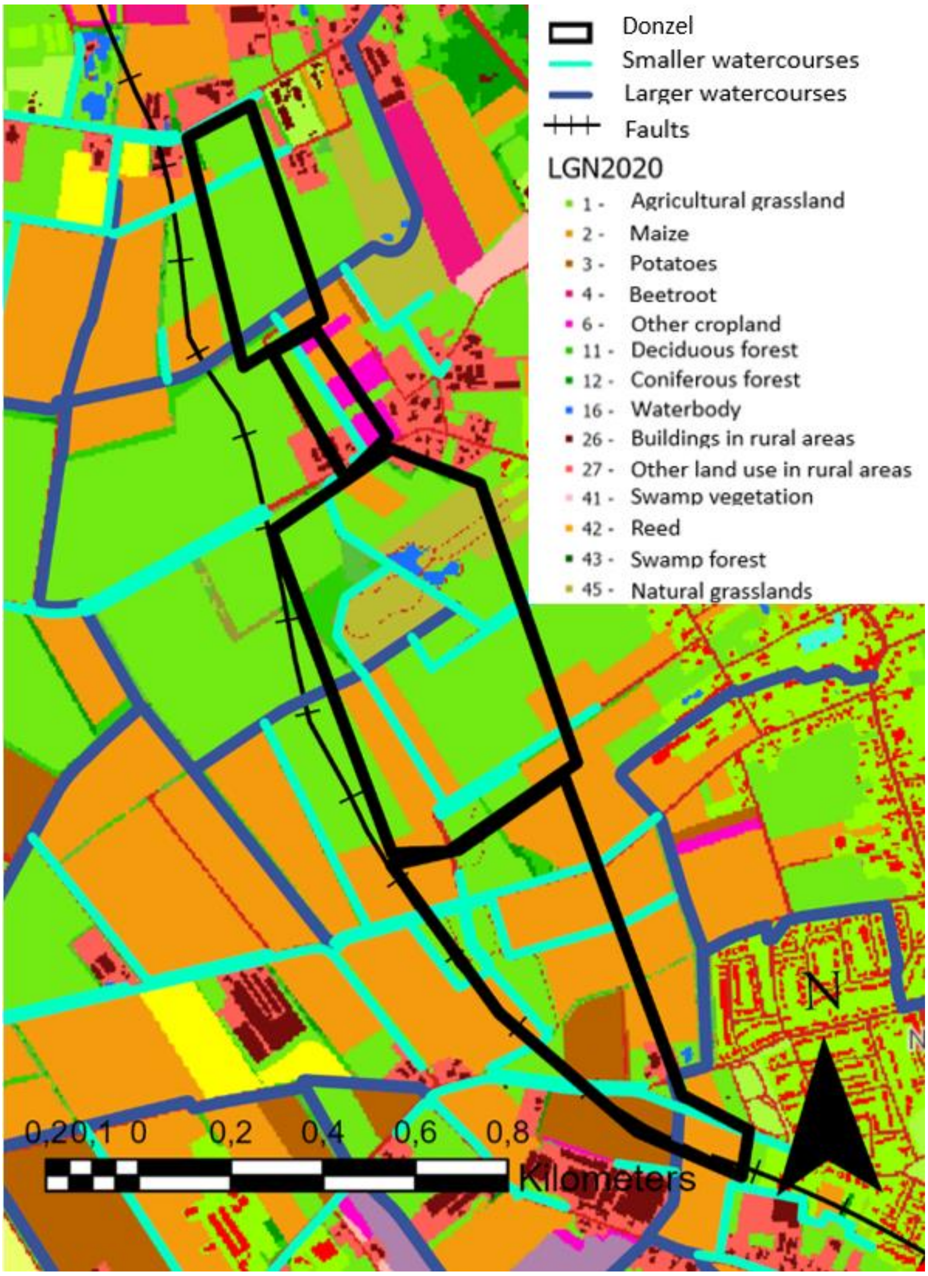


Figure 2.12. Map showing the land use at project area Donzel. Also showing the watercourses and fault.

Project area Donzel is situated to the north-west of the village of Nistelrode. The project area Donzel is a dominantly agricultural area with mostly agricultural grasslands and maize croplands (Fig. 2.12). Barely any nature can be found in this project area, therefore no ecological analysis will be conducted for this area. Witteveen+Bos defined this *wijstgebied* as four separate areas, because they are all assigned as a different type of *wijstgebied* (Fig. 2.2). This can also be seen in figure 2.13 where the different colours indicate the different categories. From north to south the categories are: A2, A2, C1 and C2 (Fig. 2.13). Meaning the visibility of the elevation is strongest at the middle of Donzel and the seepage is strongest in the north and south (Tab. 2.4).

The measures taken at Donzel are more limited compared to the project areas St Annabos and Geeneneind. Five weirs are placed throughout the project area and in the south (category C2) a watercourse has been rerouted (Fig. 2.13). The newly dug watercourse is situated close to the former course and is not designed to meander more, therefore the effect of this measure might not be substantial.

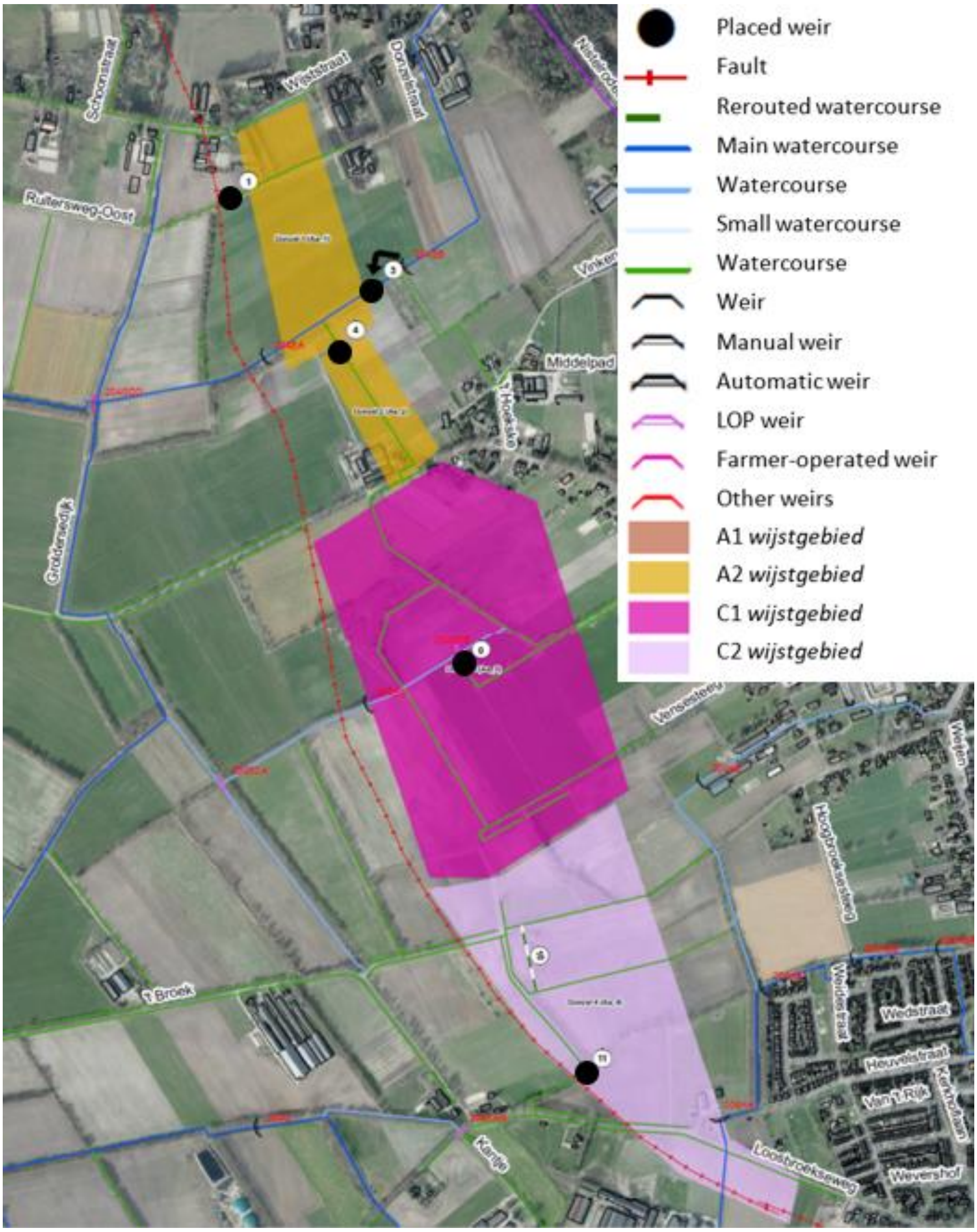


Figure 2.13. Measures taken at project area Donzel (adapted from *Projectplan Maatregelen Wijstherstel Donzel En Graspeel Fase 1*, 2015).

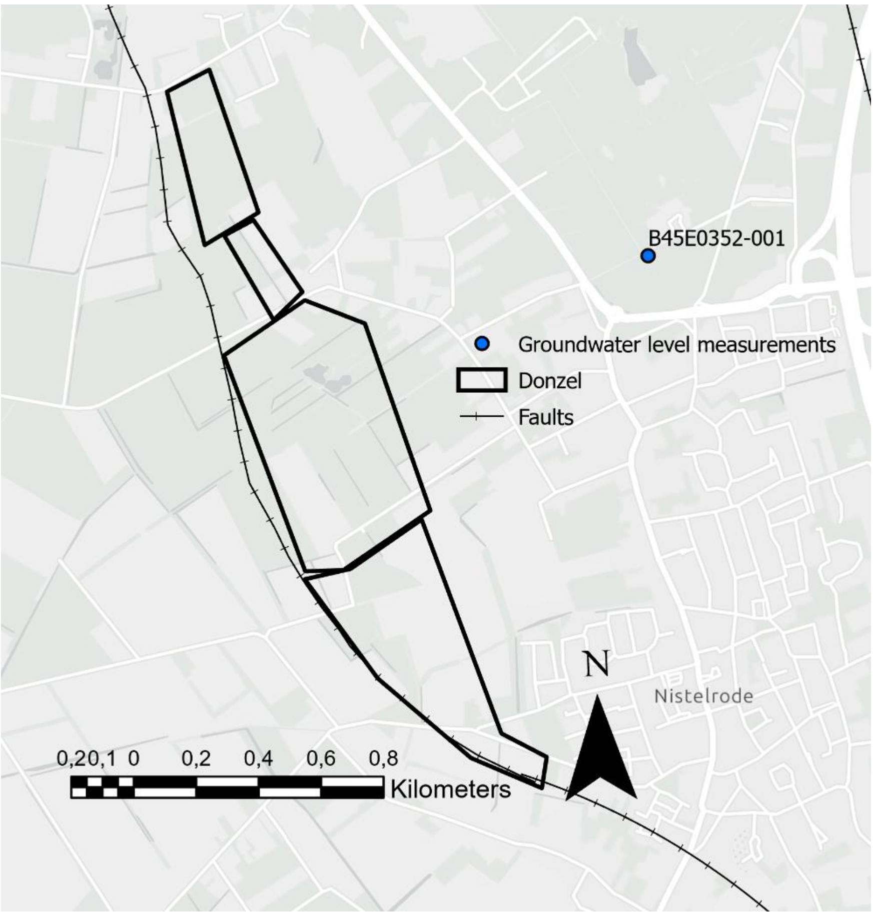


Figure 2.14. Project area Donzel and the available piezometers there for groundwater level measurements

As can be seen in figure 2.14 there is only one piezometer available close to Donzel and it is even then still situated outside of the project area. There were no baseline measurements or other piezometer networks available that could be used for this internship research. It is unlikely that this one piezometer will be enough to conclude anything about the effects the measures have had on the groundwater levels at Donzel.

2.3.5 Graspeel

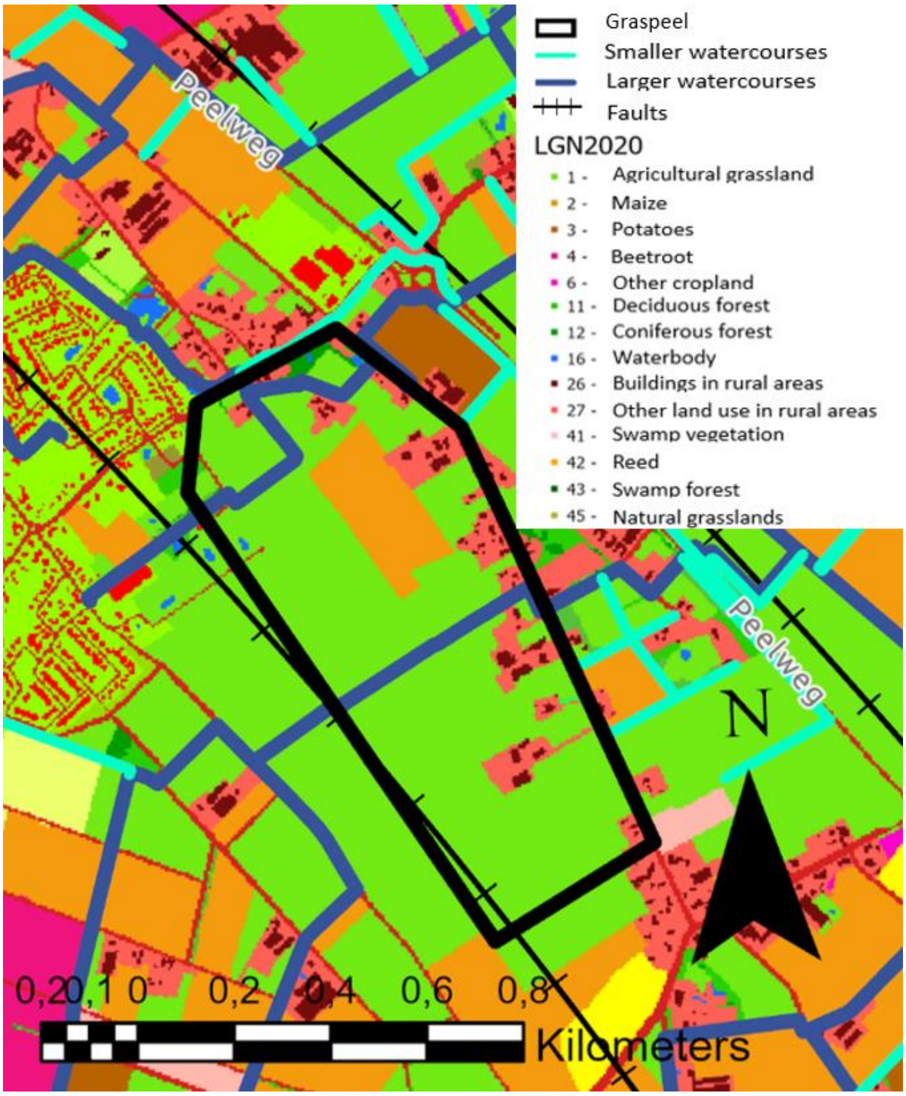


Figure 2.15. Map showing the land use at project area Graspeel. Also showing the watercourses and fault.

The project area Graspeel is situated to the east of the village of Zeeland. The area is almost entirely covered by the land use agricultural grassland together with some buildings and maize cropland (Fig. 2.15). The project area is categorised as a type C2 *wijstgebied*, this means that the seepage does not reach further than the ditches and the offset created by the fault zone is not visible in the landscape (Tab. 2.4). This project area has the least performed measures, as can be seen in figure 2.16 only three extra weirs have been placed here for rewetting the area. The project area Graspeel is situated immediately west from the weirs. These weirs are installed in three parallel flowing watercourses and are meant to hold the water in the area longer. At Graspeel no analyses were possible in the end, as the groundwater level measurement location only has measurements dating back to the middle of 2016 and therefore no measurements have been done before the measures were taken here. No difference between before and after the measures can thus be analysed.

Figure 2.16. Measures taken at project area Graspeel (adapted from *Projectplan Maatregelen Wijstherstel Donzel En Graspeel Fase 1*, 2015)

2.4 Data analysis

The presence of *wijstwater* can be determined in several ways. Firstly, high groundwater levels on the horst indicate the presence of the upward seepage. Secondly, there are hygrophilous plant species that grow on these high groundwater levels. Those conditions also attract specific fauna species that will also be investigated. Thirdly, the iron concentration in the groundwater and the surface water also indicates the presence of *wijst*. In addition there are more indicators of *wijstwater* such as groundwater temperature and the composition of the water in terms of minerals which can be used to distinguish *wijstwater* from rainwater and sea water.

2.4.1 Groundwater levels

For the time series of the groundwater tables gathered from Delft-FEWS an analysis showing the trend before and after measures were taken has been performed. This has been done using the model PASTAS in Python. The input of the model concerned:

- the code of the piezometer;
- the elevation;
- the depths of the membrane of the piezometer;
- the start, end and duration of the measurement period;
- the proximity of surface water;
- measurement points in the near surface water;
- presence of drainage nearby;
- the taken recovery measures;
- the most exact execution date of the measures.

The precipitation and evapotranspiration are also considered in the model, this data is gathered from KNMI weather station Volkel or Deurne, depending on which station was closest to the project area. The groundwater level data is split at the time that the measures were taken. Both time series are used to create a model based fitted around those measurements and trained with surface water level data, precipitation and evapotranspiration. This creates a model before measures and a model after measures (Fig 2.16). Both of these models are extrapolated over the entire time period. How well the model before measures performs in the time after measures is an indication on how the system changed, conclusions can be drawn about the behaviour of the groundwater tables before and after the measures and whether the system has become wetter or drier. These models have been plotted together with the measurements and the calculated average groundwater levels based on both models and measurements. The calculated groundwater levels are divided in the average highest groundwater level (GHG), the average lowest groundwater level (GLG) and the average spring groundwater level (GVG). The GHG is calculated as the average of the three highest groundwater levels in one year, the GLG as the average of the three lowest groundwater levels in one year and the GVG is an average of the groundwater level of March 14th, March 28th and April 14th (Knotters, n.d.). These three parameters are often indicated with the overarching term GxG. All of these calculations are done over a period of at least 8 years, therefore, if the time series of the groundwater levels was too short the model was extrapolated further into the past to create a time series of at least 8 years.

For each GxG value a map was created using ArcGIS Pro showing the difference between the modelled GxG value before and after the recovery measures were taken at the different project areas. The values for change in GxG from before to after the measures were taken were used again to create boxplots making two for each GxG value and project area: one of the piezometers situated within the area where the measures were taken and one outside of this. This was done to be able to say more about the cause of the change in GxG being due to the measures or not. The GxG values below surface level were also calculated for the different project areas before and after the measures were taken, the before and after values were plotted against each other in graphs to see the direction of change. These plots also say more of the absolute depth of the groundwater, instead of just the difference before and after the measures were taken.

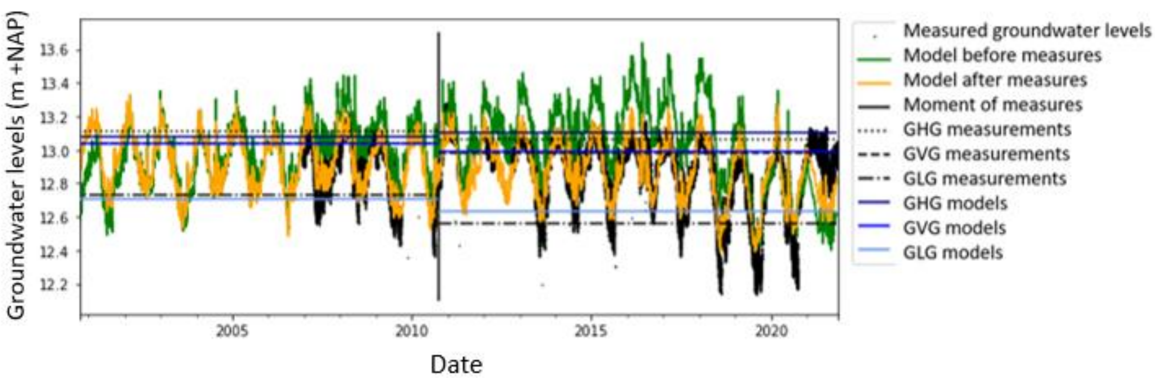


Figure 2.16. Example of the model output from PASTAS.

For every created model also the accuracy is tested based on the measurements in that same time period. The accuracy of the models is also taken into account when interpreting the results. The GxG values are not presented for all piezometers, since these values have to be calculated over a period of at least 8 years and time series of this length were not always available.

2.4.2 Groundwater quality

For the groundwater quality analysis a variety of analysis has been conducted. A van Wirdum diagram will be used to investigate the origin of the groundwater based on the ion ratio and the electrical conductivity. Stiff-diagrams will elaborate on the origin of the groundwater looking at ion concentrations. Furthermore, the time series of the iron concentration will be investigated for the two measurement locations where time series are available, both of these are at St Annabos. Lastly, the fluctuations of the groundwater temperature will be researched, because *wijstwater* comes from deeper layers in the soil the water is less prone to fluctuations of the air temperature and should therefore remain relatively constant compared to the groundwater level at other locations in the management area.

Both the measurements at St Annabos and at Geeneneind will be used to make a van Wirdum diagram. A van Wirdum diagram can be used to classify the origin of groundwater as sea water, seepage water or rainwater (Wirdum, 1991). These three categories of water origins have very distinct values in electrical conductivity (EC) and ion ratio (IR). Therefore plotting the values of EC and IR of the groundwater sample that you want analysed against each other while also showing the values for sea water, seepage water and rainwater can give an indication of the origin of the groundwater sample. The electrical conductivity is measured at all of the gathered measurement points and the ion ratio can be calculated from the concentration of calcium and chloride in the water:

$$IR = \frac{[Ca^{2+}]}{[Ca^{2+}] + [Cl^{-}]}$$

This van Wirdum diagram will be constructed for the water quality measurements at both St Annabos and Geeneneind. However, only one of the piezometers has a period of measurements that ranges across the performed measurements. Therefore, only that piezometer will give much information about the way the origin of the groundwater changes after the recovery measures were performed.

Next to this van Wirdum diagram also stiff-diagrams will be used to investigate the water quality and origin of the project areas. These diagrams show the concentrations of the macro-ions Ca^{2+}, Mg^{2+}, NA^{+} + K^{+}, HCO_3^{-}, SO_4^{2-} and Cl^{-} and the balance between the cations and anions. From this balance conclusions can be drawn about the origin of the water, since these ions had to end up in the water somewhere. Cl^{-} and K^{+} are more likely to have originated from anthropological influences while in this case SO_4^{2-} is an indication of weathering pyrite in the subsoil seepage water taking this up to the surface (van Zuilichem & Brugmans, 2011). These stiff-diagrams are only made for two piezometers, since only there a time series of these ion concentrations is available: piezometer 360018 and 360025, both situated in the project area St Annabos.

For the same two piezometers (360018 and 360025) also iron concentration time series have been made. Time series of the iron concentration will simply be plotted to investigate if there is an upward or downward trend over time. With higher iron concentrations the groundwater is more likely to be *wijstwater* that has been in deeper layers of the soil where the iron had time to dissolve in the water, before seeping upward.

Groundwater temperature in *wijstgebieden* is defined by the lack of seasonal fluctuation. Since the groundwater comes from deeper layers there is a limited effect of the weather and air temperature on the *wijstwater*. Therefore, an indication of the presence of *wijstwater* is the consistency of the groundwater temperature between summer and winter. The difference between the groundwater temperature between winter and summer was calculated for the project areas St Annabos and Geeneneind and for groundwater temperature in other areas. Boxplots and t-tests are used to determine if the project areas St Annabos and Geeneneind indeed qualify as *wijstwater* areas based on groundwater temperature as compared to other areas in the management area of the water authority.

2.4.3 Ecology

In the research on the ecology of *wijstgebieden* by Ettema (2010) a list of indicator species for *wijst*-conditions was published (Tab. 2.5). For this research the same species will be used and tested for their presence before and after the *wijst*-recovery measures were taken in the project areas. The list contains vegetative species, amphibians, birds, dragonflies, butterflies and mammals. All of these species prefer wet conditions and often also the nutrient-poor conditions that *wijstwater* provides.

The abundance of observations in a project area where agriculture is the main land use is very limited. Often those observations only consist of birds and no vegetative species are found. Therefore the ecological data will only be used to perform analyses in the project areas with nature as its main land use. This is the case at Venloop and St Annabos.

Because the measurements are gathered from different organisations there is also a variety in accuracy between the observations. Sometimes observations are given an accuracy of a surface area of 1 km^2 and sometimes less than 1 m^2, this of course also varies between the flora and fauna since flora is more likely to be observed accurately than mobile fauna. There is also a difference in methods of observation. Some of the measurements are sightings by individuals that sighted a specific species and reported this (to *waarnemingen.nl* for example) and other measurements were observed professionally as part of a research. These researches can also cause biases, as a research group might have two areas of interest and observe a considerable amount of species in those two areas and report that. That does however, not mean that the species does not occur in the rest of the management area. Next to these spatial inaccuracies, inaccuracies through time can exist. There might be a lot more ecological research in the interest of some species in the most recent years as opposed to a decade ago. All of these inaccuracies in the observations used in the ecological analyses need to be taken into account when interpreting the results.

Due to these inaccuracies the *wijst* indicator species of which observations were gathered from NDFF were tested for their presence before and after measures were taken. The ecological indication for a recovered *wijstgebied* will thus be the number of species present, rather than the number of individuals. The species data within the project area was clipped in ArcGIS Pro and then a count on species name was performed.

Table 1.5 The wijst-indicator species that will be investigated for the ecological analysis.

Dutch name	Latin name
Wezel	Mustela nivalis
Weidebeekjuffer	Calopteryx splendens
Waterral	Rallus aquaticus
Spotvogel	Hippolais icterina
Putter	Carduelis carduelis
Pluimzegge	Carex paniculata subsp. paniculata
Pinksterbloem	Cardamine pratensis
Oranjetipje	Anthocharis cardamines
Nachtegaal	Luscinia megarhynchos
Klimopwaterranonkel	Ranunculus hederaceus
Kleine watersalamander	Lissotriton vulgaris

Kleine karekiet	Acrocephalus scirpaceus
Kamsalamander	Triturus cristatus
Icarusblauwtje	Polyommatus icarus
Hooibeestje	Coenonympha pamphilus
Holpijp	Equisetum fluviatile
Heikikker	Rana arvalis
Gewone pad	Bufo bufo
Gewone dotterbloem	Caltha palustris subsp. palustris
Gewone bronlibel	Cordulegaster boltonii
Echte koekoeksbloem	Silene flos-cuculi
Bunzing	Mustela putorius
Bruine kikker	Rana temporaria
Bosrietzanger	Acrocephalus palustris
Blauwborst	Luscinia svecica
Bittere veldkers	Cardamine amara
Beekoeverlibel	Orthetrum coerulescens
Bandheidelibel	Sympetrum pedemontanum

3 Results

3.1 Groundwater levels

For the investigated project areas there seems to be no clear effect of the measures on the groundwater levels. You would expect the measures to lead to wetter conditions and therefore higher groundwater levels. However, this is not always the case for all project areas, as illustrated by the calculated effect of measures on the groundwater levels (Fig. 3.1, 3.2, 3.3, 3.4) (for the values used in these maps see Appendix C). Where some locations become wetter, neighbouring locations might become drier. St Annabos, Geeneneind and Venloop all show different results when looking at the differences between the modelled GxG values before and after the measures were taken. St Annabos showed some increases and some decreases of groundwater levels, Geeneneind showed mainly increases and Venloop mainly decreases. Below the results are elaborated on per project area.

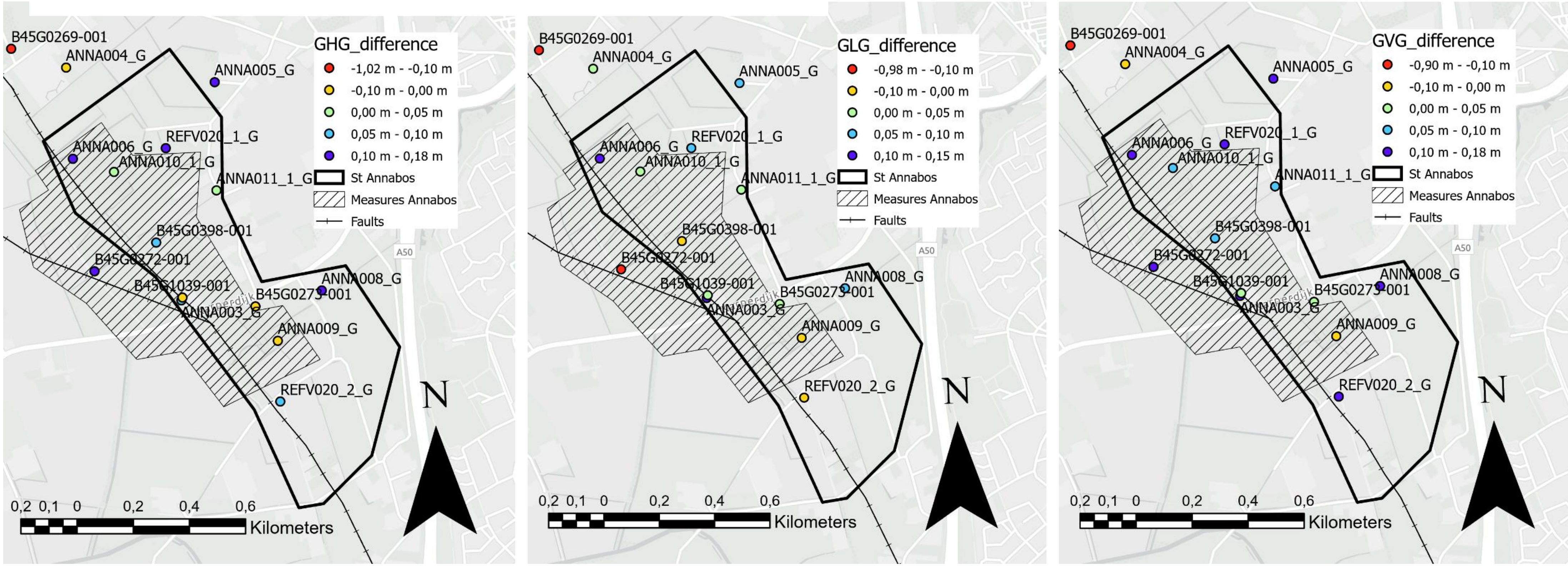
For the project area St Annabos both wetter and drier conditions are found (Fig. 3.1). For all three GxG values a strongly decreasing groundwater level can be found at piezometer B45G0269-001, which is located north of the project area. Out of all the piezometers shown here, 10 show an increasing groundwater level and 5 show a decrease. When just looking at the area where the measures were actually taken, there are 5 piezometers showing wetter conditions and 2 piezometers showing drier conditions, therefore within or outside the area where the measures are taken does not change this division much.

The same information is shown for project area Venloop (Fig. 3.2). However, at Venloop the decreasing groundwater levels are clearly in the majority. The GHG decreases for every piezometer, the GLG increases at only two piezometers and the GVG increases at only three piezometers. The increasing GLG values are found outside the project area or on its border, at piezometers MAAS003_G and B45H0107-001. It is unlikely however, that these increasing GLG values are caused by the measures, as the measures are taken far away from these piezometers and are taken in only a very small part of this project area. The GVG however increases slightly at MAAS021_G, MAAS022_G and KARL002_G, and these three piezometers are situated close to where the measures were taken.

For Geeneneind the changes in GxG values are also shown (Fig. 3.3). For all three values the majority of the piezometers show an increase in groundwater levels since the measures were taken. This increase is clearly strongest for the GVG value, especially in the string of piezometers from west to east starting with PEEL002_4_1 and ending with PEEL003_1_1. The measure taken here was to redirect water from agriculture and the Meuse to not discharge through the Esperloop but flow northward from the Esperloop, in the Snelle Loop, and the Esperloop to only discharge *wijstwater*. This measure might explain the increasing groundwater levels around the Snelle Loop and the decreasing groundwater levels to the south (around piezometer PEEL001_1_1).

At project area Donzel the one investigated piezometer shows drier conditions after the measures were taken for GHG, GLG and GVG. The decrease for all three GxG values is around the same order of magnitude. However, due to the distance between the measures and the piezometer these results are highly questionable.

Figure 3.1 The difference between the modelled GxG values before and after measures for St Annabos



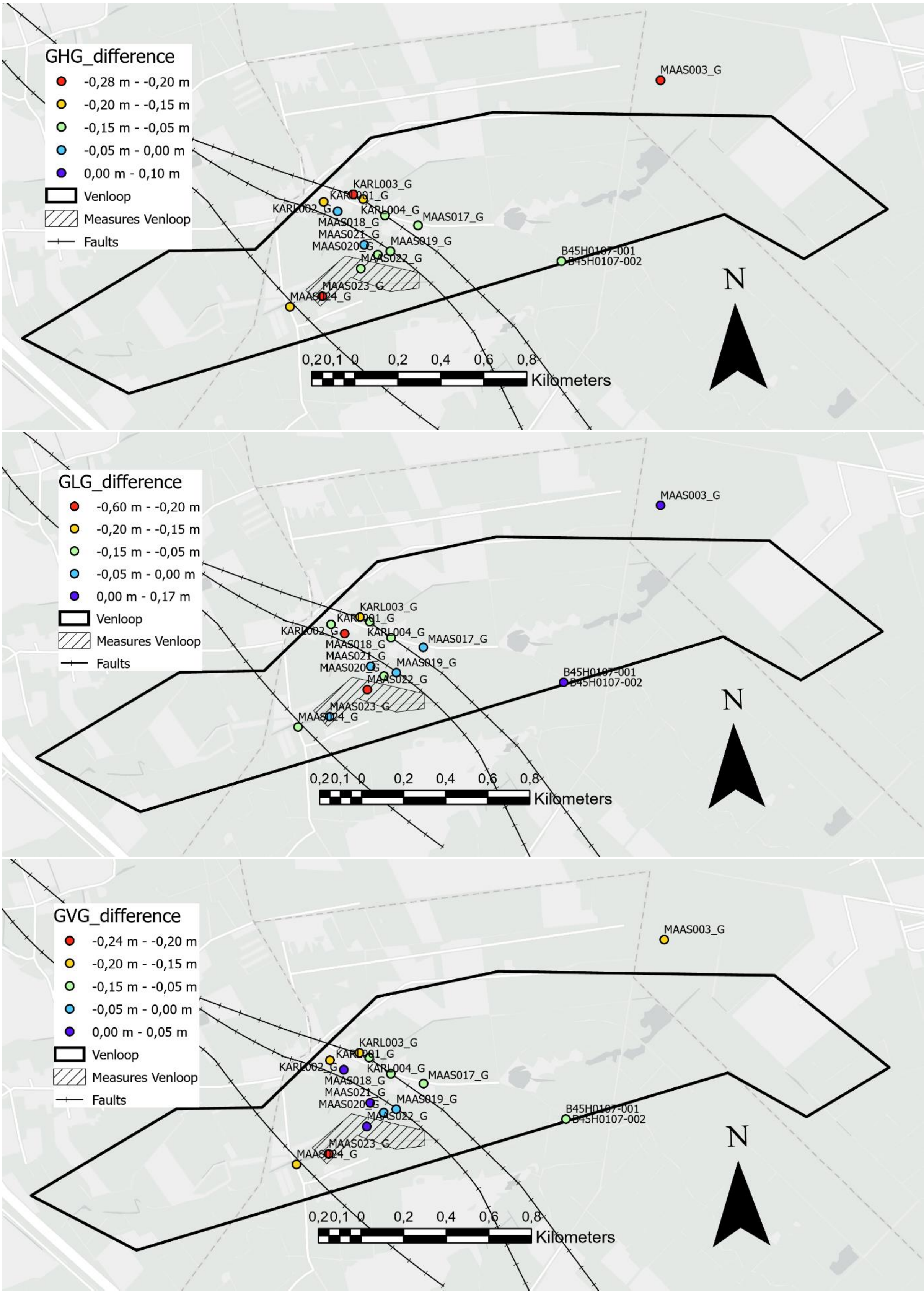
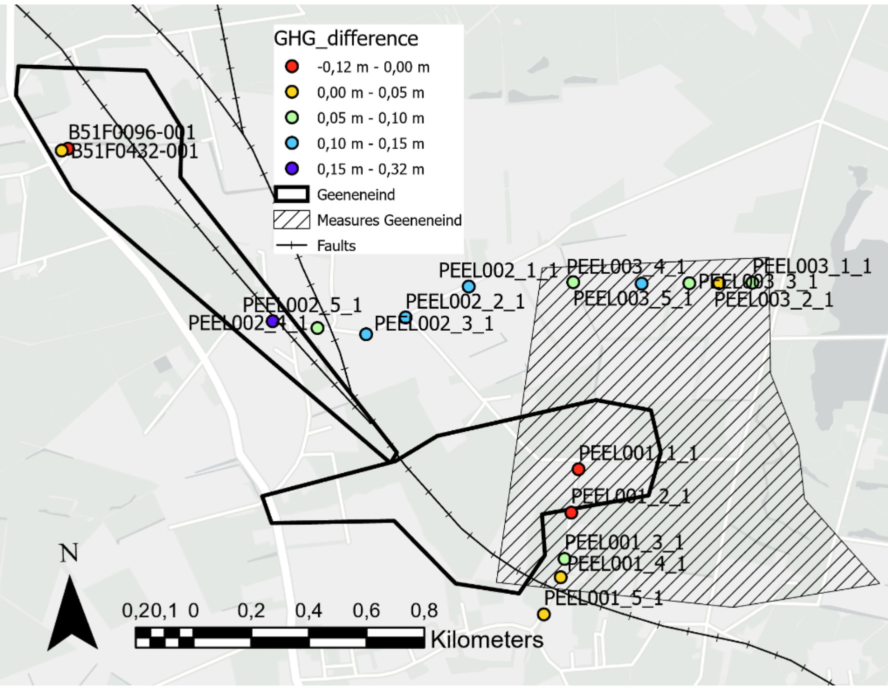
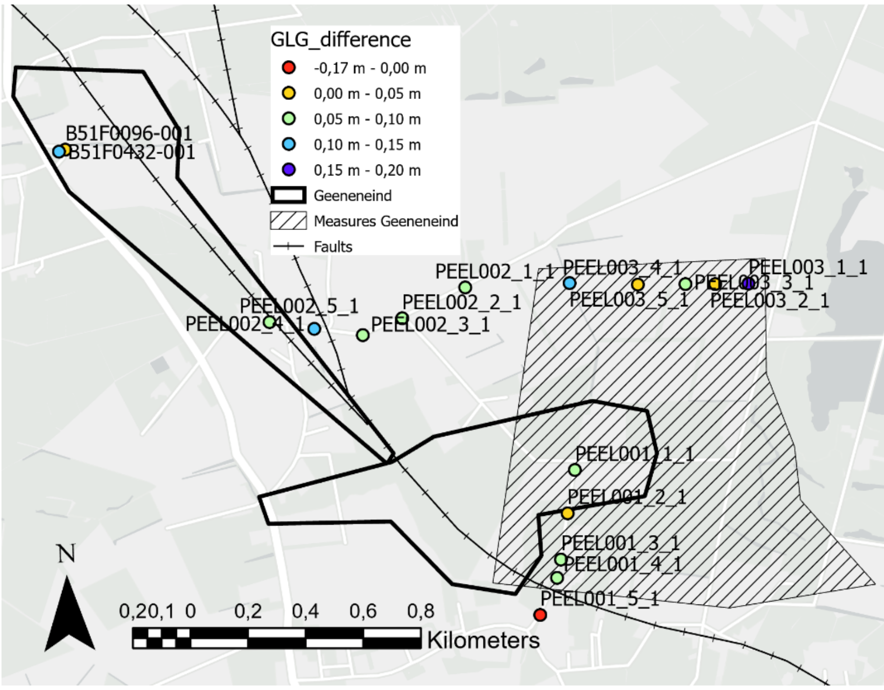


Figure 3.2 The difference between the modelled GxG values before and after measures for Venloop


GHG_difference
-0,12 m - 0,00 m
0,00 m - 0,05 m
0,05 m - 0,10 m
0,10 m - 0,15 m
0,15 m - 0,32 m
Geeneneind
Measures Geeneneind
Faults
B51F0096-001
B51F0432-001
PEEL002_1_1
PEEL002_2_1
PEEL002_3_1
PEEL002_4_1
PEEL002_5_1
PEEL003_1_1
PEEL003_2_1
PEEL003_3_1
PEEL003_4_1
PEEL003_5_1
PEEL001_1_1
PEEL001_2_1
PEEL001_3_1
PEEL001_4_1
PEEL001_5_1
N
0,20,1 0 0,2 0,4 0,6 0,8
Kilometers


GLG_difference
-0,17 m - 0,00 m
0,00 m - 0,05 m
0,05 m - 0,10 m
0,10 m - 0,15 m
0,15 m - 0,20 m
Geeneneind
Measures Geeneneind
Faults
B51F0096-001
B51F0432-001
PEEL002_1_1
PEEL002_2_1
PEEL002_3_1
PEEL002_4_1
PEEL002_5_1
PEEL003_1_1
PEEL003_2_1
PEEL003_3_1
PEEL003_4_1
PEEL003_5_1
PEEL001_1_1
PEEL001_2_1
PEEL001_3_1
PEEL001_4_1
PEEL001_5_1
N
0,20,1 0 0,2 0,4 0,6 0,8
Kilometers

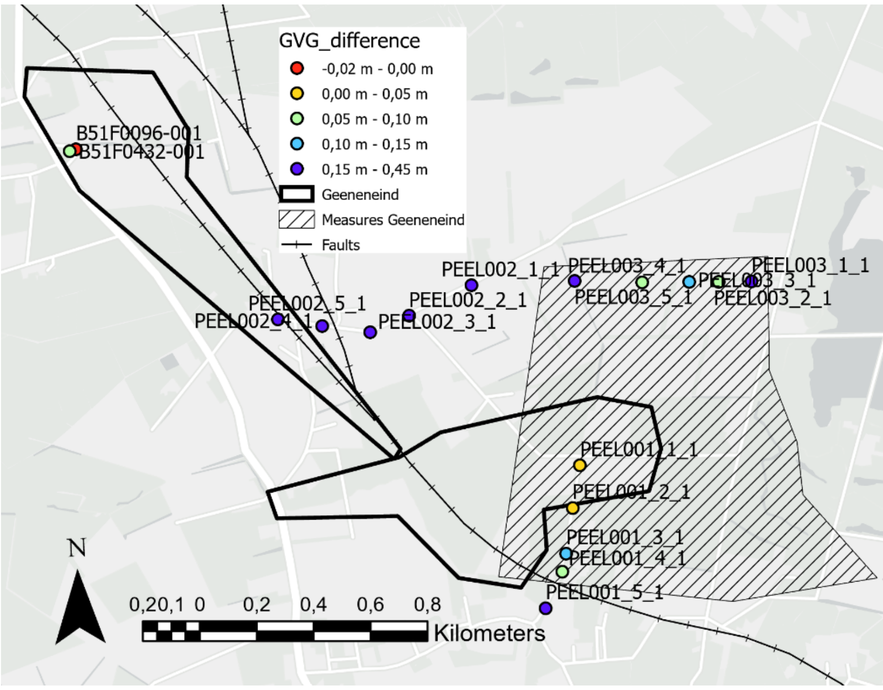


Figure 3.3. The difference between the modelled GxG values before and after measures for Geeneneind.

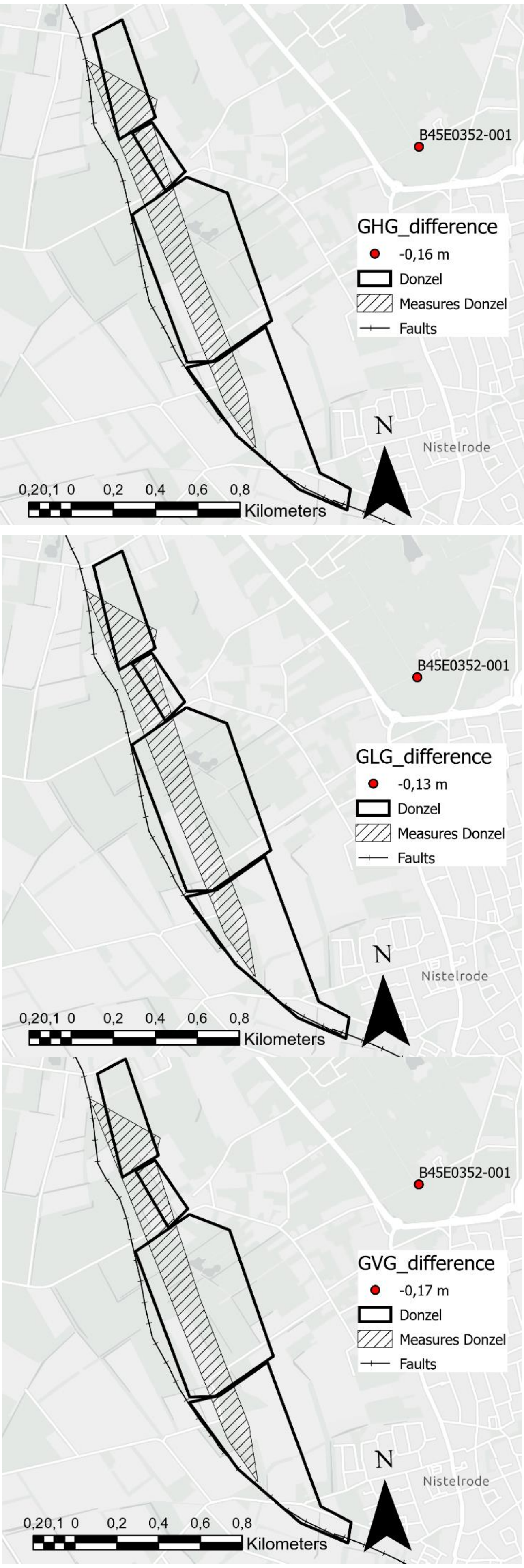
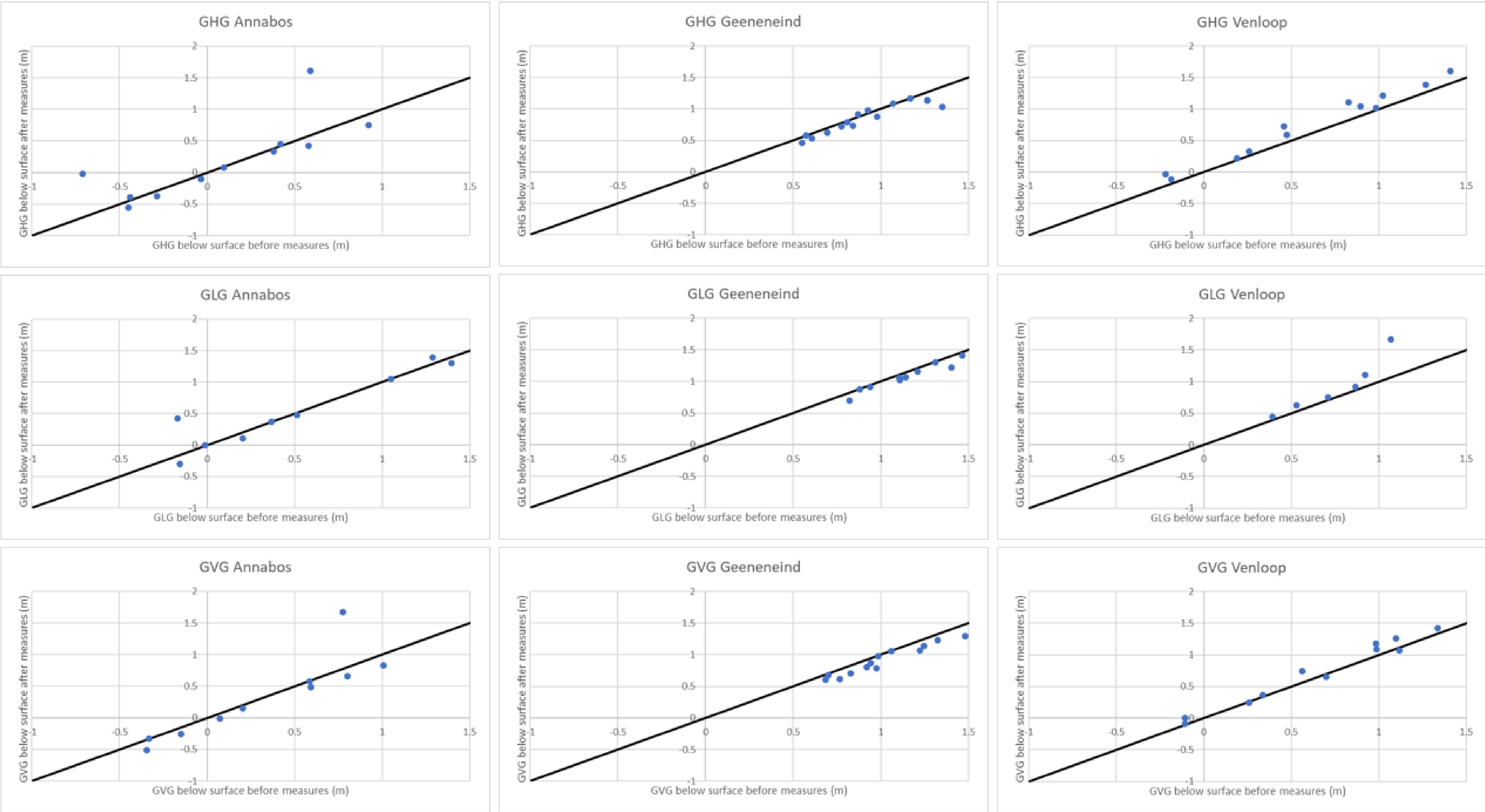


Figure 3.4. The difference between the modelled GxG values before and after measures for Donzel


GHG Annabos
GHG below surface after measures (m)
GHG below surface before measures (m)
GHG Geeneneind
GHG below surface after measures (m)
GHG below surface before measures (m)
GHG Venloop
GHG below surface after measures (m)
GHG below surface before measures (m)
GLG Annabos
GLG below surface after measures (m)
GLG below surface before measures (m)
GLG Geeneneind
GLG below surface after measures (m)
GLG below surface before measures (m)
GLG Venloop
GLG below surface after measures (m)
GLG below surface before measures (m)
GVG Annabos
GVG below surface after measures (m)
GVG below surface before measures (m)
GVG Geeneneind
GVG below surface after measures (m)
GVG below surface before measures (m)
GVG Venloop
GVG below surface after measures (m)
GVG below surface before measures (m)

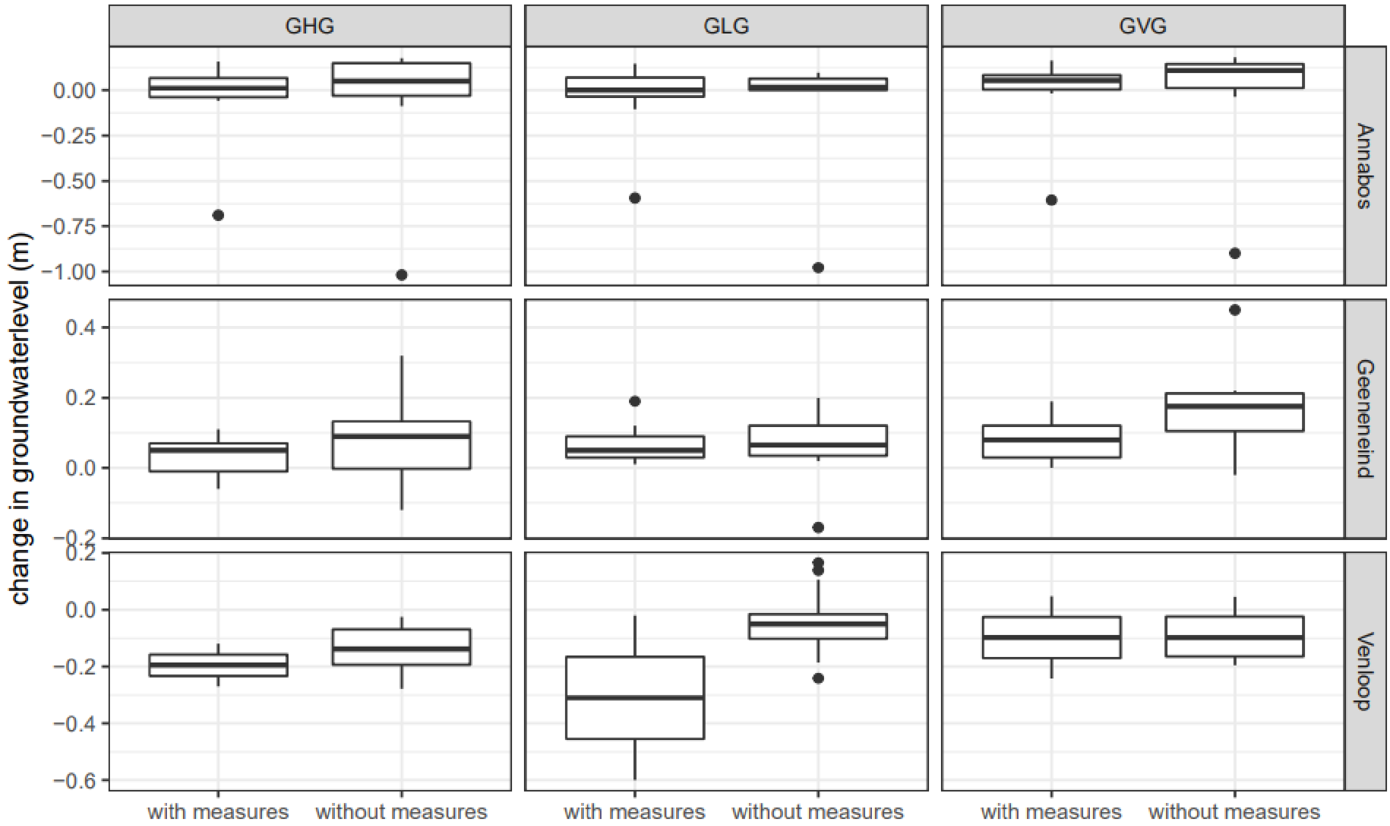


Figure 3.6. Boxplots for change in groundwater levels (same values as used in fig 3.1, 3.2 and 3.3) for each GxG value and project area. Two boxplots were formed each time: one of the measurements taken within the area where the measures were taken and one outside of this area.

From the first glance at figure 3.5 it can be seen that the values do not seem to change a considerable amount from before to after the measures were taken. The values generally stay close to the 1-1 line plotted there. Some minor fluctuations can be seen, however. The results found from the maps in figures 3.1, 3.2 and 3.3 are reflected in figure 3.5, where St Annabos shows strong hetereogeneity with values decreasing and increasing, at Geeneneind mostly the GxG values come closer to the surface and at Venloop the depth to groundwater level increases. The negative values found for St Annabos might be due to suboptimal model performance, the most negative value belongs to piezometer ANNA006_G, which has a model performance of 68% (Appendix C).

Only very small differences can be found between the measurements taken within the area where the measures were taken and just outside this area (Fig 3.6). This analysis was performed to be able to draw conclusions about the magnitude of the effect of the measures on groundwater levels on the spatial scale. Since only very small differences can be spotted from these boxplots there is not much spatial variation between the groundwater level data changes close to the measures and further away. When combining the results in this chapter it can be seen that the groundwater levels based on the data presented here do not change considerably over time or space.

3.2 Groundwater quality

The groundwater quality measurements are limited. This makes that the results are questionable and that no clear conclusions can be drawn. Only at St Annabos two piezometers are available that have measurements dating back to before the measures were taken there, but also at these piezometers only one measurement was done per year and every time these were done in another season, making intercomparison difficult. Even though this is the case, multiple analyses have been conducted. The analysis presented here are: A Van Wirdum-diagram showing the origin of the groundwater using the electrical conductivity and ion ratio; a stiff-diagram showing the balance of cations and anions in the groundwater; time series for iron concentration at two piezometers at St Annabos; boxplots and t-tests showing the difference between *wijstgebieden* and other areas about the seasonal fluctuation of the groundwater temperature. All of these will be discussed here.

To analyse the origin of the groundwater samples taken at St Annabos and Geeneneind Van Wirdum diagrams were created. On the x-axis the electrical conductivity is shown and on the y-axis the ion ratio. In these diagrams the Li (lithocline) indicates seepage water characteristics, At (atmocline) indicates rainwater characteristics and Th (thalassocline) indicates sea water characteristics (Fig. 3.7). For two of the piezometers at St Annabos a time series of measurements is available, this is for the piezometers with codes 360018 and 360025 (Fig. 2.5). The piezometer 360018 is situated just outside of the project area St Annabos (Fig. 2.5) and is located in an area that is dominated by agricultural grasslands. Piezometer 360025 is situated inside the project area and is located among wet natural vegetation. The measures are also taken in closer proximity to piezometer 360025 than to 360018. Furthermore, piezometers 360017, 360018, 360019, 360022 and 360026 are situated just north or east of the taken measures.

In the diagram the purple dots indicating this piezometer 360018 show a curved trajectory (Fig. 3.7). The measurement in 2009 is situated closest to the seepage water in the plot, while the later years curve towards the rainwater first and 2018 even towards the sea water. The measurements at 360025 remain more clustered around the same location. The piezometer 360025 is situated within the area where the measures were taken and 360018 is situated outside of this area. This can explain the persisting origin of seepage water for piezometer 360025. The other piezometers only contained measurements in 2009, these are situated in a cluster and close to the seepage water in the plot as well.

The measurements for the van Wirdum diagram at Geeneneind all date back to 2015 from the monitoring program that was set up then. The different points for each piezometer indicate different measurements in different months, measurements were taken from July to December. The groundwater composition is more or less the same for the different locations, as the points in the van Wirdum diagram are situated close together and are closest to the Li-point indicating the seepage water characteristics. No conclusions about the taken measures can be taken here, since no measurements from after measures are available.

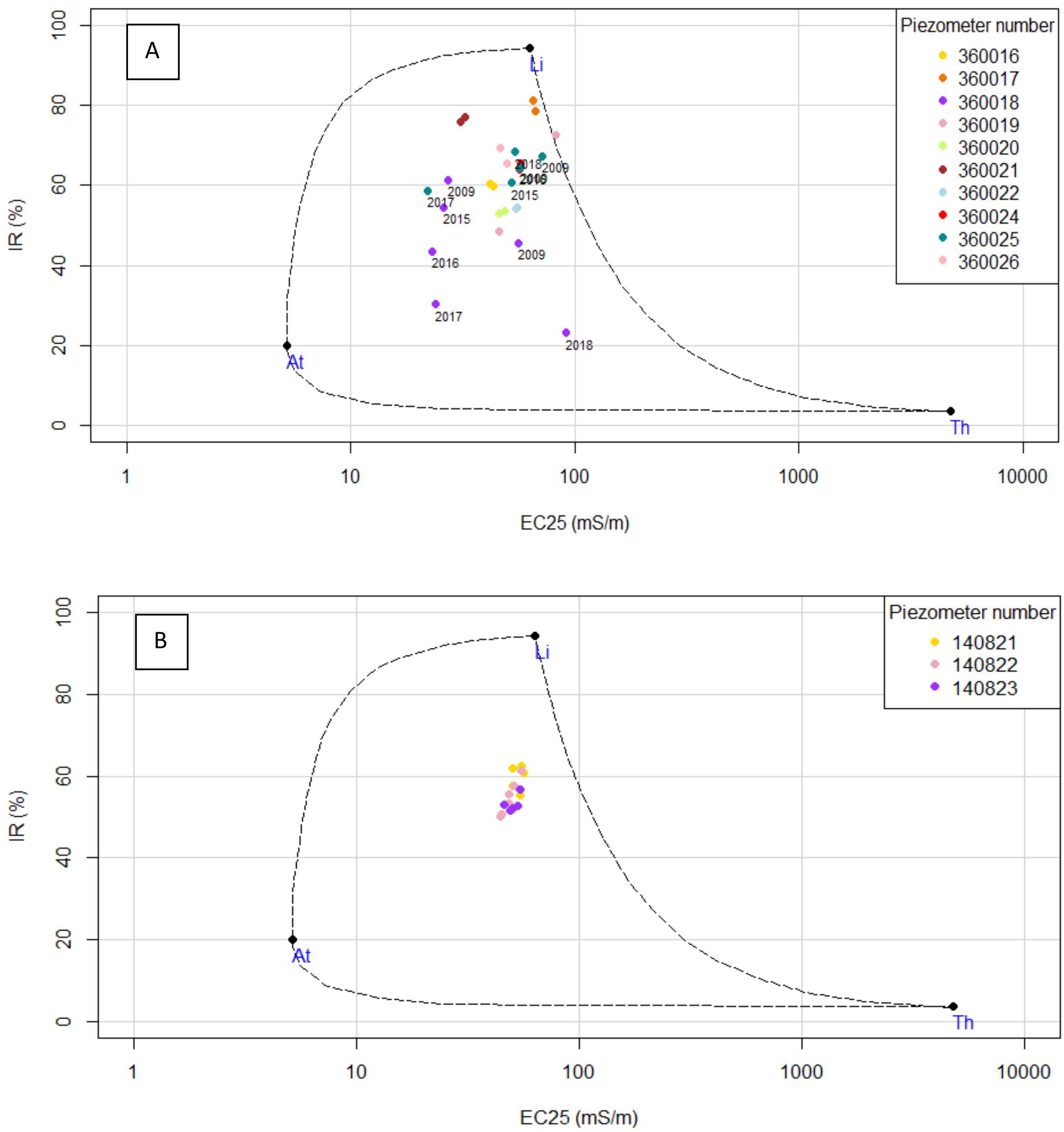


Figure 3.7. Van Wirdum diagram showing an indication of the origin of the groundwater at the project area St Annabos (A) and Geeneneind (B). The lithocline (Li) water is seepage water, the atmocline (At) water is precipitation and the thalassocline (Th) water is sea water.

Iron concentrations are generally high for *wijstwater* (van Balen, 2009), therefore the change in iron concentration before and after the measures has also been investigated (Fig. 3.8). There are two piezometers available at St Annabos where measurements were taken over a longer time period, these piezometers are used for the time series analysis on iron concentration in figure 3.8. The trendlines in both figure 3.8A, 3.8B are sloping downwards, indicating that less iron was present in the groundwater at St Annabos after the measures were taken. For 360025 however, the values of the iron concentration are approximately three times larger. The piezometer situated within the area where the measures were taken (360025) is therefore showing more characteristics of *wijstwater* here. There are only six measurements shown for these piezometers, and since these six measurements were also done in different seasons these results are based on very questionable data.

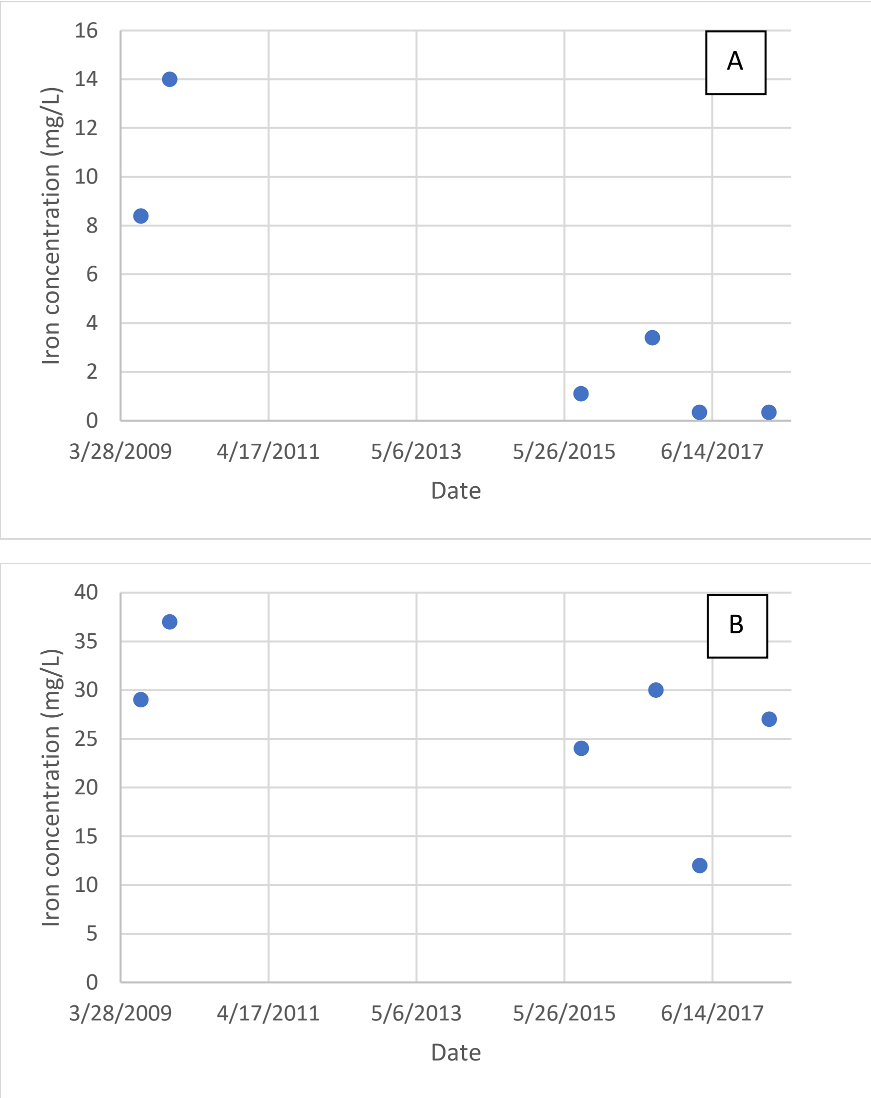


Figure 3.8. Iron concentration at two piezometers at St Annabos: piezometer 360018 (A) and piezometer 360025 (B).

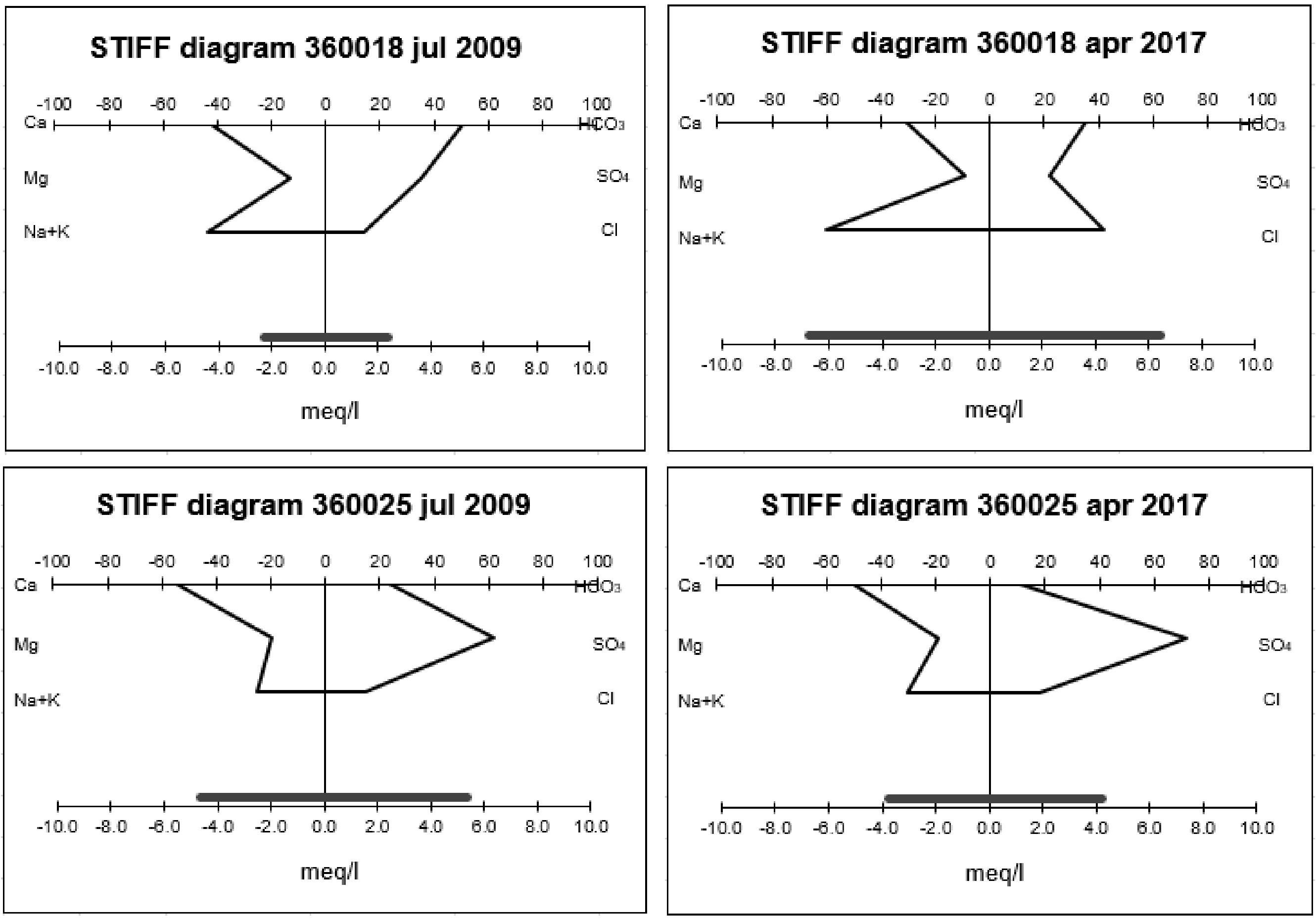


Figure 3.9. Stiff diagrams before and after the measures (2009 and 2017) for two piezometers at St Annabos (360018 and 360025).

The stiff-diagrams display the macro-ion concentrations in the groundwater (Fig. 3.9). The cations are displayed on the left side of the graph and the anions on the right side. For both piezometers one stiff-diagram before the measures were taken and after the measures were taken are shown (for the other stiff-diagrams see Appendix D). Piezometer 360018 is situated just outside of the area where the measures were taken and 360025 is situated within this area (Fig. 2.5). There is some difference in the shapes of the stiff-diagrams. The measurements in 2009 at location 360018 shows high concentrations of Na+K, Ca and HCO_3. The measurements at 2017 for location 360018 show high concentrations of Na+K and Cl. The measurements from 2009 at 360025 show high concentrations of Ca and SO_4 and so do the measurements of 360025 from 2017, but with even higher SO_4 concentrations.

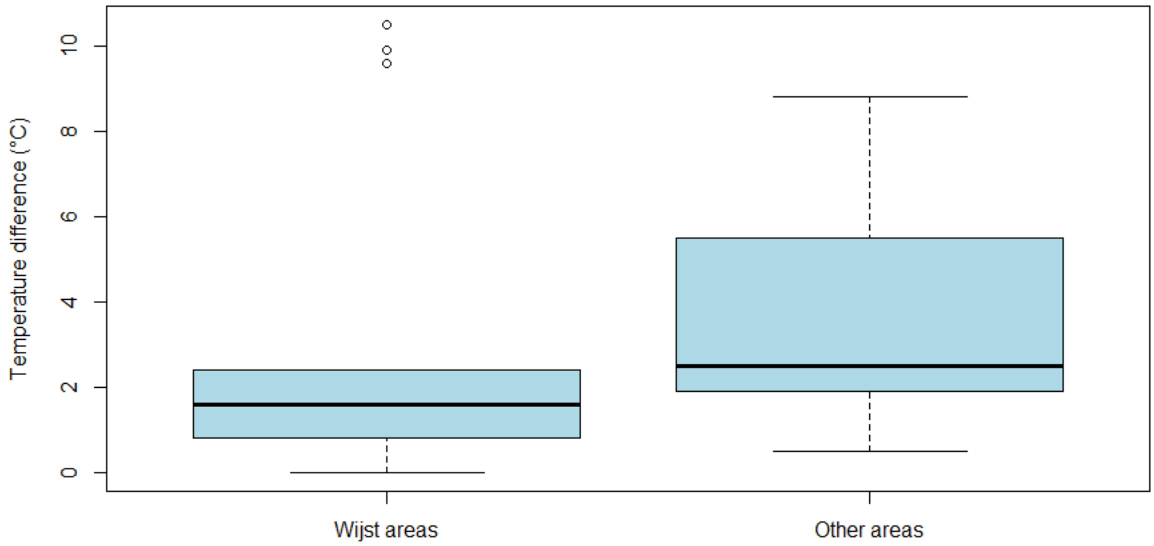


Figure 3.10. A boxplot for the temperature difference between July and December for the project areas Geeneneind and St Annabos and other areas in the management area of the water authority.

The most important characteristic defining groundwater temperature in *wijst* areas is the lack of seasonal fluctuation. Since the groundwater comes from deeper layers there is a limited effect of the weather and air temperature on the *wijstwater*. Therefore, an indication of the presence of *wijstwater* is the consistency of the groundwater temperature between summer and winter. The difference between the groundwater temperature between winter and summer was calculated for the project areas St Annabos and Geeneneind and for groundwater temperature in other areas (Fig. 3.10). This data was however only available in winter and summer in 2009 and therefore these results only analyse the *wijstwater* before the measures were taken. The mean for the *wijst* areas is 3.19 °C and for the other areas 3.60 °C, a t-test also indicates that there is no significant difference between the two groups shown in figure 3.6, with a high p-value of 0.73. However, the three outliers for group *wijst* areas in figure 3.6 are the three values belonging to project area Geeneneind. When not counting these but only testing for the values from St Annabos the mean temperature difference for the *wijst* areas becomes 1.15 °C. The t-test between the St Annabos values and the other areas also returns a significant p-value, with a value of 0.0001.

3.3 Ecology

In the most project areas an increase in the number of present *wijst*-indicator species can be seen after the measures (Tab. 3.1). At St Annabos this change is largest with an increase of 47%. The increasing number of species is hard to ascribe to the taken measures. In table 3.1 also the change in the nature area in km^2 is shown, as this probably also holds an explanatory role for the change in number of species.

The largest difference in present indicator species has been found for St Annabos. Venloop shows some increase in number of present indicator species. At Geeneneind, Donzel and Graspeel no analysis on indicator species was performed since these three areas consist of agricultural land instead of nature areas (see section *Methods- Study area background*) (For a list of the observed species see Appendix F).

Furthermore, table 3.1 also shows the surface area of the nature within the project area, since this might also be an explanatory variable for a change in number of species present aside from the taken measures. The nature area can be forest or natural grassland or swamp vegetation. When the land use is changed from agricultural or building to a type of nature, it can be expected that the number of species also increases. The highest increase in nature area can be seen for St Annabos, where also the number of species increased the most. Venloop has larger surfaces of nature area compared to St Annabos. However, at Venloop the majority of the nature area consists of forests. This does not necessarily support the *wijst*-indicator species.

Table 2.1. Count of species indicating wet conditions at the different project areas.

	# species before	**# species after**	**Species increase (%)**	**Nature area before (km^2)**	**Nature area after (km^2)**	**Nature area increase (%)**
St Annabos	15	22	+46.7	0.16	0.27	+67
Venloop	17	21	+23.5	1.3	1.4	+7.7
Geeneneind	n/a	n/a	n/a	n/a	n/a	n/a
Donzel	n/a	n/a	n/a	n/a	n/a	n/a
Graspeel	n/a	n/a	n/a	n/a	n/a	n/a

4 Discussion

4.1 Groundwater levels

The purpose of the taken *wijst*-recovery measures for the groundwater levels, was to increase these values by keeping more water in the project areas. The results in section 3.1 show maps indicating the GxG values for each project area. The results show a heterogeneity in the results. At the project areas St Annabos and Geeneneind these maps show that the majority of measurement locations have experienced an increase in groundwater levels, however, at Venloop decreasing groundwater levels are dominant.

At St Annabos the GHG and GVG values have increased the most, followed by smaller increases for the GLG values. St Annabos does show some heterogeneity within the project area where some areas show decreasing groundwater levels and other increasing groundwater levels. Microtopography can also attribute to difference in groundwater levels and groundwater composition, especially in shallow groundwater systems (van der Ploeg et al., 2012). One of the characteristics of groundwater fed systems is that the seasonal fluctuation of the groundwater levels is minimized (Burt et al., 2002). However, at St Annabos the decreasing GLG and increasing GHG and GVG seem to indicate that the fluctuations have become larger instead. The system at St Annabos has thus overall become slightly wetter, but perhaps the extra water can be attributed to rain water, which is more prone to seasonal fluctuations.

At Venloop the GxG values (Fig. 3.2) show mostly decreasing groundwater levels. At Venloop the taken measures were also less impacting than at Geeneneind and St Annabos. At Venloop only a small part of the stream has been altered and rerouted and logs were placed in the waterbed. Due to the fact that the measures taken were so minimal and only in a small part of the area it is hard to draw conclusions about the changes in the groundwater levels, because it is rather unlikely that these changes were caused by these small interferences. On top of that weirs were removed, therefore no longer keeping the water in the area. The piezometers showed that the GHG only decreased and that the GLG decreased strongest, therefore also increasing the seasonal fluctuation. Climate change will also enhance these fluctuations found at St Annabos and Venloop in the future, the GVG might be minimally affected, while the GLG could decrease more drastically (Geertsema et al., 2014). So, it is unlikely that the measures caused these changes, but if the measures had anything to do with these effects on groundwater levels, the measures did not have the desired effects.

At Geeneneind the GVG increased strongest of the three GxG values. The GVG can be used as an indication of water availability in the rooting zones of plants (van der Gaast et al., 2009). The groundwater levels at Geeneneind are often not so high that water stress in the root zone is concerning. Therefore, the increase of GVG at Geeneneind would be a start for better conditions for hygrophilous plants. However, the dominant land use in the area remains to be agriculture, therefore the flora and fauna cannot benefit from these wetter conditions. The influence of agriculture is also reflected by the relatively low groundwater levels in Geeneneind. The highest groundwater levels (GHG) are still 50 cm below surface level, while the groundwater tables in the nature areas (St Annabos and Venloop for example) are much higher and often reach the surface. The GLG increased the least of the three GxG values, therefore also increasing the seasonal fluctuation, perhaps indicating that the system is not mainly groundwater fed (Burt et al., 2002). However, at Geeneneind a lot more piezometers were included that do not fall into the area where the measures were taken, therefore this conclusion would be more questionable than at St Annabos.

Most of the hygrophilous plants that are desired in these nature areas need very high groundwater tables. The swamp and Alder swamp wood need the highest groundwater levels, 3 cm and 9 cm below surface, the wet grasslands need the groundwater at 25 cm below surface and the flowery grassland at 42 cm below surface (van Rens, 2009). In figure 3.5 it can be seen that also at the project areas St Annabos and Venloop, where nature is the prominent land use, at most measurement locations the groundwater levels remained deeper. Therefore, even after the measures, not offering this vegetation the optimal conditions.

In general the data presented here does not show a large change in groundwater levels. Most of the time the changes are in the order of centimetres. Also there is a diffuse pattern in the sense that some locations became wetter and neighbouring locations became drier, mostly at St Annabos. In addition, in the areas without measures we see similar changes. Therefore the main conclusion is that the effect of the taken measures based on this data is minimal. Maybe there is noise in the used method to predict the effect of measures on the groundwater level as well. Especially when the groundwater level time series are not long enough (before and after measures) to train the model, decreasing the prediction power. However, the R^2 of the predictions is often in the range of 60% to 100% indicating that the predictions are still quite well. Maybe the model predictions are also affected by succession of dry years (2018, 2019 and to a lesser extent 2020). In the period before measures such a dry period was missing, leading to other training results of the models and therefore to other predictions.

4.2 Groundwater quality

There is a shortage on groundwater quality measurements to monitor the changes from before to after the recovery measures are taken. The two available time series have annual measurements that are done in a different months every time, since groundwater quality parameters often fluctuate with the seasons (Nelson, 2002) (Appendix E) these time series are suboptimal to use. Therefore the results are questionable. Furthermore for the groundwater quality measurements no correction for the fluctuations in weather were done, as was done for the groundwater level analyses. Therefore a large part of the found fluctuations and changes over the years could be explained by the fluctuations of the weather.

In the Van Wirdum diagram in figure 3.7 the measurements for St Annabos from 2009 show a cluster close to the point indicating seepage water characteristics. This suggests that the groundwater before (or partly during) the measures consisted mostly of seepage water. The time series at piezometer 360025 also remained clustered at that approximate location after the measures were taken. However, for the other time series that was measured here (piezometer 360018) the following years showed groundwater properties that were more similar to the rainwater characteristics. This could be an indication that at 360018 the influence of the *wijstwater* is less, since it is located a couple hundred meters away from the fault. Figure 3.8, showing a time series of the iron concentration supports this suggestion. Iron concentrations are typically higher for *wijstwater* (van Balen, 2009) but at St Annabos the parameter shows a decrease after the measures were taken in the second half of 2009. This therefore could also suggest that the sampled groundwater was no longer of seepage origin, but consisted of more rainwater than before. However, since there are only six measurements and they are all taken in different seasons this decrease could also very likely be ascribed to the seasonal dependence of iron concentrations in groundwater (Nelson, 2002). However, if the rainwater lens prevents the seepage water to reach the surface, this can have a negative effect on the species richness of the wetland when species prefer the specific characteristics of the seepage water (Schot et al., 2004). In other fen restoration projects shallow open drains are used to discharge the incoming precipitation superficially in order to hamper the forming of rainwater lenses (Van der Hoek, 2005). If the root zones of the *wijst*-indicator species cannot reach the *wijstwater* at all in St Annabos, action might be needed. Whether this is already necessary at St Annabos depends on the depth of the rainwater lens and the heterogeneity of its thickness. Some patchiness in the vegetation due to a heterogeneous rainwater lens might only benefit the biodiversity of the project area (personal communication).

The van Wirdum diagram also shows that the measurement at St Annabos for piezometer 360018 is headed towards characteristics that resemble sea water in the year 2018. A possible explanation for this behaviour could be that the year 2018 was exceptionally dry, the lack of incoming precipitation and ongoing evapotranspiration could have resulted in higher concentrations of minerals in the groundwater (Tomaz et al., 2020).

In the stiff-diagrams also different ion concentrations can be found for the piezometer 360018 and 360025. At piezometer 360025 high concentrations of sulphate were found, which has been documented before (van Zuilichem & Brugmans, 2011). These high concentrations can be caused by human interference, but here it is more likely that these high concentrations are caused by the oxidation of pyrite (FeS_2) in the subsoil (van Zuilichem & Brugmans, 2011). Furthermore, the presence of iron in the groundwater inhibits the reduction of sulphate to sulphide, therefore increasing the sulphate concentration (Van der Hoek, 2005). This makes the high concentrations of sulphate an indicator of seepage water at 360025, this is in agreement with the higher iron concentrations as found in figure 3.8. Piezometer 360025 is situated within the area where measures to recover *wijst* have been taken and wet vegetation is the prominent land use. Piezometer 360018 is situated more to the north-east of the locations where the measures were taken and the dominant land use here is agricultural grasslands. The stiff-diagrams also show different patterns of ion concentrations for 360018 than for 360025. The K and Cl at 360018 are relatively high. These ions can be found in fertilizers and therefore these high concentrations are likely caused by humans and the agricultural land use (van Zuilichem & Brugmans, 2011).

The difference between piezometer 360018 and 360025 as described above was investigated with the groundwater level data. The groundwater level at 360025 and 360018 both showed wetter conditions after the measures were taken, especially 360018 had three increasing GxG values. However, the groundwater level at 360018 remained deeper than for 360025, since the latter already had groundwater levels of approximately 10 cm below surface, smaller differences were expected. However, the smallest increase at 360018 was found for the GLG, therefore increasing the seasonal fluctuation while this was not the case for 360025. This increased seasonal fluctuation is also an indication of less seepage water influenced areas (Burt et al., 2002).

The most important characteristic of groundwater temperature of seepage water in *wijstgebieden* is the consistency throughout the year. Because the water comes from deeper layers in the soil only little influences of the air temperature and the weather are to be expected. This results in rather constant temperatures. Therefore the temperature remains higher than the air temperature in winter and lower in summer (Anderson, 2005). For St Annabos and Geeneneind the groundwater temperature was measured in both July of 2009 and December of 2009. The difference between those two temperatures was on average smaller than between the summer and winter temperature of groundwater samples in other areas within the management area of the water authority. At St Annabos the difference between winter and summer varied significantly less than that difference in other areas, this was not the case for Geeneneind or the combination of St Annabos and Geeneneind. For St Annabos the conclusion can thus be drawn that the parameter ground water temperature supports that St Annabos is a *wijstgebied*. However, nothing can be concluded regarding the measures, since the temperature measurements (2009) took place before the measures were taken. For Geeneneind no conclusions about the measures can be drawn either, since all the groundwater quality measurements, including the groundwater temperature, are only measured in 2015, before the measures were conducted. However, for project area Geeneneind the groundwater temperature is less constant than expected. Since the area is next to the fault line and the *wijstwater* is supposed to be the only discharge in the Esperloop, a more consistent groundwater temperature was expected. The location of the measurement points are not exactly at the Esperloop or Snelle Loop, but more in between alongside a ditch. This could also have affected the influence of *wijst* at those specific locations.

4.3 Ecology

Investigating the presence of *wijst*-indicator species in the nature area parts within the project areas showed an increase for three project areas and a slight decrease for one. The largest difference in numbers of present indicator species was found at St Annabos. In table 3.1 it was also seen that the land use change towards nature area was largest for St Annabos, creating more locations for the flora to grow and more habitat for the fauna. This could be a more plausible explanation of the increasing number of species than the taken measures. However, this location has the longest time since the measures were taken, the measures at St Annabos date back to 2009 and the measures at the other locations have been performed from 2014 to 2016. More mobile organisms have the capability to inhabit a recovered nature area almost immediately (Moreno-Mateos et al., 2015), however larger vegetative species will take much longer (Bennett et al., 2009). Therefore, since the system at St Annabos has had the most time to function as an ecosystem again, it is in line with the expectations that St Annabos has the largest increase in number of species. What the exact reason for this is (the taken measures or the increased nature area surface) cannot be concluded from this research.

The NDFF database is the most extensive database on ecological observations in the Netherlands (NDFF, 2021). However, it is dependent on the organisations that provide it with measurements, this can result in a bias in the database. For example a project where a specific species was of interest at a certain location can also provide their data to the database, this can result in a sudden spike of observations, while this does not represent the actual situation.

Furthermore, a population in a nature area requires 500 reproducing pairs to be stable (Ettema & van der Wijst, 2012). In none of the investigated project areas enough observations were done to count 500 pairs, the data is thus unable to draw conclusions about the stability of the population. Just the presence of a species means very little for their means of survival. The project areas are all rather small areas as well, therefore, the amount of space necessary to sustain a stable population might have to consist of multiple project areas that are inter-connected.

4.4 Synthesis

The species richness of a groundwater dependent nature area has been investigated before, Johansen et al. (2018) showed a significant positive correlation between groundwater level and the number of present fen species. At the *wijst* project areas where an ecological analysis was done the same correlation is hard to be found. At St Annabos both the groundwater levels increased a little and there was a clear increase in number of present species, which might be a weak positive correlation. However, at Venloop where the groundwater levels mostly decreased there was also an increase in the number of present species, which would then indicate a negative correlation between these parameters.

The groundwater quality analysis agrees more with the results on the groundwater levels. At St Annabos the indications of *wijstwater* become more questionable after the measures have been taken. The Van Wirdum diagram shows that the water's origin is increasingly atmocline, the iron concentration decreases and the groundwater levels start to fluctuate more annually, these three results could all be hinting towards more rainwater fed systems. However, there are too few groundwater quality measurements to draw conclusions. This is because of the low frequency of measurements and the inconsistency of the timing of these measurements within a year. Because of this there was no other option than to compare only 6 measurements over time, with only one before the measures and in the months July, December, August, April and March. Shallow groundwater temperatures can be influenced by the air temperature and therefore by seasons. Furthermore, higher temperatures are measured in summer and iron concentration is dependent on this fluctuation in temperature, warmer water can dissolve more iron (Nelson, 2002). It can therefore not be ruled out that almost all of the variation that can be found over time might be explained by the seasonal fluctuation.

For the analysis on the groundwater levels the model PASTAS corrected for the fluctuations of meteorological years in temperature and evapotranspiration. However, this correction was not done for the groundwater quality or ecology. Therefore, the time series on ecology and especially groundwater quality are prone to weather conditions. This makes it difficult to draw conclusions from the data about the effects of the measures.

5 Conclusion

The project area selection at the start of the internship was done based on the inventory of the existing *wijstgebieden*. There were five project areas where measures had been taken prior to this internship, other measures are still in progress. These five project areas did not have the desired data availability, therefore, not all analyses could be conducted for all five project areas. The project areas are St Annabos, Geeneneind, Venloop, Donzel and Graspeel. For these areas we investigated if the *wijst*-restoration measures paid off; did the groundwater levels increase, did the groundwater quality show more signs of *wijstwater* and do we see more flora and fauna species characteristic for *wijst*-areas? Distinguishing the effect of *wijst*-restoration measures has proven difficult because of often few and infrequent measurements that are also often not spanning a long time period.

The groundwater levels have the longest and most frequently measured time series. Both wetter and drier conditions after the measures were found from this data. At St Annabos small differences indicated wetter and drier conditions in close proximity to each other, Geeneneind had mostly wetter conditions after the measures were taken and Venloop had mostly drier conditions after the measures were taken. To what extent these changes can be attributed to the taken measures is difficult to infer, since noise induced by the used analysis can also play a role.

It was not possible to conclude if the taken measures affect the groundwater composition. The groundwater quality measurements were too few and infrequent for that. Only for St Annabos there were locations where the groundwater quality was measured more than once in time. However, at these two locations a comparison before and after measures was difficult because the measurements were done in different months each year. This hampers the comparison, given the seasonal fluctuations in the groundwater composition due to the weather. Also because these seasonal variations are probably bigger than the effect of the taken measures. The groundwater quality time series did show that at St Annabos the measurements done closer to the taken measures showed more signs of *wijstwater* with higher iron and sulphate concentrations and seepage water characteristics in terms of ion balances. This spatial difference between these locations is also found in the groundwater level analysis where the piezometer within the area where the measures were taken showed smaller seasonal fluctuations.

The ecological analysis pointed out that overall the number of present species has been increasing since the measures were taken. However, whether this is due to the taken measures or the similarly changing acreage of nature area within the project area, is hard to conclude.

Drawing conclusions about the effect of the taken measures has proven to be difficult, to be able to draw conclusions about the effects monitoring needs to be improved. Measuring methods where baseline measurements are available and the measurements are done continuously might improve the monitoring of the *wijstgebieden*. Therefore, an advice for the future monitoring has also been included in this report.

6 Monitoring advice

In this internship research the possibilities for monitoring *wijst*-recovery measures have been investigated. The largest obstacle for this monitoring now is to find appropriately long time series of relevant measurements. Only for groundwater levels the time series were often long enough and contained appropriate measurement frequencies. However, for Graspeel not a single groundwater level measurement was done before the measures. The groundwater quality measurements only contained two time series, which were both situated at St Annabos, and these measurements were only done once a year and not in the same season, because of which the seasonal fluctuation has a large effect on these measurements. The ecological analysis is mostly difficult because it solely consisted of observations that are potentially highly biased. Therefore, to monitor the effect of *wijst*-recovery measures it is important to decide at forehand what parameters need to measured, where and how often, and how long before and after taking the measures.

Reeze and Lenssen (2015) have written a global roadmap for brook recovery monitoring. They distinguish seven different steps, that could also be beneficial to follow in a *wijst*-recovery monitoring project:

Step 1: Formulate the project goals

Step 2: Water system analysis (driving forces and important parameters)

Step 3: Decide the scale of the project in space, time and money

Step 4: Formulate the monitoring goals

Step 5: Decide when the project goals have been reached

Step 6: Selection of parameters and measuring methods

Step 7: Monitoring network design

This advice will focus on the two last steps: "Selection of parameters and measuring methods" and "Monitoring network design". However, when setting up a monitoring strategy for a specific *wijst*-recovery project it is important to first go through the first five steps. As these steps determine the shape of the last two steps. For here, the main goal is defined as 'monitoring the effect of *wijst*-recovery measures on groundwater levels, groundwater quality and the occurrence of *wijst*-specific flora and fauna'. Given this goal, some important considerations are given to design step 6 and 7.

Selection of parameters and measuring methods

To monitor the effects of taken restoration measures the right parameters should be measured, this should be done at the right time, time-interval and place and with the right method. Measurements can be done on groundwater levels, groundwater quality and ecology. The measurement frequency and period will be very different between the parameters.

Groundwater levels are likely to react first. They are very sensitive to weather conditions and therefore have to be measured frequently, preferably at a daily basis. The groundwater levels can be measured in piezometers, sometimes these are already available, this possibility should be explored before installing new piezometers. High groundwater levels with low annual fluctuations are a good indicator of *wijst*, to capture this fluctuation the data is best gathered at least once a day. Groundwater level measurements best start 8 years before taking the measures, since this is the best length for training a model on this data and to correct for meteorological years. Often the model can be extrapolated, but the shorter the measurement period, the more likely the model is to perform worse. The same holds true for the measurements after taking the measures: at least 8 years.

Groundwater quality parameters can fluctuate considerably over seasons (Nelson, 2002) (for iron concentration and groundwater temperature variations see Appendix E) and should therefore be measured more than once a year. Four measurements a year might cover the extent of these fluctuations. The important groundwater quality parameters can be chosen more carefully but should definitely have more measurement moments in time. Right now, when measurements have been taken plenty of parameters were measured, but this was often not specified for monitoring the measures. Important parameters for *wijst*-monitoring are iron concentration, sulphate concentration, nickel concentration, phosphate concentration, calcium and chloride concentrations accompanied by electrical conductivity (van Wirdum-diagram) and groundwater temperatures. Groundwater samples to measure can be gathered from the piezometers that also measure the groundwater levels. They should also be measured at least two years before the measures are taken to establish the baseline situation. The groundwater levels influence the groundwater quality parameters. Due to this and because the groundwater levels are advised to be measured for 8 years before and after the measures are taken the same measurement period is advised for the groundwater quality measurements.

For an ecological recovery of a system more time is required than for a hydrological recovery. Revegetation will be the first ecological effect that will become visible, mammals and birds will follow. There is a time lag here due to the time it takes for vegetation to form habitat in the form of tree hollows and fallen branches (Bennett et al., 2009). In wetlands these processes are slightly different for most species, as soon as the hydrological functioning of the system has reached the desired level the more mobile organisms colonize the wetland almost immediately (Moreno-Mateos et al., 2015). However, in project areas where agricultural land has been reformed to a natural wetland the revegetation and regaining the natural functioning of the system is proven to be more difficult compared to other land management types (Moreno-Mateos et al., 2015). This is likely because of the artificially high nutrient pools negatively affecting the new and desired vegetation (Moreno-Mateos et al., 2015). The ecological analysis on monitoring the recovery of *wijstgebieden* should take this into account. Measurements on the mobile *wijst*-indicator species should continue immediately after the measures are taken. Some other species might have a longer lag time before (re-)installing themselves in the area. Therefore observations would be best to be at around 1 year, 5 years and 10 years after the measures are taken. Ecological measurements can be done more structured in the future. Thorough field observations before and after the measures should be done with the same method, to minimize the bias in the observations. The same people could do these observations, in the same time of the year and with the same duration to create observational datasets with the least biases.

Monitoring network design

Important to think about when designing a monitoring network is that the analyses can both be done temporally and spatially (Fig 6.1). When there is a possibility to include a control area (Control-Impact) in the monitoring design and combine this with a before-after analysis this will increase the capability of the monitoring research to conclude about the effect of the taken measures. This Before-After Control-Impact (BACI) design can help draw conclusions about the severity of the changes caused by the measures, as it shows changes that would have occurred due to for example weather anyway. Especially when the effects of the measures are expected to be rather small the BACI approach can be used to differentiate between changes caused by noise or weather and the taken measures. The control area has to be sufficiently similar to the impact area beforehand, otherwise the results after the measures are taken are not reliable (Verdonschot et al., 2020).

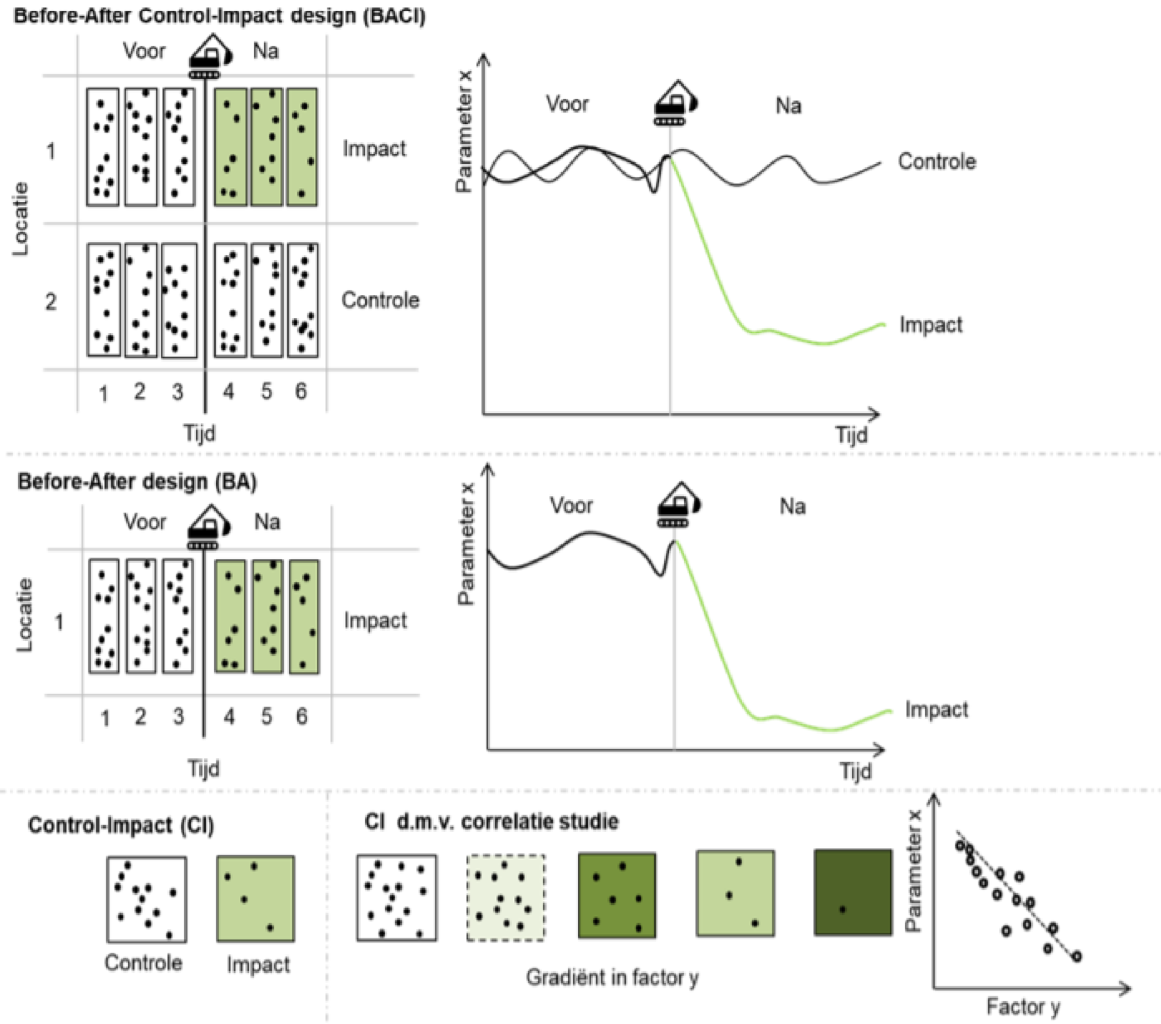


Figure 6.1. Before-After Control-Impact designs realize a monitoring network where both spatial and temporal analyses are possible (Verdonschot et al., 2020)

It is important to know the baseline situation, in order to be able to conclude if measures taken to restore nature are functional and have the intended effect. This needs to be known for groundwater levels, groundwater quality and ecology. Baseline measurements, taken before starting the measurements are critical during the evaluation of the restoration efforts (Ettema & van der Wijst, 2012). When using a BACI (Before-After Control-Impact) design the baseline measurements will have to be done both at the impact and the control site.

Of course, every *wijstgebied* is unique. Therefore monitoring will always remain customised to one area. The variety in possible measures enhances the need for this customisation, since the reaction of the system to a filled up ditch and a raised weir can be different. However, using the same methods and measuring the same parameters makes learning from other project a better possibility (Reeze & Lenssen, 2015). Groundwater levels should be measured with a high spatial density, and are best installed close to the taken measures. The further away the measures have been taken, the harder it becomes to conclude on the reason for potential change. The measurements are best taken not too close to surface waterbodies, to not resemble the surface water levels too much. The groundwater quality measurements can be done on samples taken from the piezometers where the groundwater levels are measured as well. This would make it easier to investigate the conditions at specific locations. Ecological observations would be best to perform multiple times before and multiple times after the measures are taken but especially comparisons between the same time of year are important. To be able to sustain a stable population at least 500 reproducing pairs are necessary (Ettema & van der Wijst, 2012), since all project areas are on the smaller side connecting these areas for the more mobile species might be favourable for the spread and survival of the species. If there are already connected *wijstgebieden* the ecological monitoring can be done in an overarching way to investigate the fitness of these populations.

The text above and the advice given has been summarized in this table accompanied with a short explanation.

Advice	Explanation
Groundwater level measurements best start and continue 8 years before and after the measures	Without a solid baseline situation barely anything can be concluded about the effect of the measures. Therefor starting the measurements early enough is just as important as continuing long enough. The PASTAS model to correct for weather impacts works best with 8 years of data.
Groundwater level measurements at least daily	To capture the fluctuations of the groundwater levels and the fast changes that can be caused by interferences and weather changes the measurements are best done at least once a day.
Groundwater quality measurements best start a best start and continue 8 years before and after the measures	Measurements should be taken at the same moments in a year. They can be done at each available groundwater level measurement point (piezometer). Since the groundwater level measurements are done for 8 years before and after the measures, doing the same for the groundwater quality measurements would be logical. Having these measurements over the same period in time and at the same location would result in the ability to couple these hydrological analyses.
Groundwater quality measurements four times a year	In order to ensure that the groundwater quality parameters are not mostly determined by seasonal fluctuation, this seasonal fluctuation is best to also be monitored. A measurement for each season should help with this influence.
Ecological analysis with baseline measurement	Include baseline measurements for the ecological analysis and perform multiple elaborate analysis in the entire project area before and after the measures are taken.
Consider lag time of ecology and measure multiple times after the measures are taken	Plenty of species will take some time to return to the project areas, ecological monitoring should therefore span multiple years. For example these observations can be done 1 year, 5 years and 10 years after the measures are taken.
Ecological analysis combining project areas	Since a population needs 500 reproducing pairs to be stable (Ettema & van der Wijst, 2012) and most project areas are relatively small the ecological monitoring can span over multiple *wijstgebieden* when there is possibility of migration between them.
When possible include a BACI approach	Improve the monitoring of the *wijstgebieden* by using not only a Before-After analysis but also include a Control-Impact design and choose a suitable control site. This setup allows to distinguish the effect of the measures from other effects by for example weather.

7 References

Anderson, M. P. (2005). Heat as a Ground Water Tracer. *Ground Water*, *43*(6), 951–968. https://doi.org/https://doi.org/10.1111/j.1745-6584.2005.00052.x

Bennett, A. F., Haslem, A., Cheal, D. C., Clarke, M. F., Jones, R. N., Koehn, J. D., Lake, P. S., Lumsden, L. F., Lunt, I. D., MacKey, B. G., Mac Nally, R., Menkhorst, P. W., New, T. R., Newell, G. R., O'Hara, T., Quinn, G. P., Radford, J. Q., Robinson, D., Watson, J. E. M., & Yen, A. L. (2009). Ecological processes: A key element in strategies for nature conservation. *Ecological Management and Restoration*, *10*(3), 192–199. https://doi.org/10.1111/j.1442-8903.2009.00489.x

Bonte, M., & Witjes, G. J. (2007). *Nadere Inventarisatie Wijstgebieden*.

Bonte, Matthijs, Geris, J., van Dijk, H., & Post, V. (2007). Brabantse wijst opnieuw in beeld. *H2O*, *12*.

Burt, T. P., Pinay, G., Matheson, F. E., Haycock, N. E., Butturini, A., Clement, J. C., Danielescu, S., Dowrick, D. J., Hefting, M. M., Hillbricht-Ilkowska, A., & Maitre, V. (2002). Water table fluctuations in the riparian zone: Comparative results from a pan-European experiment. *Journal of Hydrology*, *265*(1–4), 129–148. https://doi.org/10.1016/S0022-1694(02)00102-6

Epting, J., & Huggenberger, P. (2013). Unraveling the heat island effect observed in urban groundwater bodies - Definition of a potential natural state. *Journal of Hydrology*, *501*, 193–204. https://doi.org/10.1016/j.jhydrol.2013.08.002

Ettema, N. (2010). *Vijf wijstreservaten in Noord-Brabant*.

Ettema, N., & van der Wijst, J. (2012). Monitoringsplan Natuurgebied De Maashorst. *Natuur- En Milieuverenigingen De Maashorst, Uden*.

Geertsema, W., Vos, C., Wamelink, W., Baveco, H., & Mol-Dijkstra, J. (2014). *Klimaatverandering en natuur* (Issue november).

Johansen, O. M., Andersen, D. K., Ejrnæs, R., & Pedersen, M. L. (2018). Relations between vegetation and water level in groundwater dependent terrestrial ecosystems (GWDTEs). *Limnologica*, *68*, 130–141. https://doi.org/10.1016/j.limno.2017.01.010

Knotters, M. (n.d.). *Parameters Grondwaterdynamiek*. Retrieved November 19, 2021, from https://www.wur.nl/nl/onderzoek-resultaten/onderzoeksinstituten/environmental-research/faciliteiten-tools/software-en-modellen/grondwaterdynamiek/parameters.htm

Lappere, R., & Blok, K. (2012). *Herstel Brongebied Geneneind*.

Lappere, R. E. (2016). *Monitoring wijstgebied Geneneind*.

Lapperre, R. E., Kasse, C., Bense, V. F., Woolderink, H. A. G., & Van Balen, R. T. (2019). An overview of fault zone permeabilities and groundwater level steps in the Roer Valley Rift System. *Netherlands Journal of Geosciences*, *98*. https://doi.org/10.1017/njg.2019.4

Meuwissen, I. J. M., & Van den Brand, L. (2003). *Brabantse Wijstgronden in Beeld: Inventarisatie en Verkenning van de Aanpak*. 35.

Moreno-Mateos, D., Meli, P., Vara-Rodríguez, M. I., & Aronson, J. (2015). Ecosystem response to interventions: Lessons from restored and created wetland ecosystems. *Journal of Applied Ecology*, *52*(6), 1528–1537. https://doi.org/10.1111/1365-2664.12518

NDFF. (2021). *Nationale Databank Flora en Fauna Uitvoerportaal*. https://www.ndff-ecogrid.nl/uitvoerportaal/secure/index.zul

Nelson, D. (2002). Natural Variations in the Composition of Groundwater Total Dissolved Solids in

Groundwater. *Groundwater Foundation Annual Meeting*, 3–7.

Projectenboek Benutten en herstellen Wijst. (2020).

Projectplan maatregelen wijstherstel Donzel en Graspeel fase 1. (2015).

Reeze, B., & Lenssen, J. (2015). *Handleiding monitoring beekherstel*.

Schot, P. P., Dekker, S. C., & Poot, A. (2004). The dynamic form of rainwater lenses in drained fens. *Journal of Hydrology*, *293*(1–4), 74–84. https://doi.org/10.1016/j.jhydrol.2004.01.009

Spinoni, J., Vogt, J. V., Naumann, G., Barbosa, P., & Dosio, A. (2018). Will drought events become more frequent and severe in Europe? *International Journal of Climatology*, *38*(4), 1718–1736. https://doi.org/10.1002/joc.5291

Streefbeeld Venloop. (2004).

Termaat, T., & Groenendijk, D. (2005). *De gewone bronlibel op de Esperloop: beschermingsplan en gebiedsvisie*.

Tomaz, A., Palma, P., Fialho, S., Lima, A., Alvarenga, P., Potes, M., & Salgado, R. (2020). Spatial and temporal dynamics of irrigation water quality under drought conditions in a large reservoir in Southern Portugal. *Environmental Monitoring and Assessment*, *192*(2). https://doi.org/10.1007/s10661-019-8048-1

van Balen, R. (2009). Maashorst en peelrandbreuk. *Grondboor & Hamer*, *6*, 155–160. http://www.falw.vu/~balr/pubs/PEELRANDBREUK_1-1.pdf

Van den Eertwegh, G., Bartholomeus, R., De Louw, P., Witte, F., Van Dam, J., Van Deijl, D., Hoefsloot, P., Clevers, S., Hendriks, D., Van Huijgevoort, M., Hunink, J., Mulder, N., Pouwels, J., & De Wit, J. (2019). *Droogte in zandgebieden van Zuid-, Midden- en Oost-Nederland*. *september*.

van der Gaast, J. W. J., Massop, H. T. L., & Vroon, H. R. J. (2009). Effecten van klimaatverandering op de watervraag in de Nederlandse groene ruimte : analyse van de waterbeschikbaarheid rekeninghoudend met de freatische grondwaterstand. *Alterra-Rapport;1791*. http://edepot.wur.nl/7870

Van der Hoek, D. (2005). *The effectiveness of restoration measures in species-rich fen meadows De effectiviteit van herstelmaatregelen in blauwgraslanden*.

van der Ploeg, M. J., Appels, W. M., Cirkel, D. G., Oosterwoud, M. R., Witte, J. P. M., & van der Zee, S. E. A. T. M. (2012). Microtopography as a Driving Mechanism for Ecohydrological Processes in Shallow Groundwater Systems. *Vadose Zone Journal*, *11*(3).

van Rens, C. (2009). *Inrichtingsvisie St. Annabos*.

van Zuilichem, H., & Brugmans, B. (2011). *Verkenning grondwaterkwaliteit in Natte Natuurparels in het beheergebied van waterschap Aa ein, Hann Maas*.

Verbeek, G. (n.d.). *Wijs(t)heid is vooruitzien : water bergen in Brabant*.

Verdonschot, R. C. M., Maas, G. J., & Penning, E. (2020). *Monitoringstrategieën voor het meten van de effectiviteit van beekherstelprojecten*.

Wirdum, G. (1991). *Vegetation and hydrology of floating rich-fens*. Universiteit van Amsterdam.

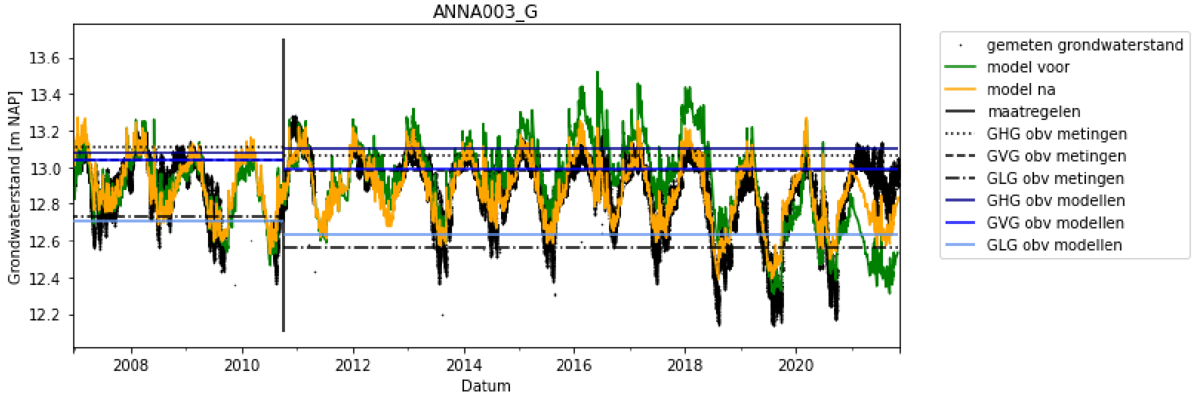
Witjes, T., Tünnissen, T., Rooijakkers, J., Kits, M., & Melisie, E. (2016). *Inrichtingsplan Venloop*.

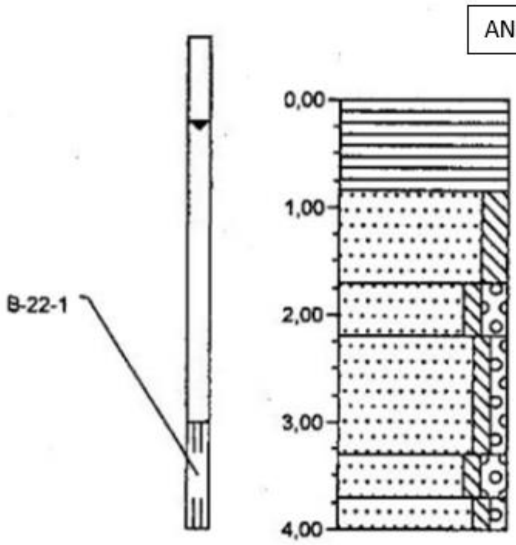
Appendix A: Inventory of the assembled information on the *wijstgebieden* in the management area of the water authority

nr	Porject area	Size (ha)	Status			Year of executio	Goal	Availability data			coordinates
			Executed	in progress	planning			Ecology	Groundwater quality	Groundwater quantity	
1	st Annabos	14.5 / 77.3	x	x		2008-2011	Nature	x	x	x	5,5897713°E 51,6636097°N
2	Esperloop	0.7 / 90	x	x		2014/2015 + 202:	Nature / ecological	x	x	x	5,7303112°E 51,5210609°N
3	Peelvenen	20		x		2021/2022	Peat recovery	x	x	x	5,8651978°E 51,3836606°N
4	Landerd Hooge F	geen vorm file aan		x							5,7000308°E 51,7109305°N
5	Donzel	14.5	x	x		2016	Ecological connecti	x		x	5,5418782°E 51,7177432°N
6	De Berkt	3.6			x	2019					5,5011234°E 51,7166629°N
7	Nistelrode- Heu	2.2			x	2019-2021	Nature	x			5,5490585°E 51,7045152°N
8	Meerkensloop	~100			x		Ecological connection				5,6353389°E 51,6270492°N
9	Zeeland	5.7	x	x		2005 + 2016	Nature (forest)	x	x	x	5,6890702°E 51,6972353°N
10	Kooldert	24 / 15.5			x		Nature (grassland)	x			5,6268423°E 51,6359257°N
11	Kievitweg Wilge	2.65			x		Nature	x			5,8027230°E 51,4861881°N
12	Bus Nistelrode	1.5			x		Nature	x			5,5946371°E 51,6987009°N
13	Waterparkeren I	17			x			x			5,6941906°E 51,6646401°N
14	De Burgt	geen vorm f			x		Residential area with park			x	5,6803376°E 51,6077191°N
B3	Venloop	~216	x			2016	Nature	x		x	5,6140808°E 51,6957505°N

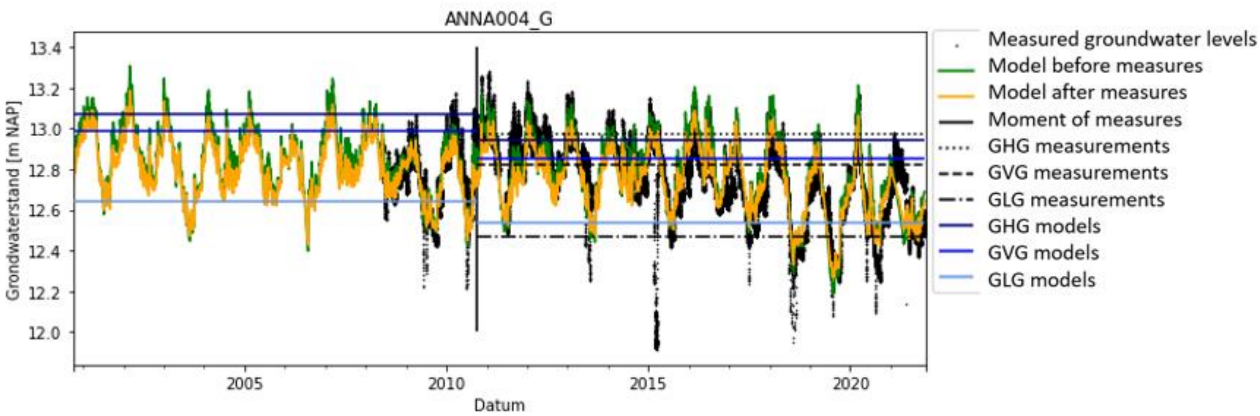
Appendix B: PASTAS models with soil profiles

St Annabos





0,00: Peat, mineral poor, brown
0,65: Very fine sands, moderately silty, moderately peaty, grey
1,70: Moderately fine sands, faintly silty, moderately gravelly, grey
2,20: Moderately find sands, faintly silty, faintly gravelly, dark grey
3,30: Moderately fine sands, faintly silty, moderately gravelly, grey
3,70: Moderately fine sands, faintly silty, faintly gravelly, grey



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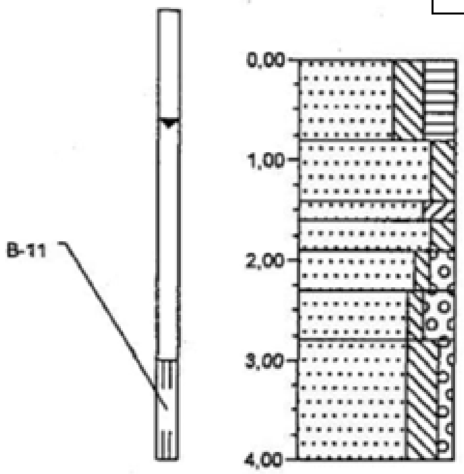
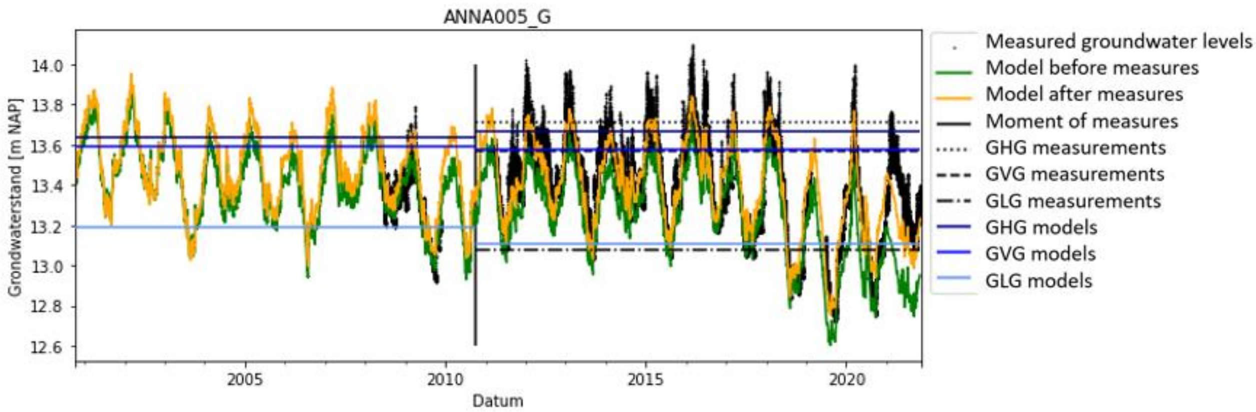


0,00: Very fine sands, very silty and humus rich, faintly rooted, black
0,80: Very fine sands, moderately silty, moderately rusty, light brown
1,40: Very fine sands, clayey, moderately peaty, brown
1,60: Very find sands, moderately silty, faintly rusty, grey
1,90: Very fine sands, faintly silty, moderately gravelly, grey
2,30: Moderately fine sands, faintly silty, very gravelly, grey
2,80: Very fine sands, very silty, faintly gravelly, clay lumps, grey



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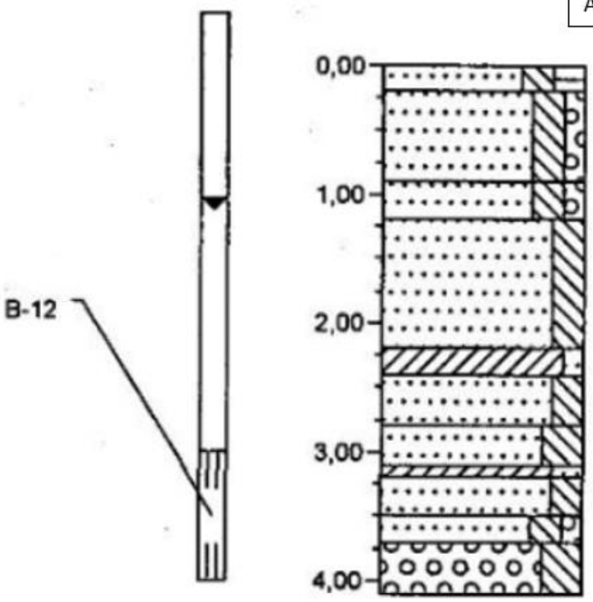
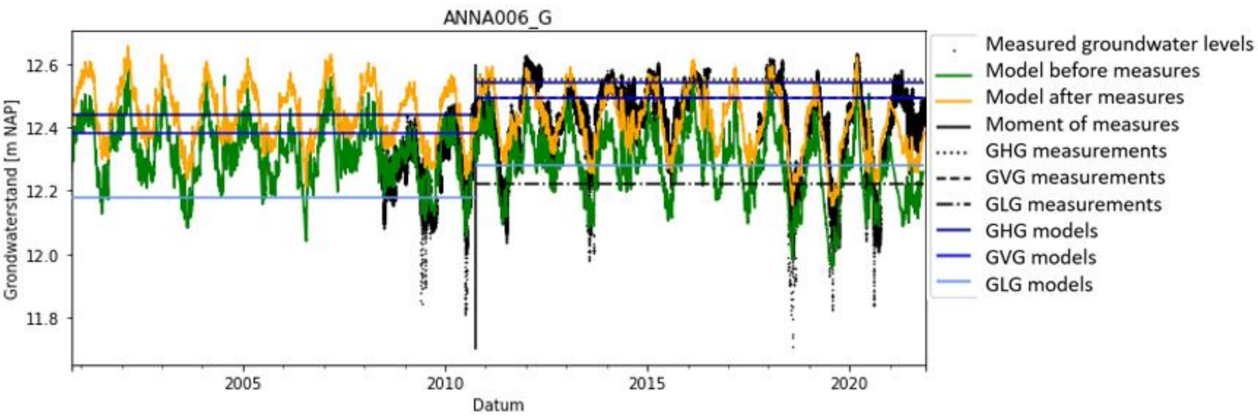


0,00: Very fine sands, moderately silty and humus rich, black
0,20: Very fine sands, moderately silty, faintly gravelly, black
0,90: Very fine sands, moderately silty, faintly gravelly, grey
1,20: Very find sands, moderately silty, grey
2,20: Clay, faintly sandy, grey
2,40: Very fine sands, moderately silty, faintly rusty, brown-grey
2,80: Very fine sands, very silty, grey
3,10: Clay, moderately sandy, grey
3,20: Moderately fine sands, moderately silty, moderately rusty, yellow-brown
3,50: Moderately fine sands, moderately silty, faintly gravelly, grey
3,70: Fine gravel, silty, grey



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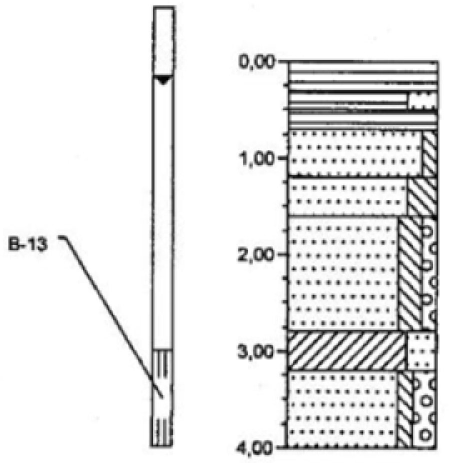
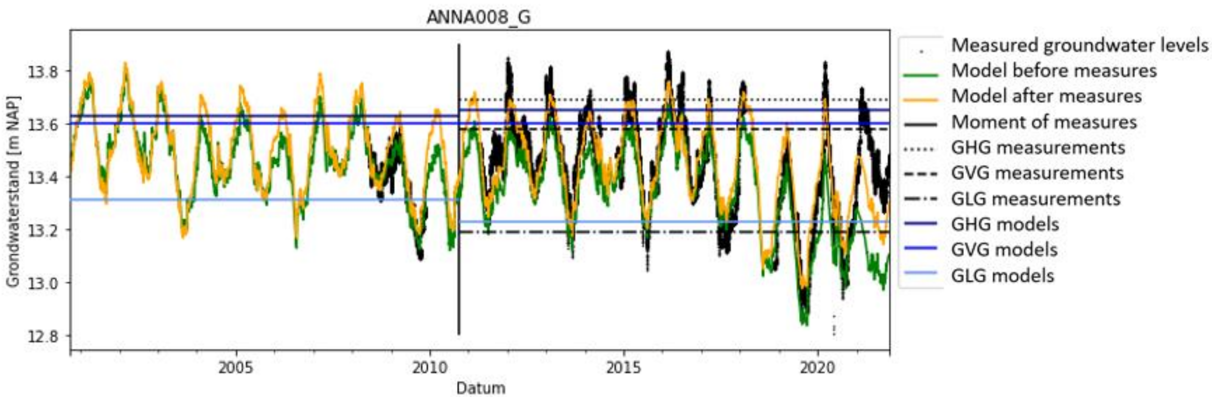
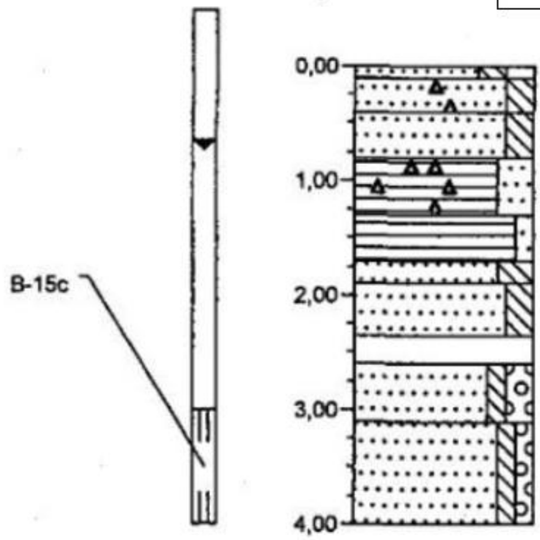


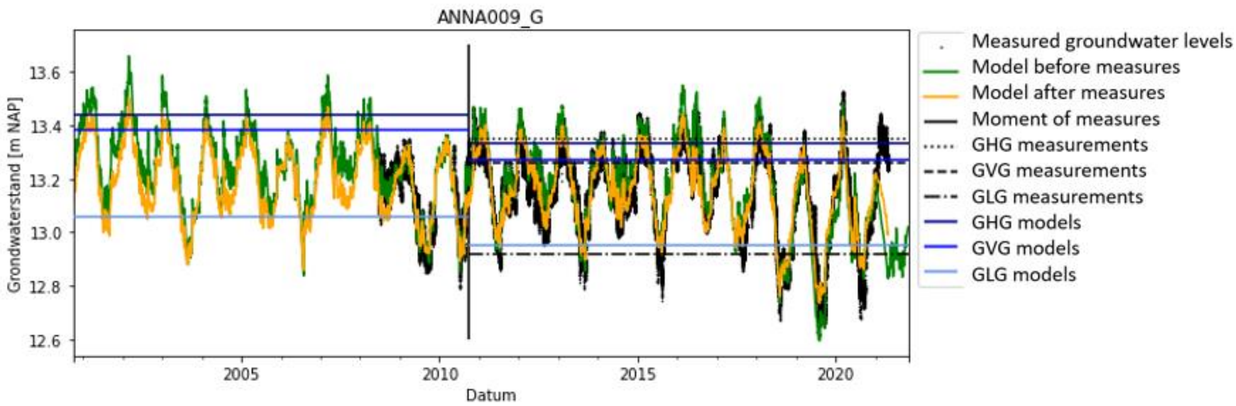
0,00: Peat, mineral poor, strongly rooted, brown
0,30: Peat, strongly sandy, moderately rooted, grey
0,50: Peat, mineral poor, moderately rooted, black
0,70: Moderately fine sands, faintly silty, moderately peaty, moderately rooted, light brown
1,20: Moderately fine sands, strongly silty, grey
1,80: Moderately fine sands, moderately silty, faintly gravelly, grey
2,80: Strongly sandy clay, dark grey
3,20: Moderately coarse sand, strongly silty, moderately gravelly, grey



ANNA008_G



0,00: Very fine sands, moderately silty and humus rich, black
0,10: Very fine sands, moderately silty, faintly gravelly, black
0,40: Very fine sands, moderately silty, black-grey
0,80: Very sandy peat, moderately silty, faintly gravelly, faintly woody, black
1,30: Faintly sandy peat, dark brown
1,70: Very fine sands, very silty, faintly woody, black-grey
1,90: Very fine sands, moderately silty, grey
2,35: Wood
2,60: Very fine sands, faintly silty, moderately gravelly, grey
3,10: Very fine sands, moderately silty, moderately gravelly, grey



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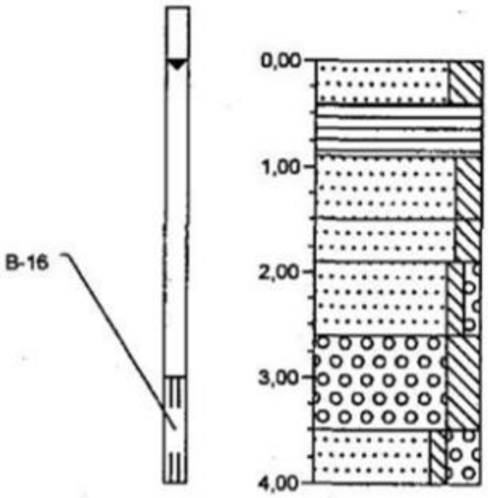
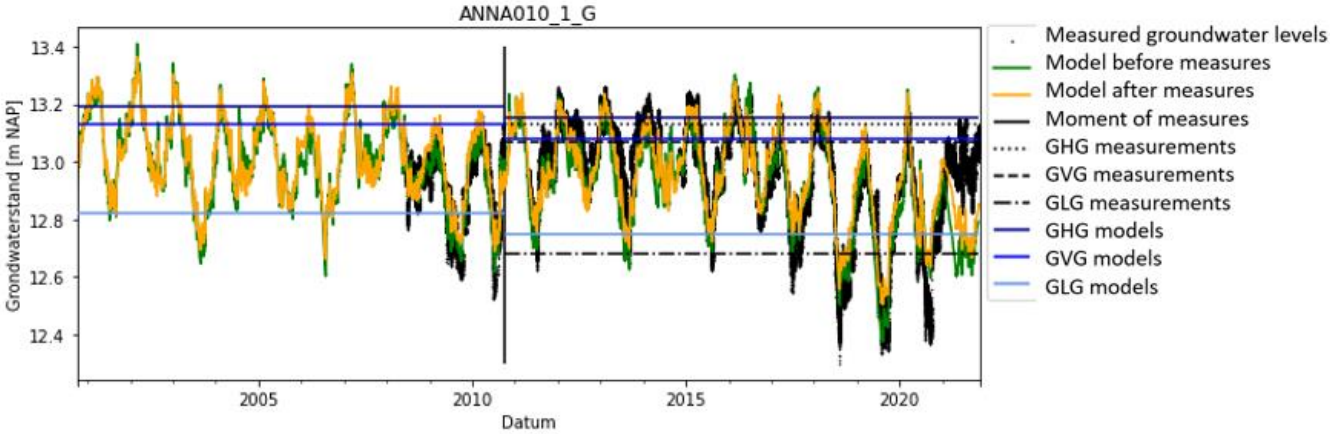
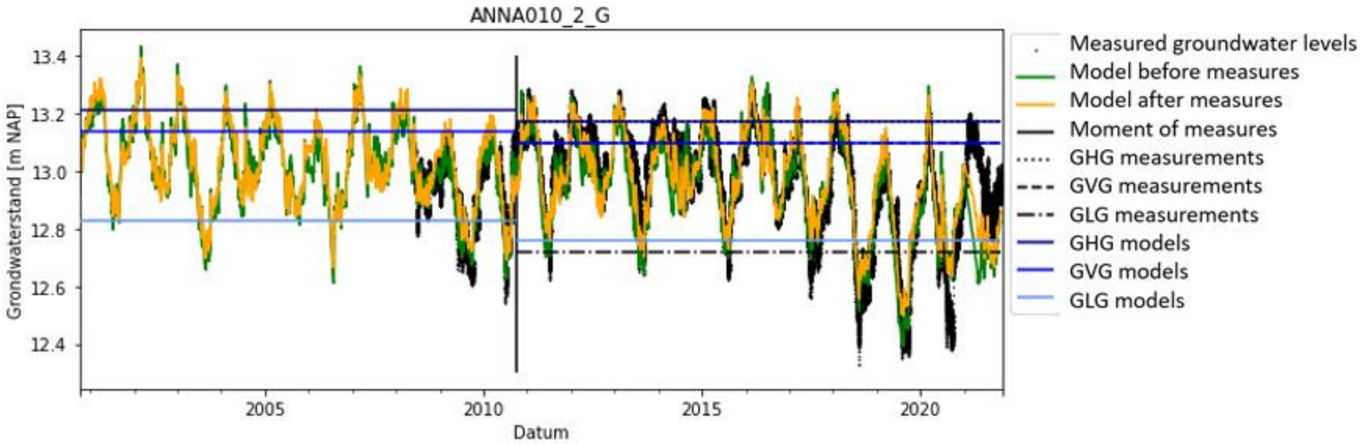
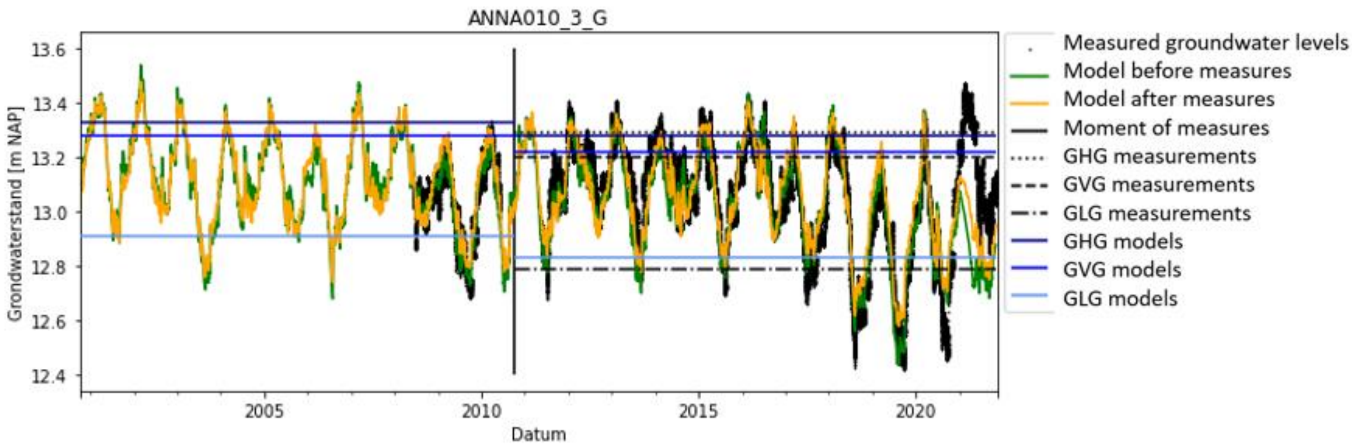
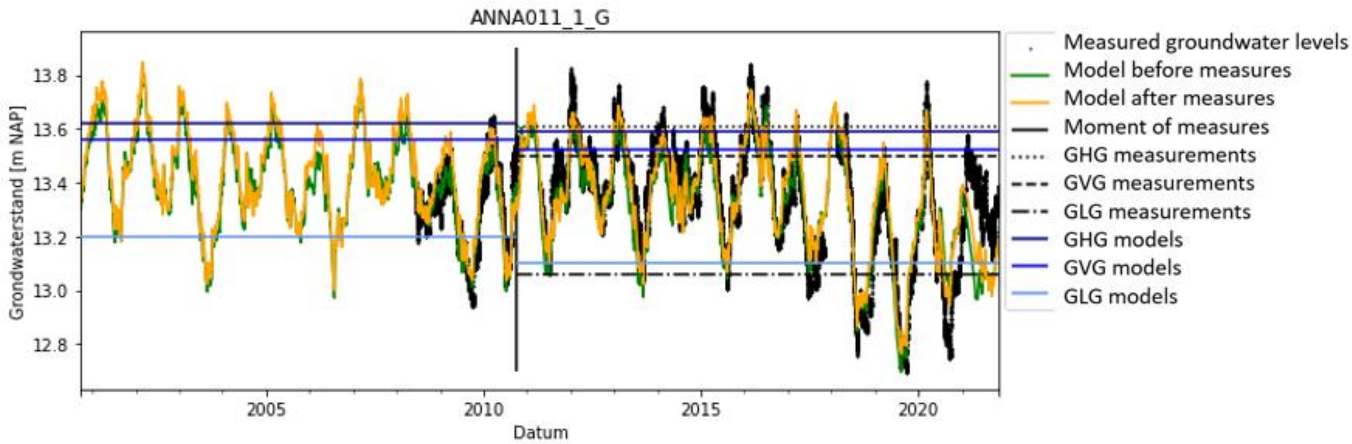


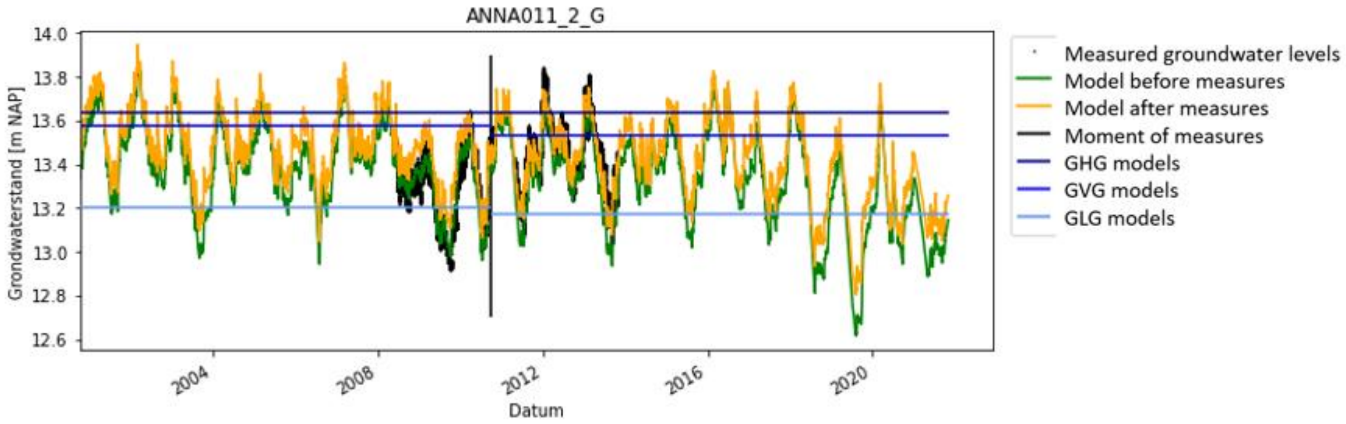
0,00: Very fine sands, very silt, very peaty, brown
0,40: Peat, mineral poor, brown
0,90: Very fine sands, moderately silty, moderately rusty, moderately woody, faintly rooted, grey
1,50: Very fine sands, moderately silty, moderately rusty, grey
1,90: Very fine sands, faintly silty, faintly gravelly, grey
2,60: Fine gravel, silty, grey
3,50: Moderately course sands, faintly silty, very gravelly, grey


ANNA010_1_G
Grondwaterstand [m NAP]
Datum
Measured groundwater levels
Model before measures
Model after measures
Moment of measures
GHG measurements
GVG measurements
GLG measurements
GHG models
GVG models
GLG models


ANNA010_2_G
Grondwaterstand [m NAP]
Datum
Measured groundwater levels
Model before measures
Model after measures
Moment of measures
GHG measurements
GVG measurements
GLG measurements
GHG models
GVG models
GLG models


ANNA010_3_G
Grondwaterstand [m NAP]
Datum
Measured groundwater levels
Model before measures
Model after measures
Moment of measures
GHG measurements
GVG measurements
GLG measurements
GHG models
GVG models
GLG models


ANNA011_1_G
Grondwaterstand [m NAP]
Datum
Measured groundwater levels
Model before measures
Model after measures
Moment of measures
GHG measurements
GVG measurements
GLG measurements
GHG models
GVG models
GLG models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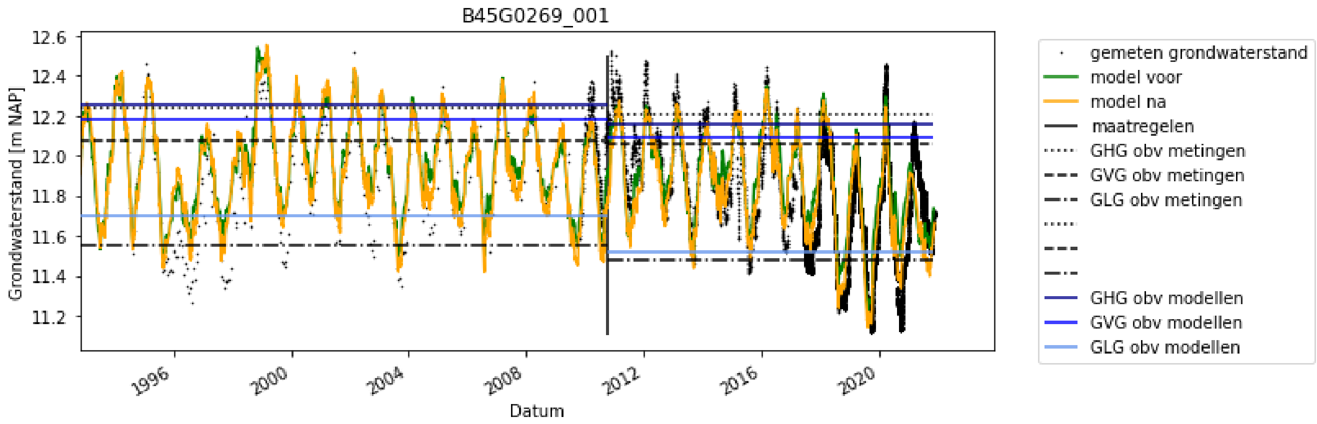
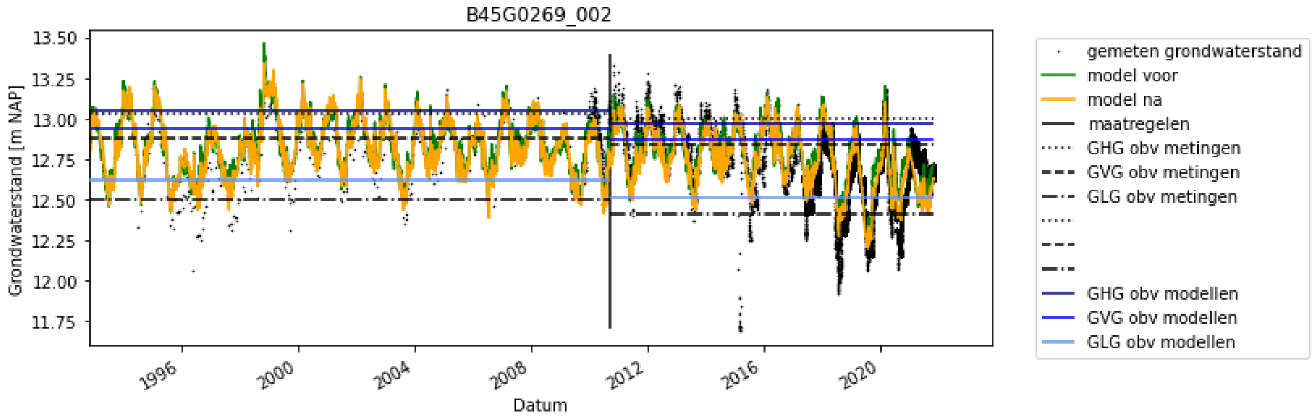
Datum
Measured groundwater levels
Model before measures
Model after measures
Moment of measures
GHG models
GVG models
GLG models


B45G0269_001
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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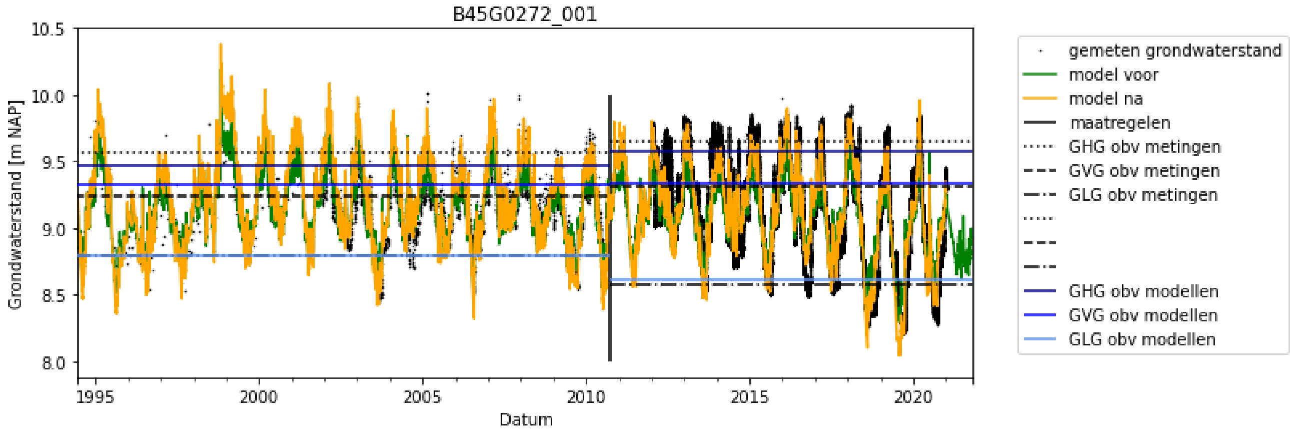
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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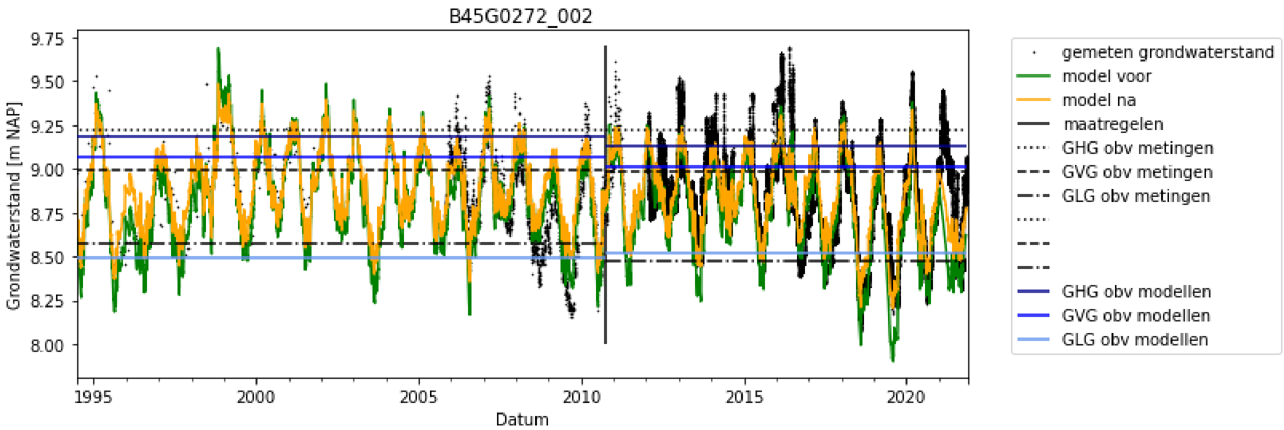
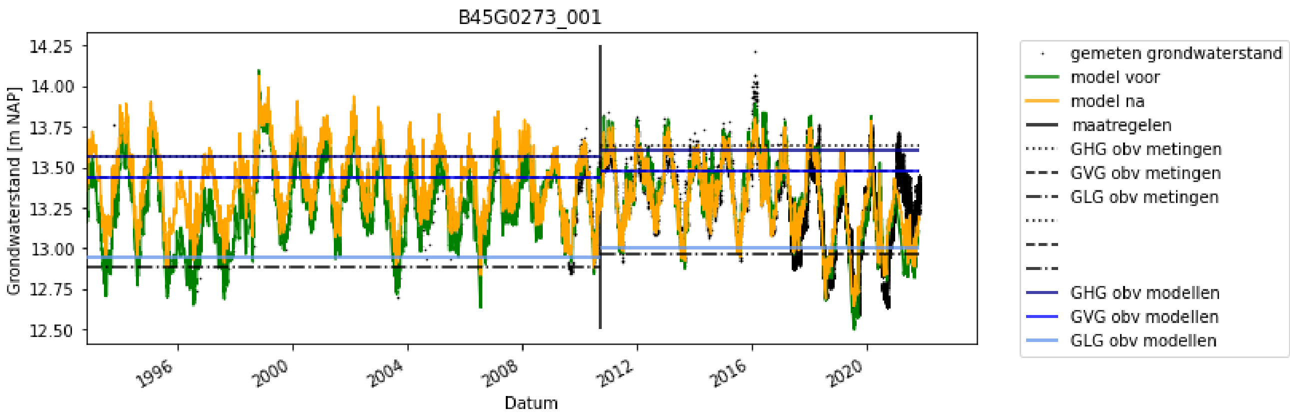
Grondwaterstand [m NAP]
10.5
10.0
9.5
9.0
8.5
8.0
1995
2000
2005
2010
2015
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


B45G0272_002
Grondwaterstand [m NAP]
9.75
9.50
9.25
9.00
8.75
8.50
8.25
8.00
1995
2000
2005
2010
2015
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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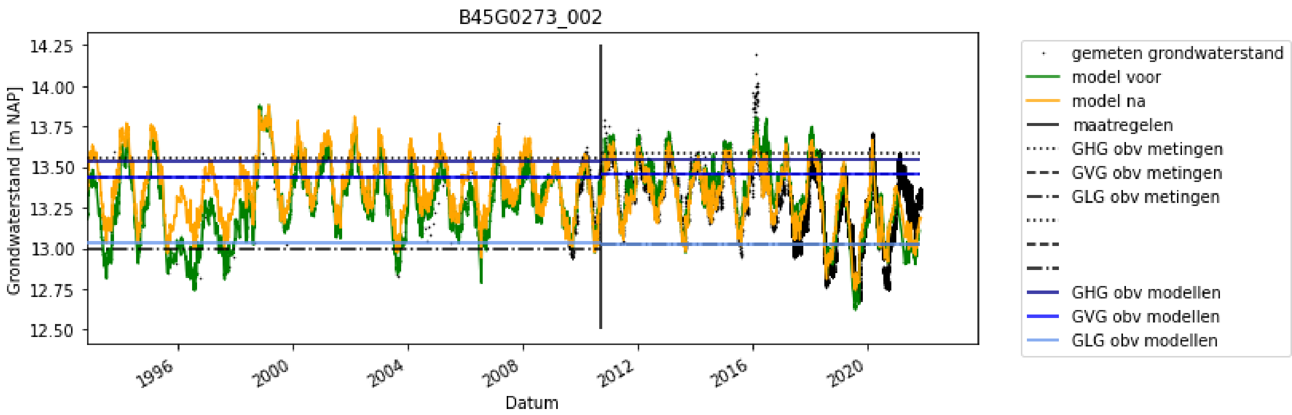
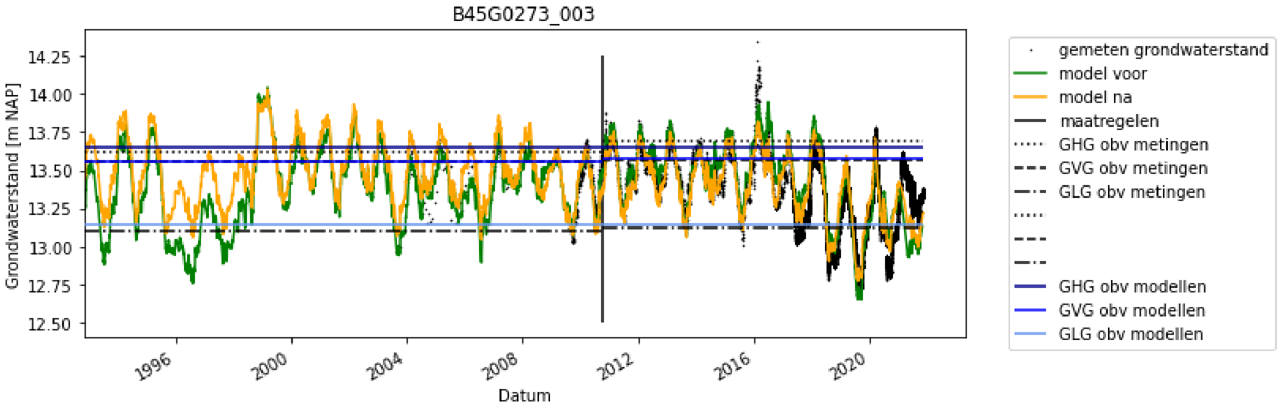
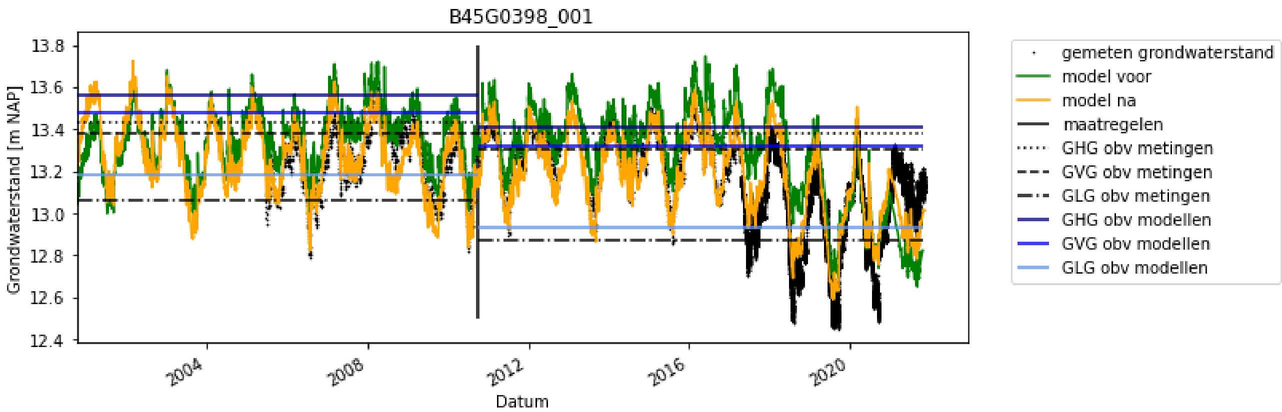
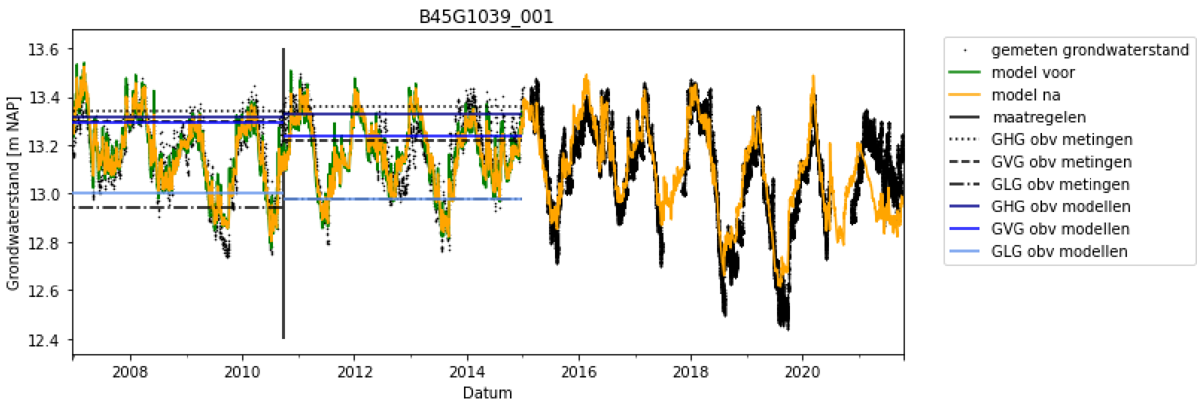
Grondwaterstand [m NAP]
14.25
14.00
13.75
13.50
13.25
13.00
12.75
12.50
1996
2000
2004
2008
2012
2016
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen

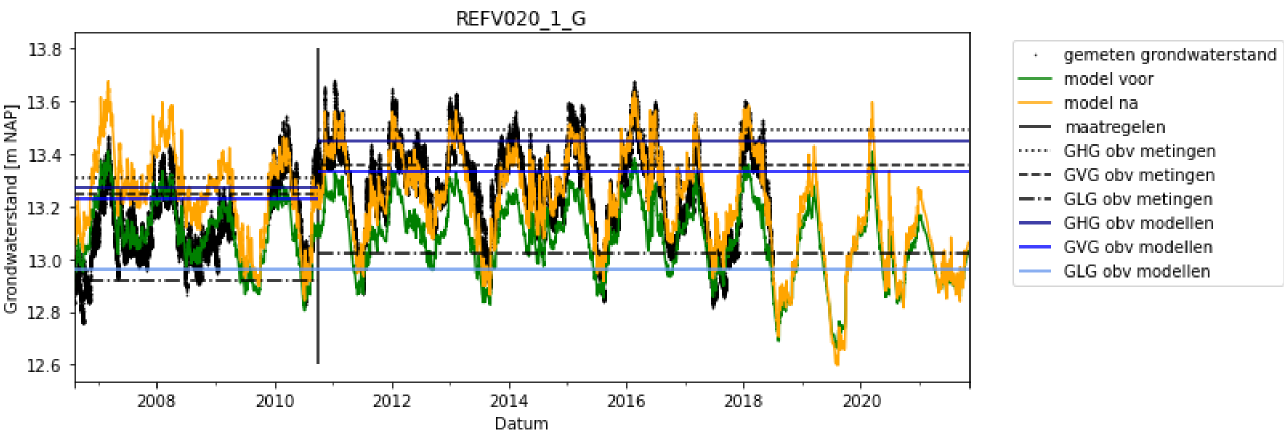

B45G0273_002
Grondwaterstand [m NAP]
14.25
14.00
13.75
13.50
13.25
13.00
12.75
12.50
1996
2000
2004
2008
2012
2016
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen

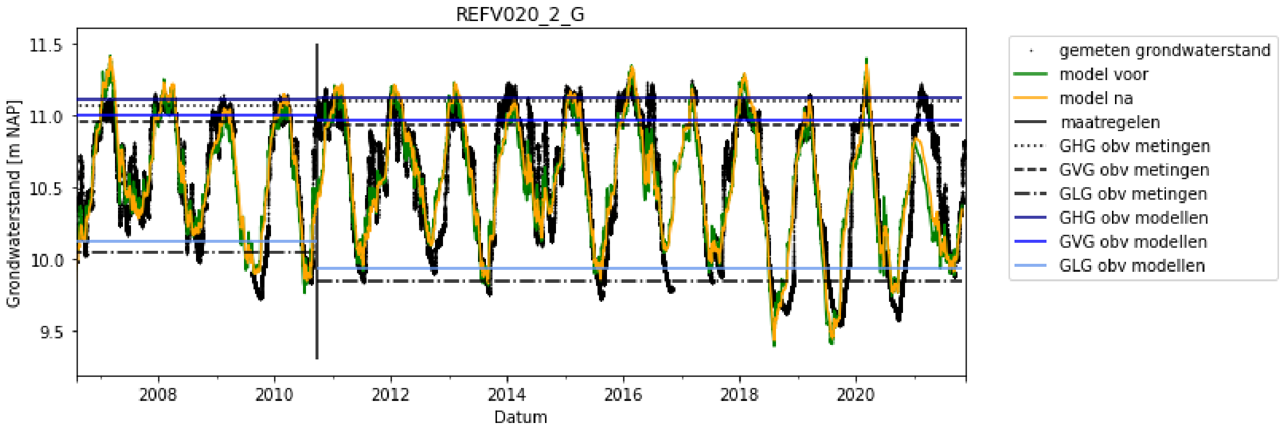




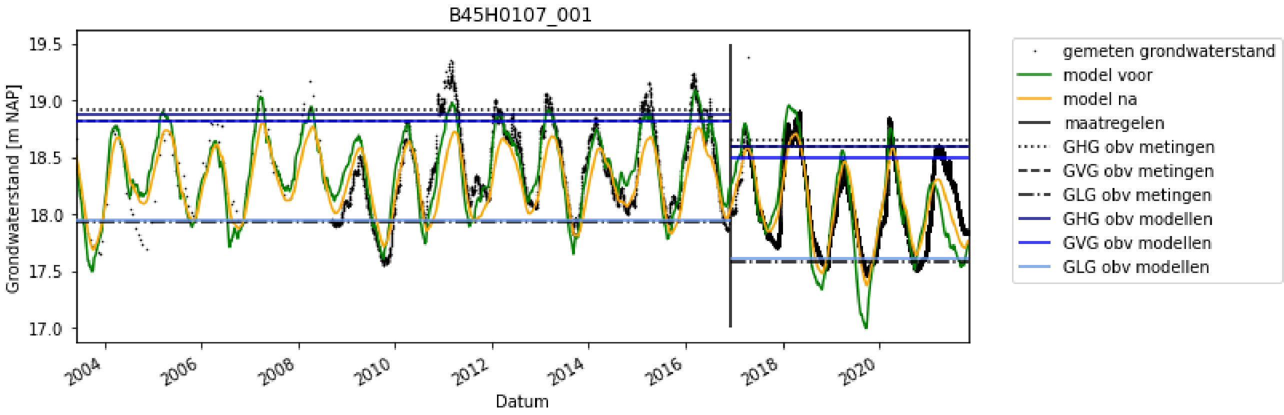


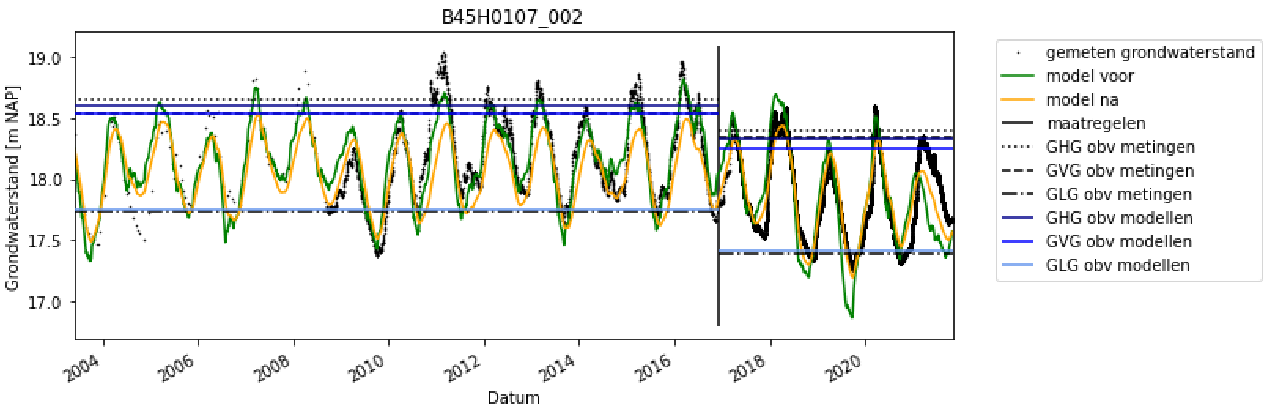
The model before measures showed a strange disruption from 2015 onward, therefore this was left out.




REFV020_2_G
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen

Venloop


B45H0107_001
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


B45H0107_002
Grondwaterstand [m NAP]
Datum
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model voor
model na
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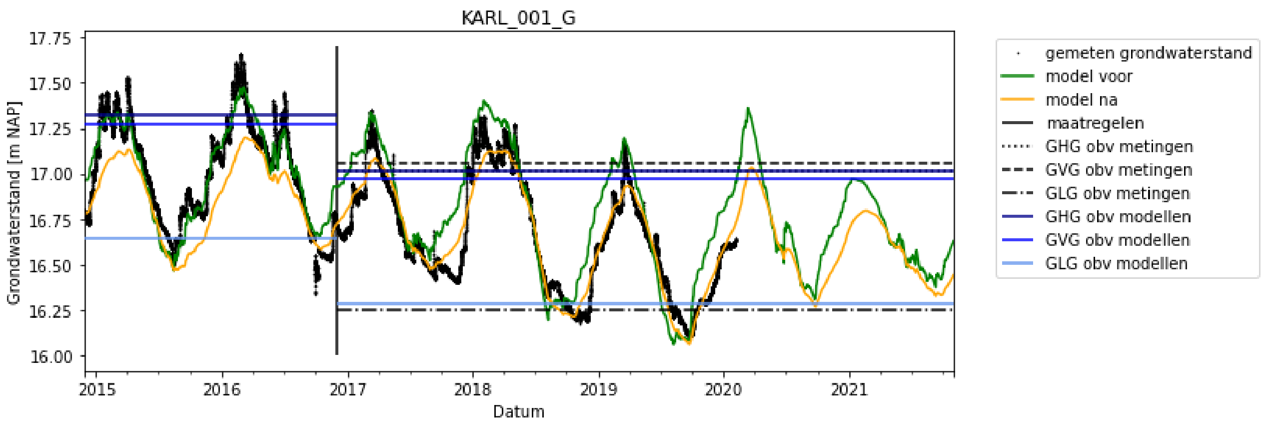
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


KARL_001_G
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
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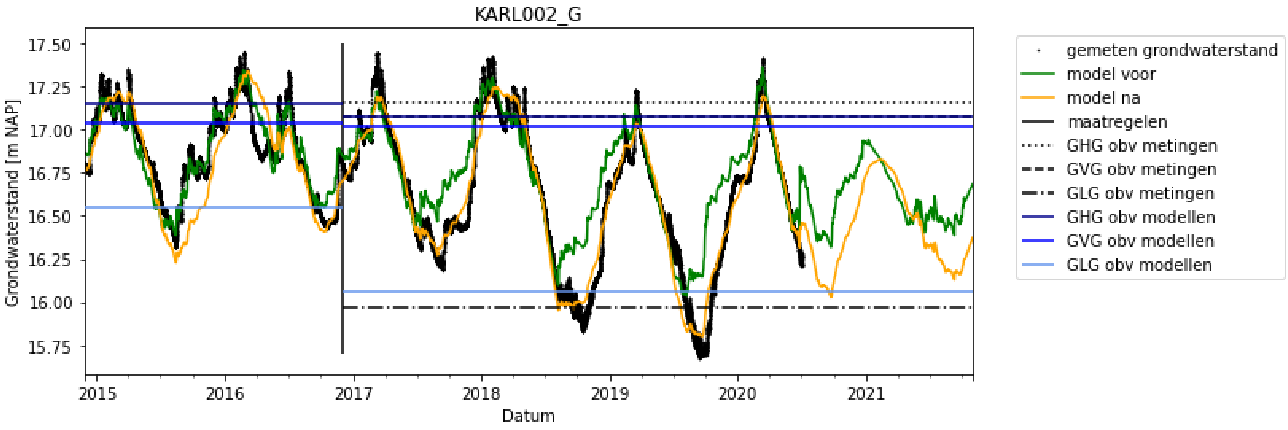
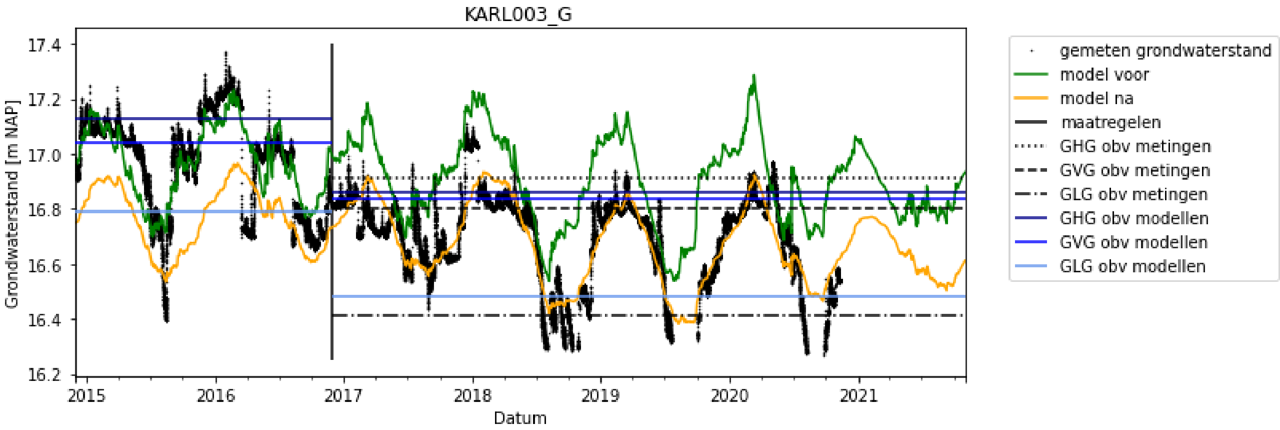
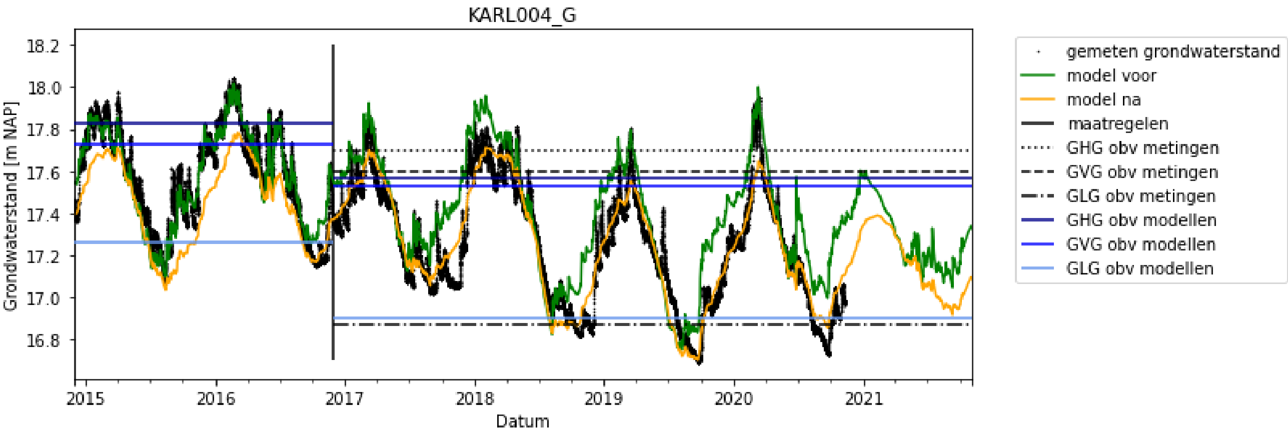
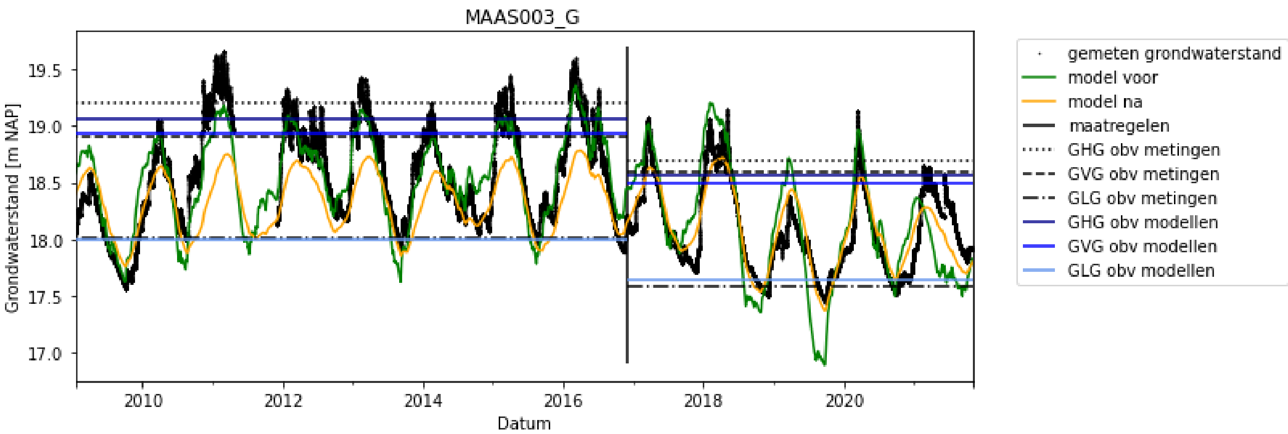
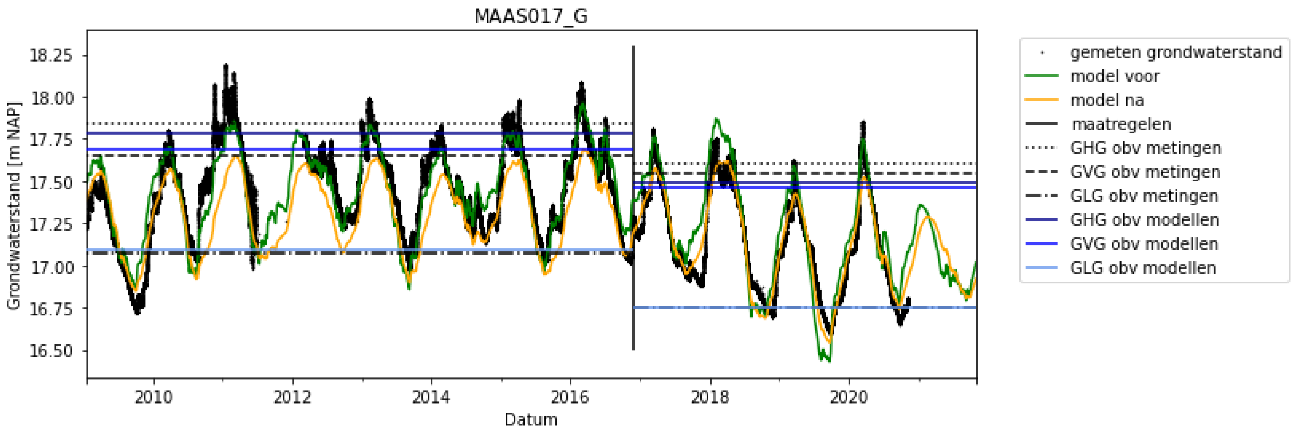
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen

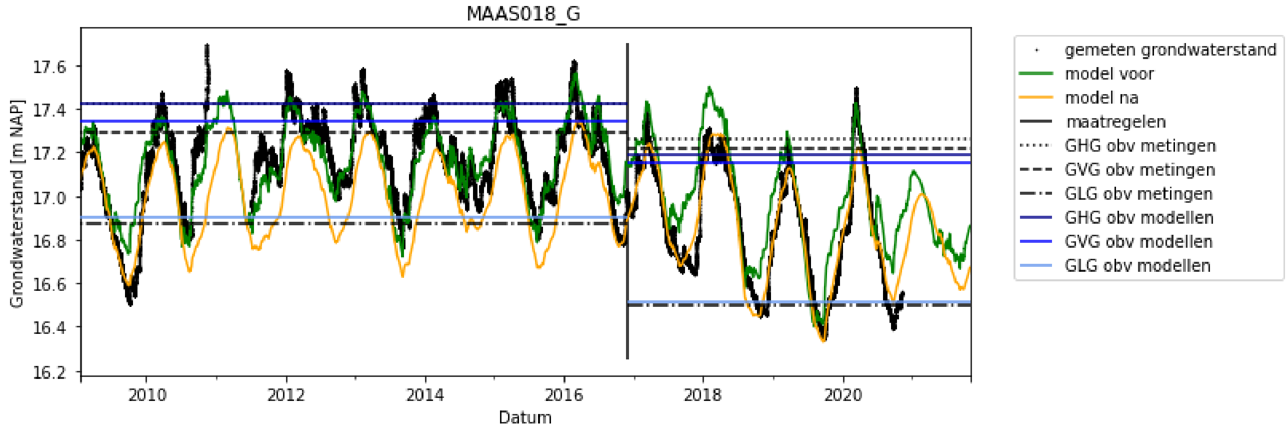

KARL002_G
Grondwaterstand [m NAP]
Datum
17.50
17.25
17.00
16.75
16.50
16.25
16.00
15.75
2015
2016
2017
2018
2019
2020
2021
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen

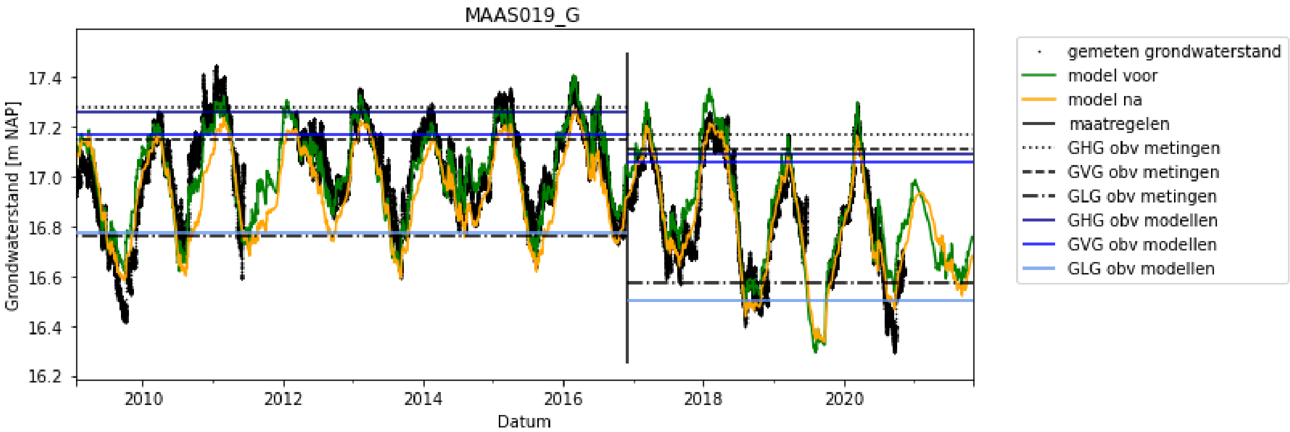

KARL003_G
Grondwaterstand [m NAP]
Datum
17.4
17.2
17.0
16.8
16.6
16.4
16.2
2015
2016
2017
2018
2019
2020
2021
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


KARL004_G
Grondwaterstand [m NAP]
Datum
18.2
18.0
17.8
17.6
17.4
17.2
17.0
16.8
2015
2016
2017
2018
2019
2020
2021
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


MAAS003_G
Grondwaterstand [m NAP]
Datum
19.5
19.0
18.5
18.0
17.5
17.0
2010
2012
2014
2016
2018
2020
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


MAAS017_G
Grondwaterstand [m NAP]
18.25
18.00
17.75
17.50
17.25
17.00
16.75
16.50
2010
2012
2014
2016
2018
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


MAAS018_G
Grondwaterstand [m NAP]
17.6
17.4
17.2
17.0
16.8
16.6
16.4
16.2
2010
2012
2014
2016
2018
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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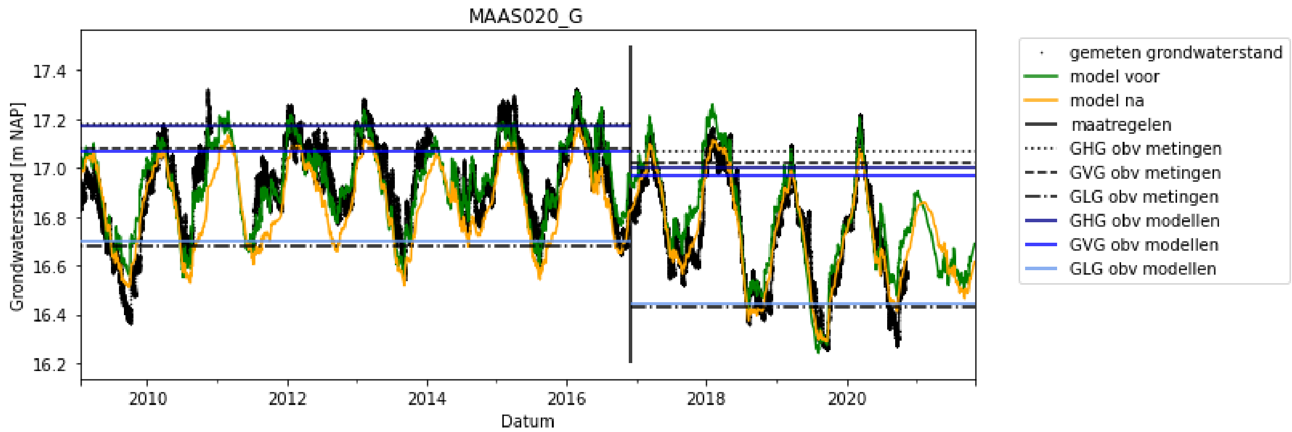
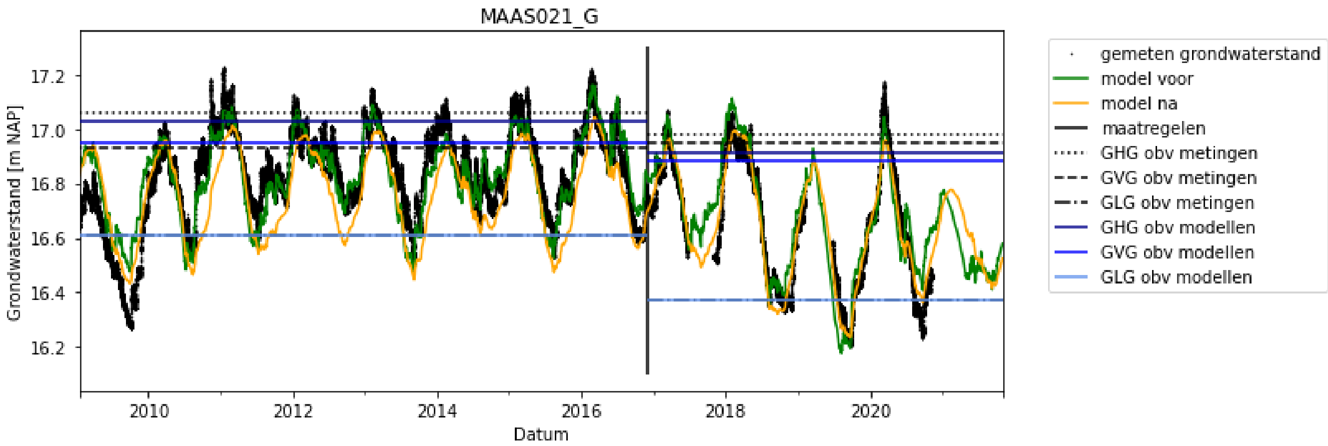
Grondwaterstand [m NAP]
17.4
17.2
17.0
16.8
16.6
16.4
16.2
2010
2012
2014
2016
2018
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


MAAS020_G
Grondwaterstand [m NAP]
17.4
17.2
17.0
16.8
16.6
16.4
16.2
2010
2012
2014
2016
2018
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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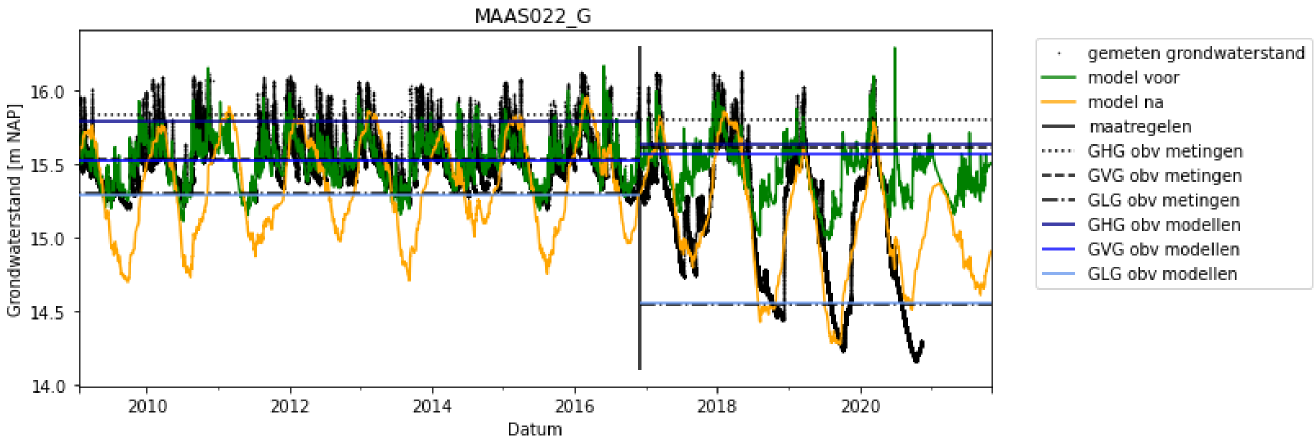
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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Grondwaterstand [m NAP]
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gemeten grondwaterstand
model voor
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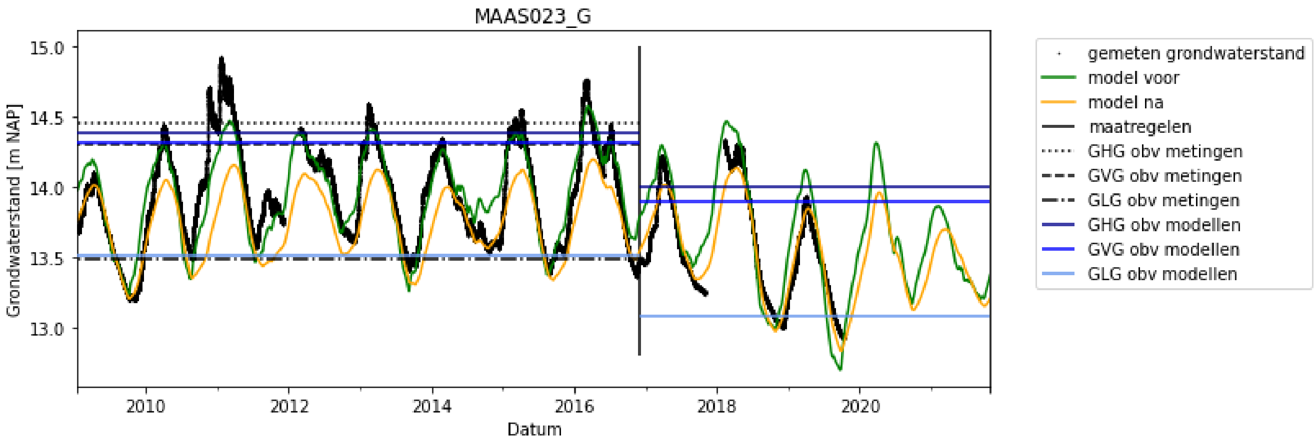
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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Datum
gemeten grondwaterstand
model voor
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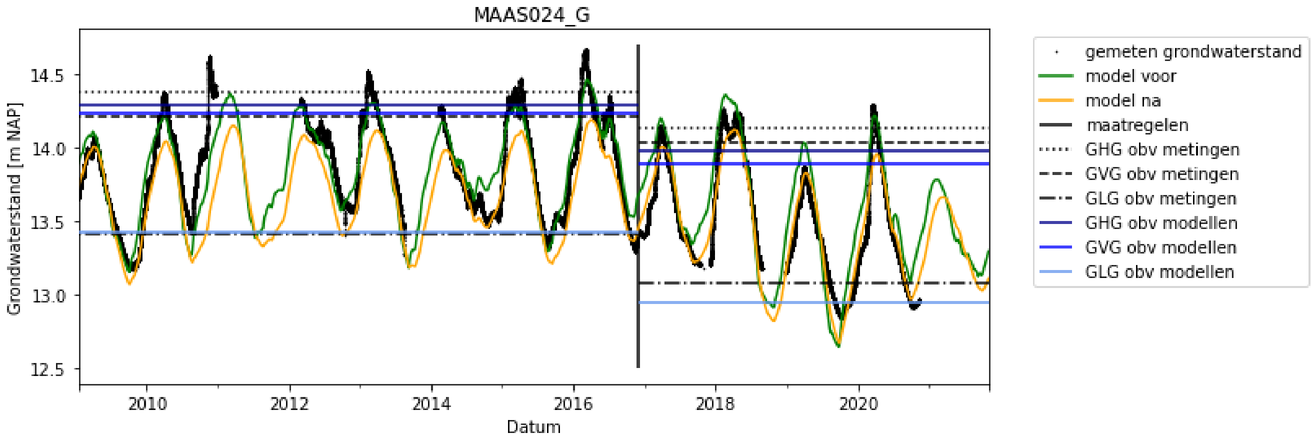
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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Datum
gemeten grondwaterstand
model voor
model na
maatregelen
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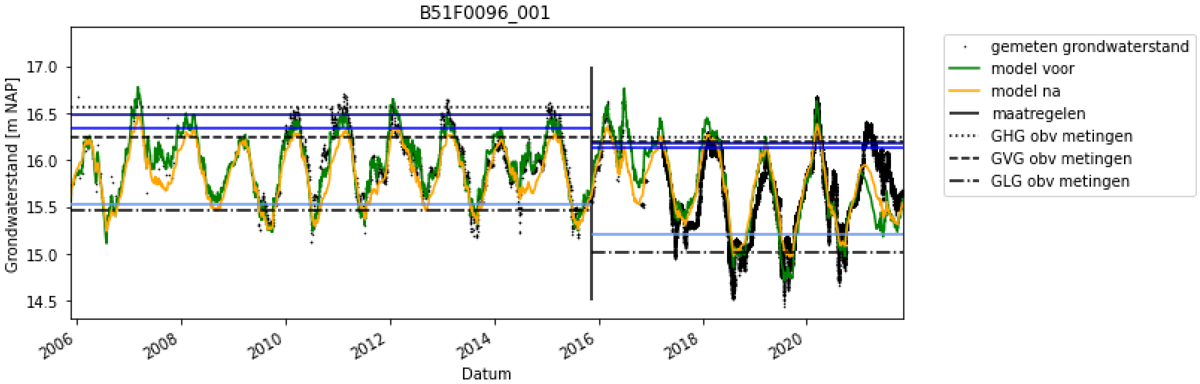
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen

Geeneneind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model na
maatregelen
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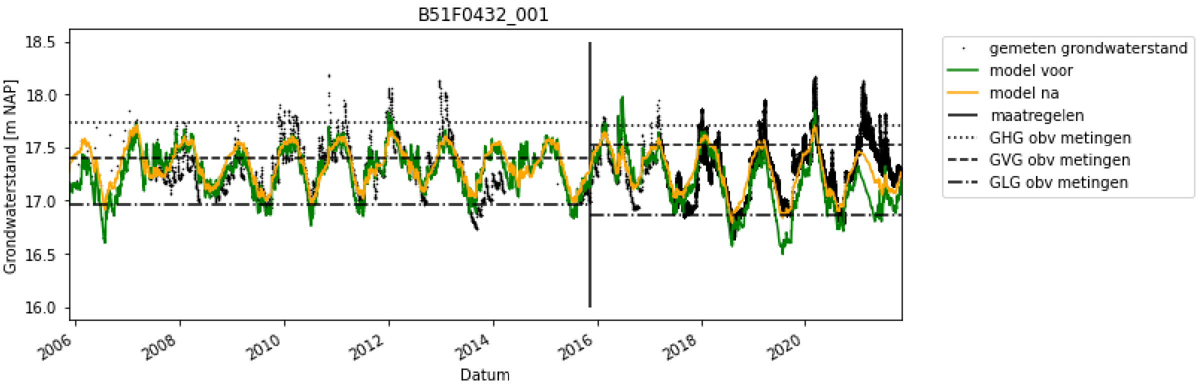
GLG obv metingen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model na
maatregelen
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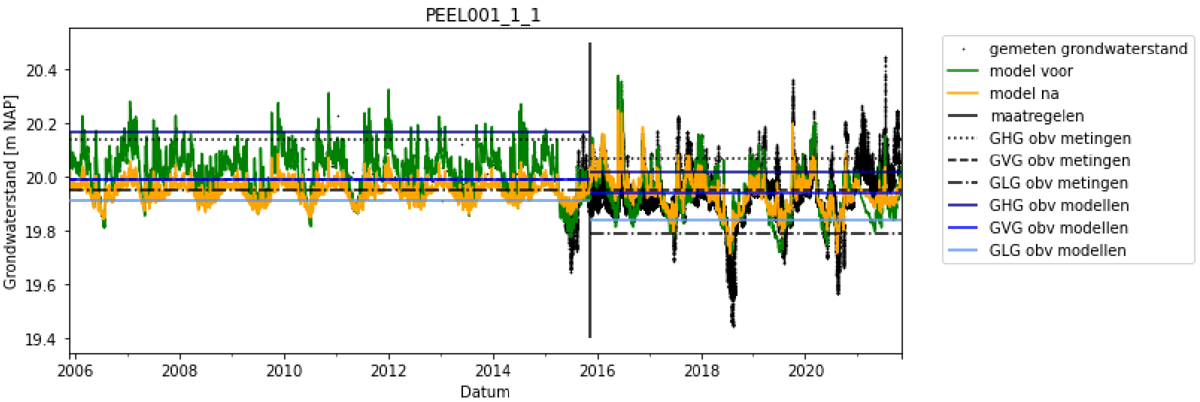
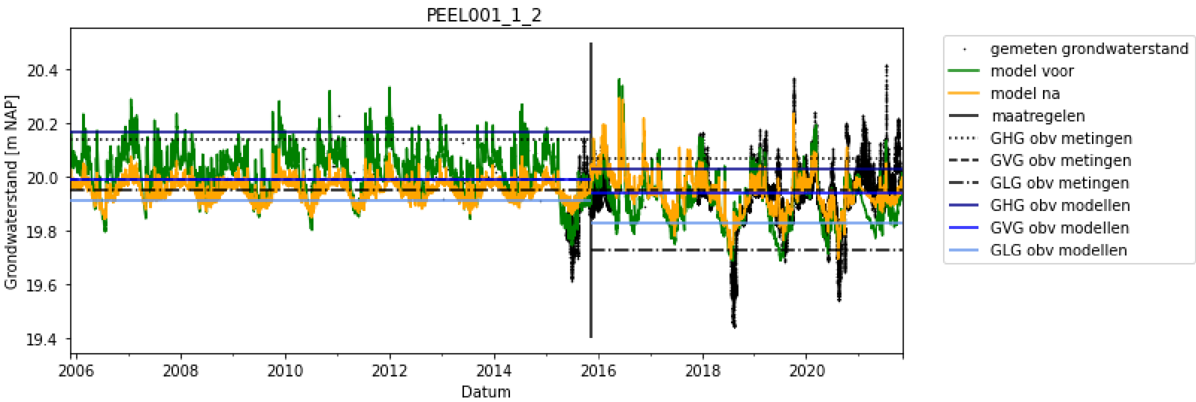
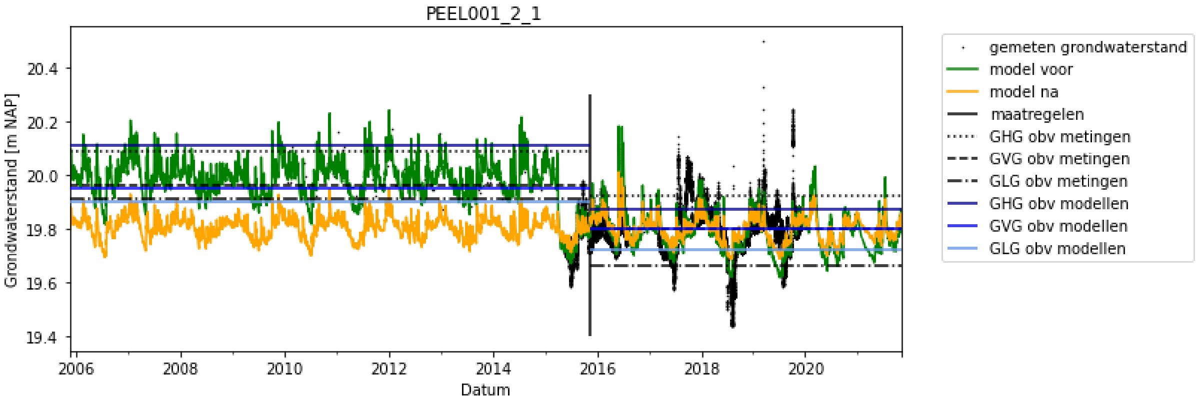
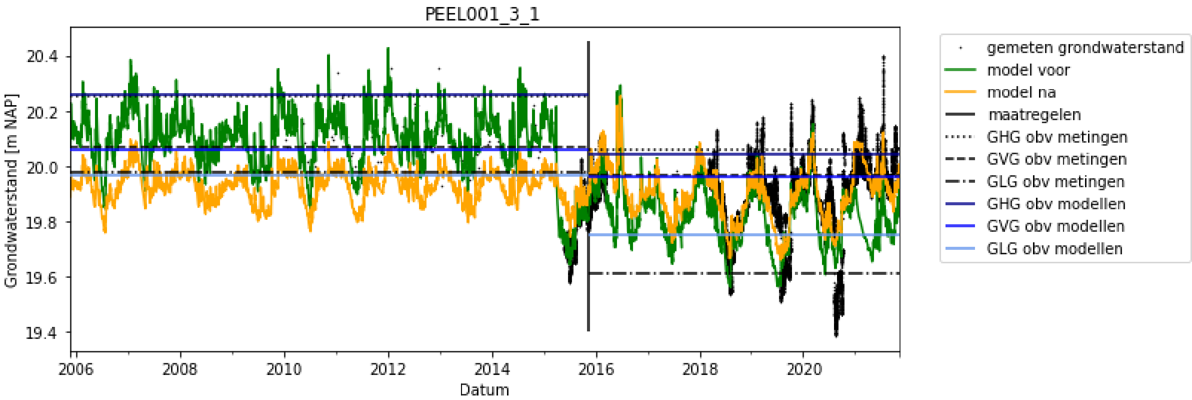
GLG obv metingen


PEEL001_1_1
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL001_1_2
Grondwaterstand [m NAP]
20.4
20.2
20.0
19.8
19.6
19.4
2006
2008
2010
2012
2014
2016
2018
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL001_2_1
Grondwaterstand [m NAP]
20.4
20.2
20.0
19.8
19.6
19.4
2006
2008
2010
2012
2014
2016
2018
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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Grondwaterstand [m NAP]
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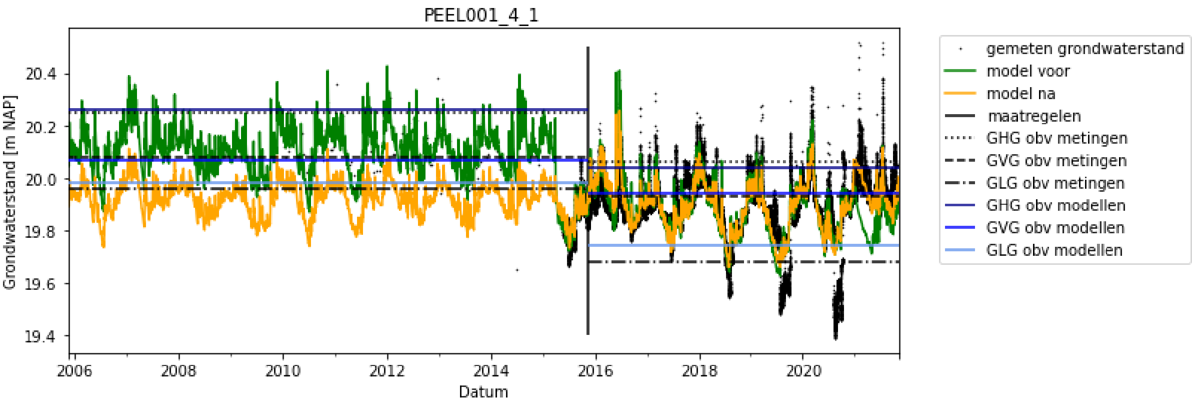
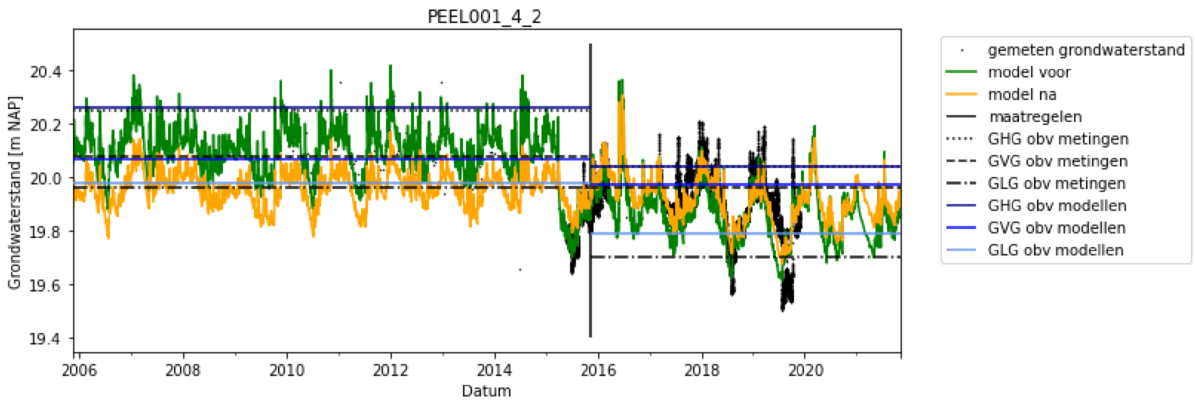
20.0
19.8
19.6
19.4
2006
2008
2010
2012
2014
2016
2018
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL001_4_1
Grondwaterstand [m NAP]
20.4
20.2
20.0
19.8
19.6
19.4
2006
2008
2010
2012
2014
2016
2018
2020
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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Grondwaterstand [m NAP]
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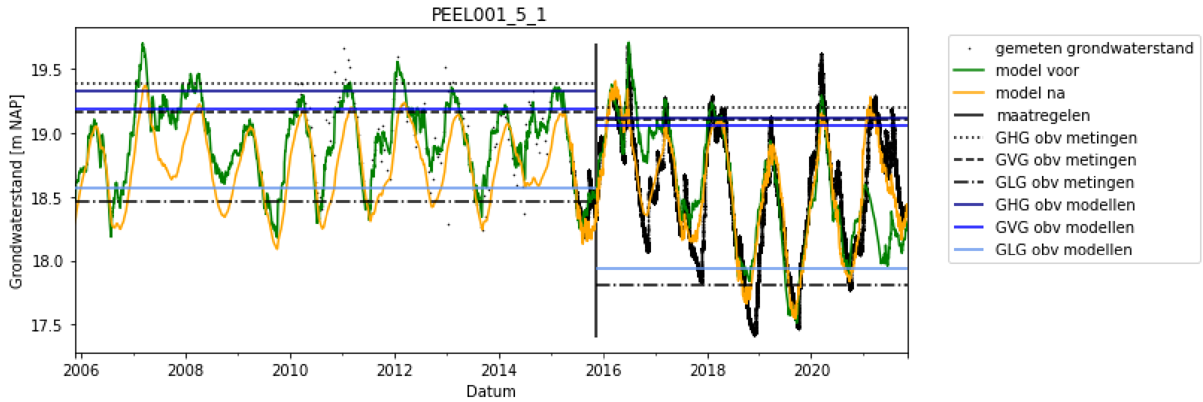
GVG obv modellen
GLG obv modellen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Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
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GHG obv metingen
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GLG obv metingen
GHG obv modellen
GVG obv modellen
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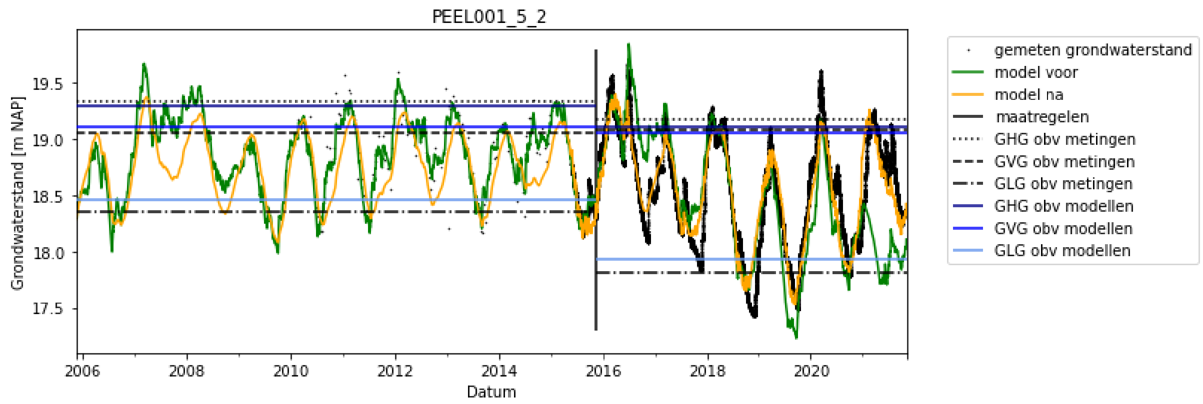
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Grondwaterstand [m NAP]
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gemeten grondwaterstand
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model na
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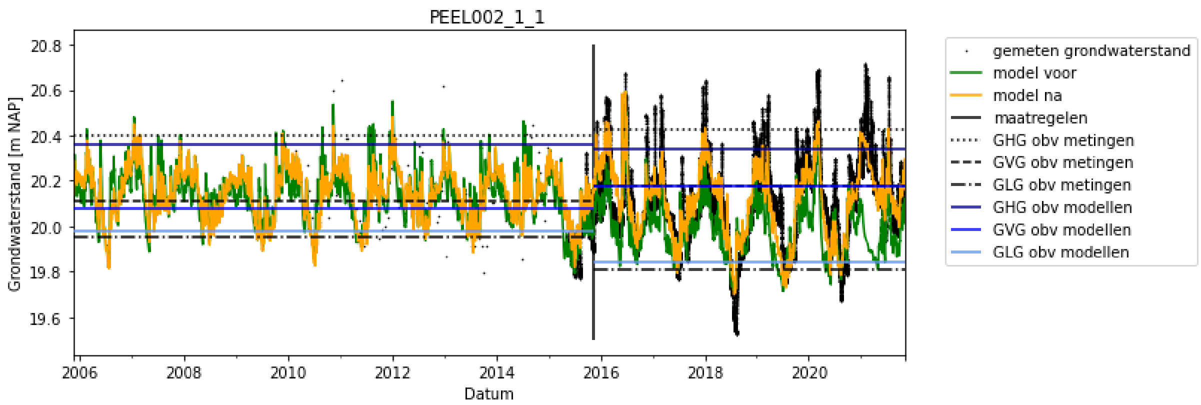
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL002_1_1
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
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GHG obv metingen
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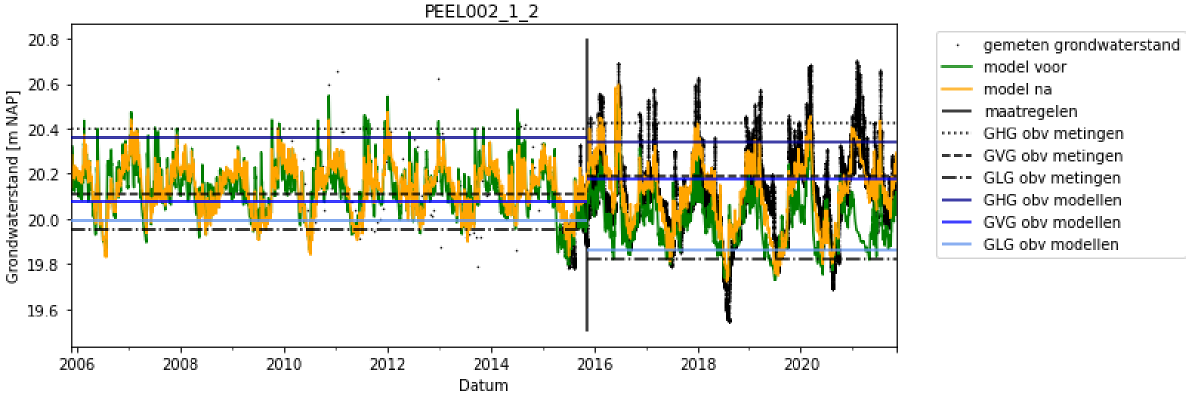
GHG obv modellen
GVG obv modellen
GLG obv modellen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Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
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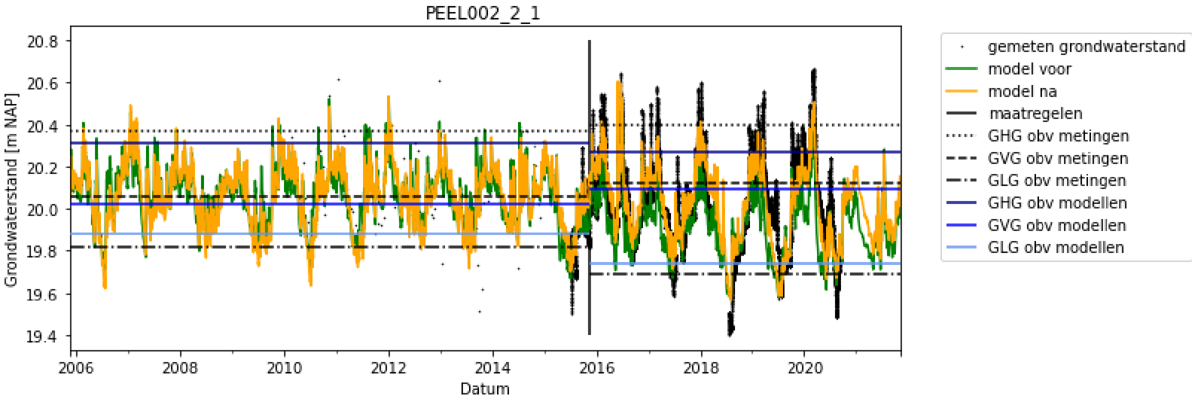
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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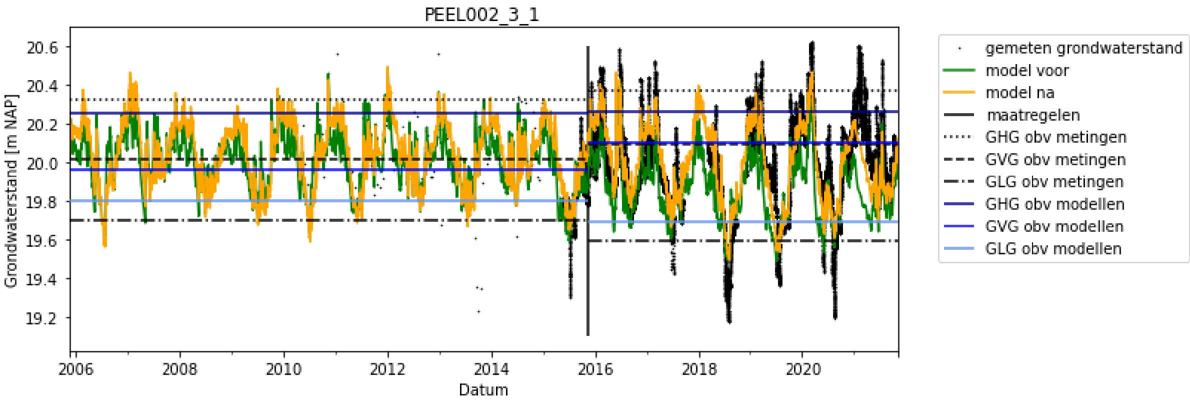
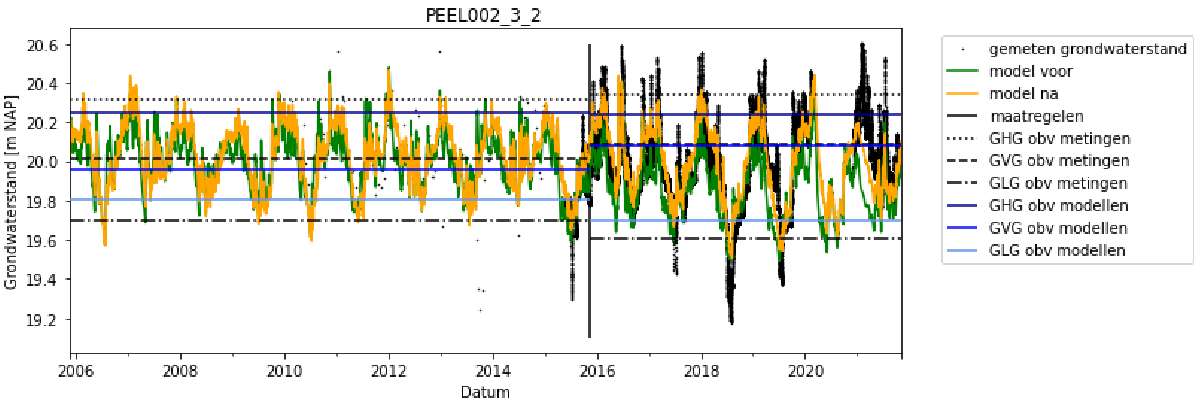
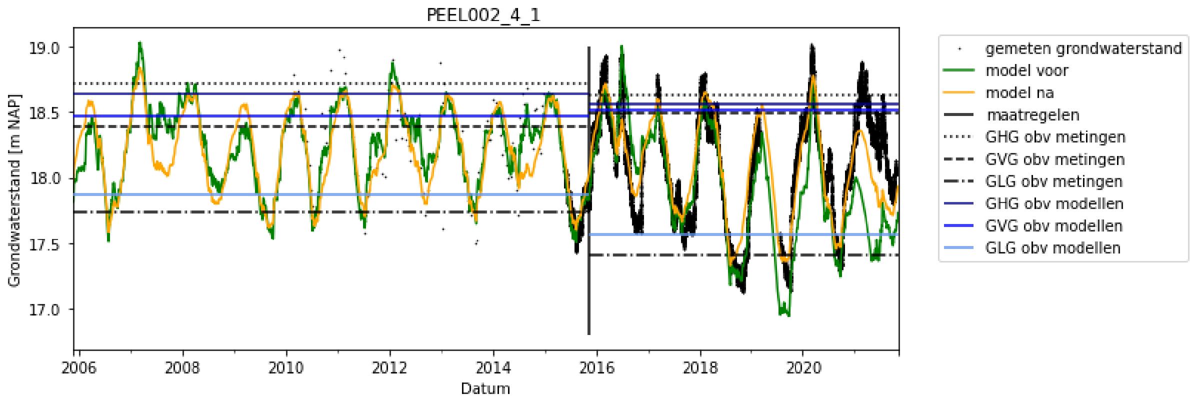
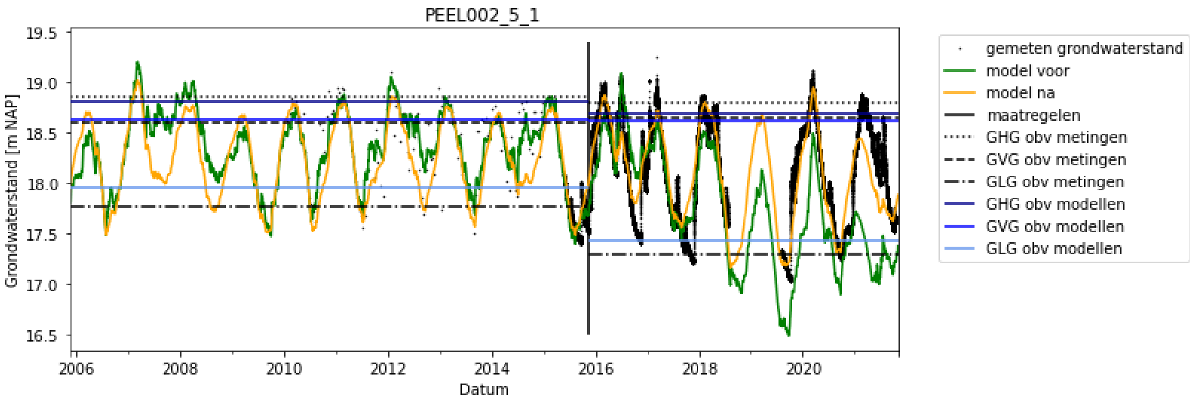
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL002_3_1
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL002_3_2
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL002_4_1
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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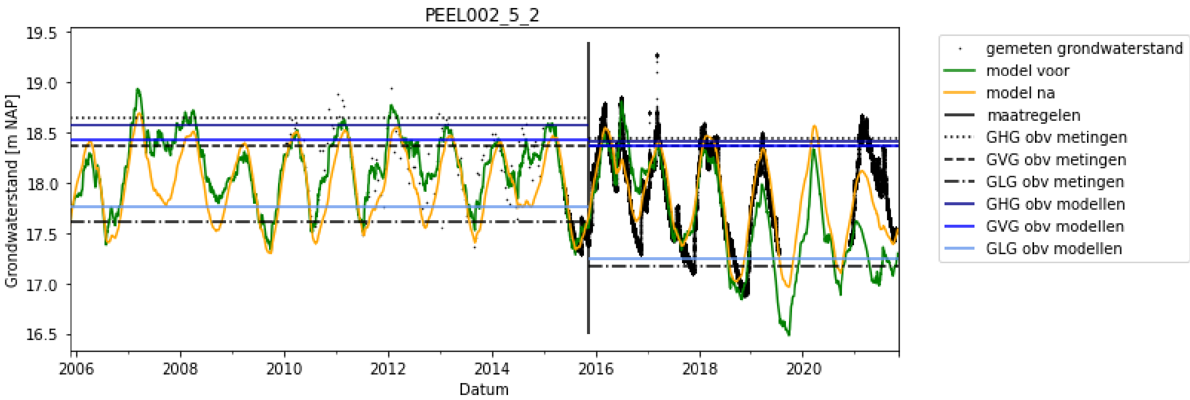
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL002_5_2
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
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GHG obv metingen
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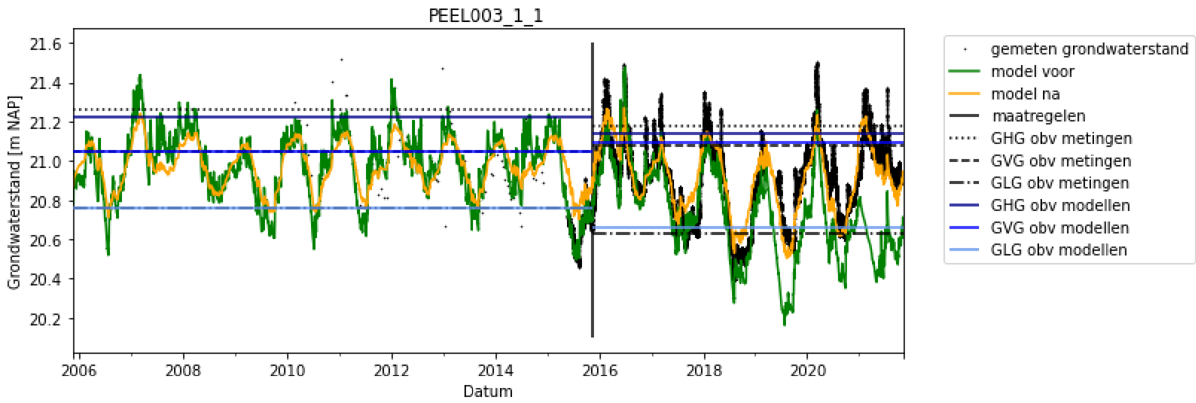
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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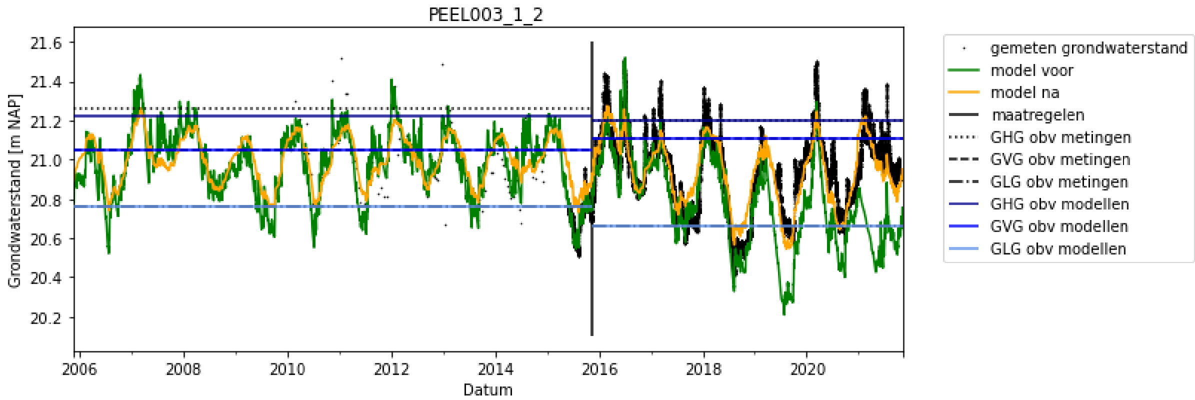
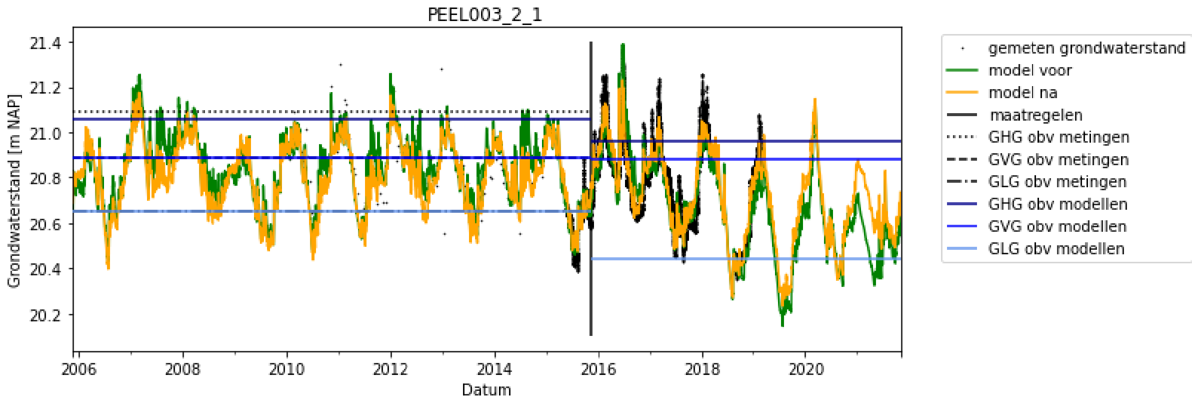
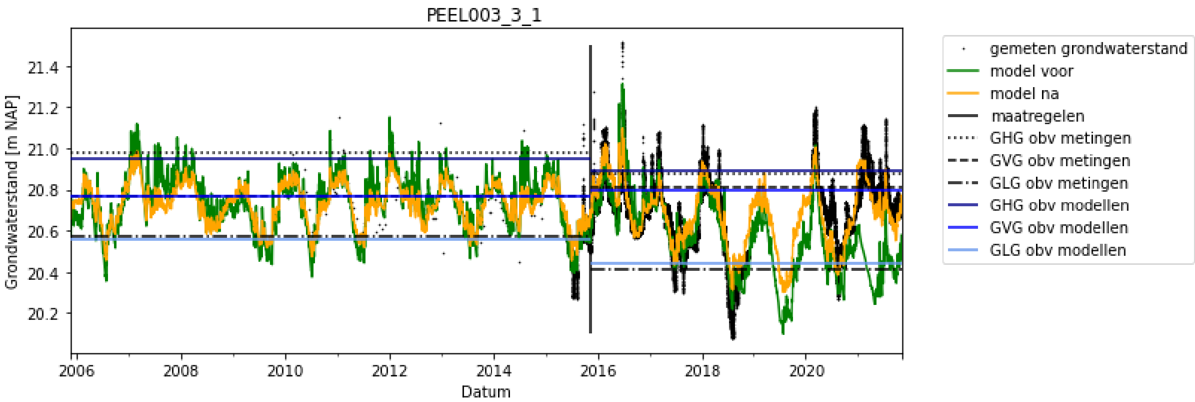
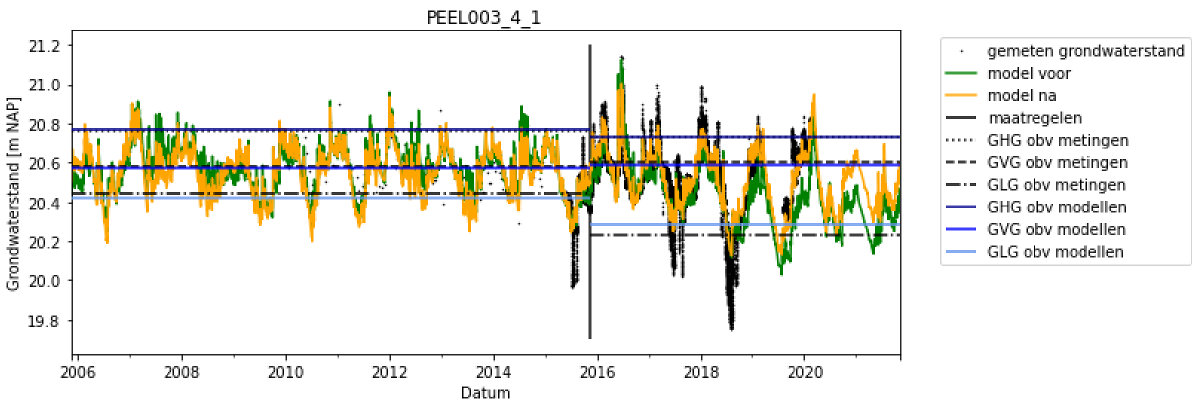
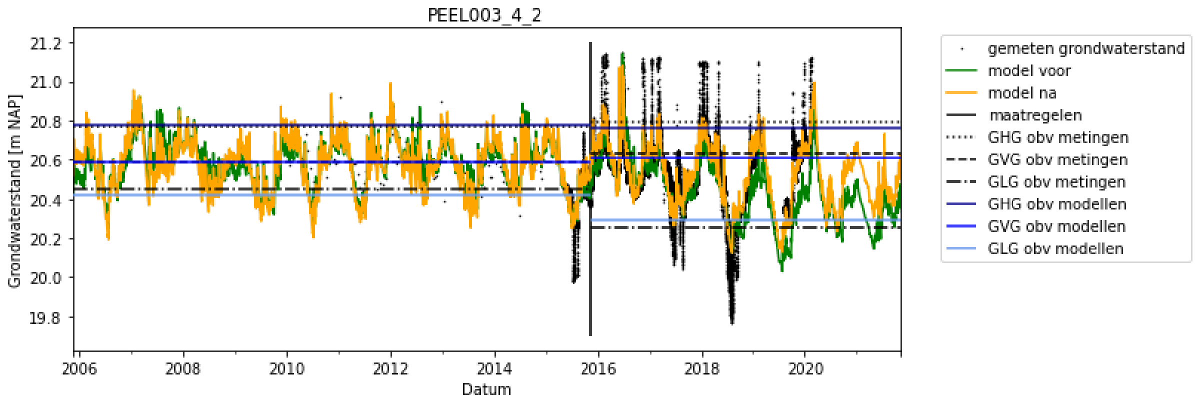
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL003_1_2
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL003_2_1
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL003_3_1
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen


PEEL003_4_1
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen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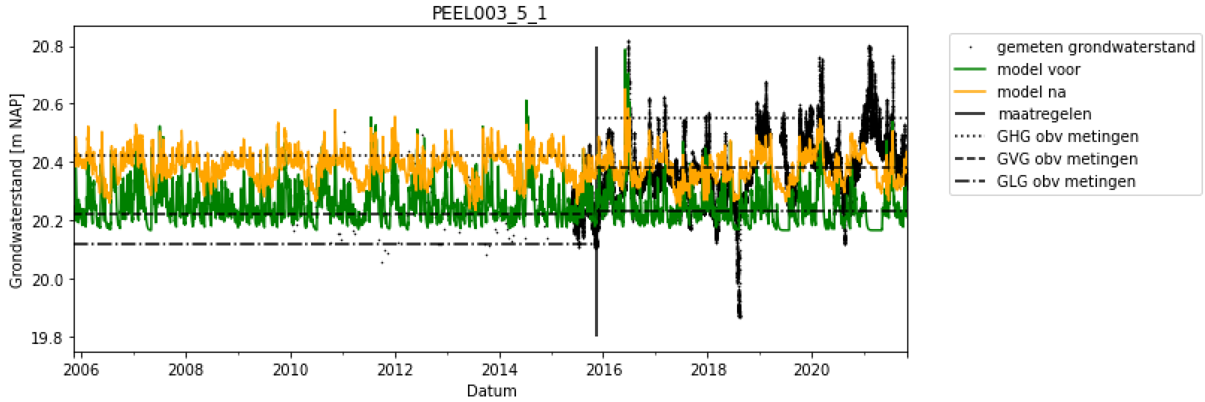
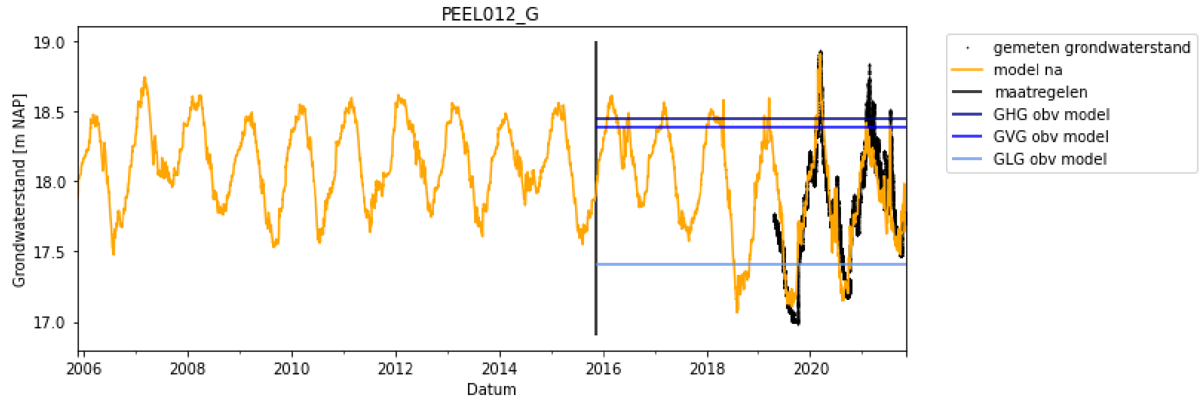
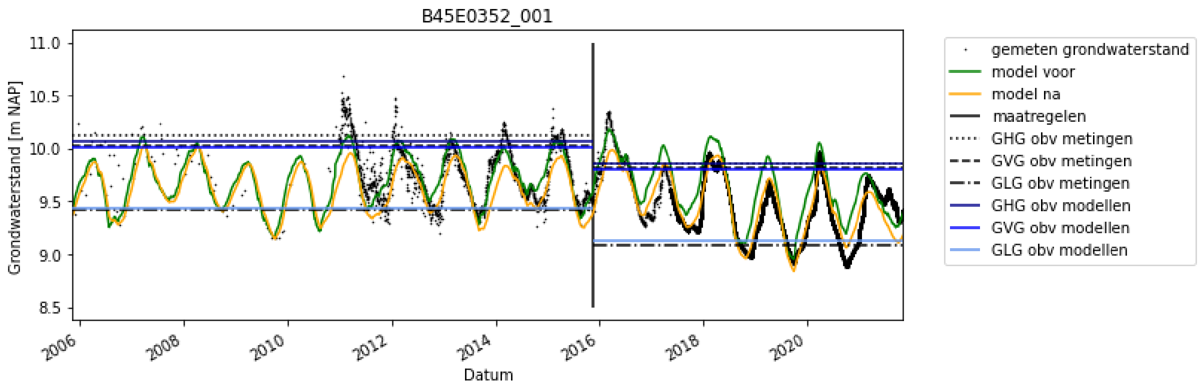
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen

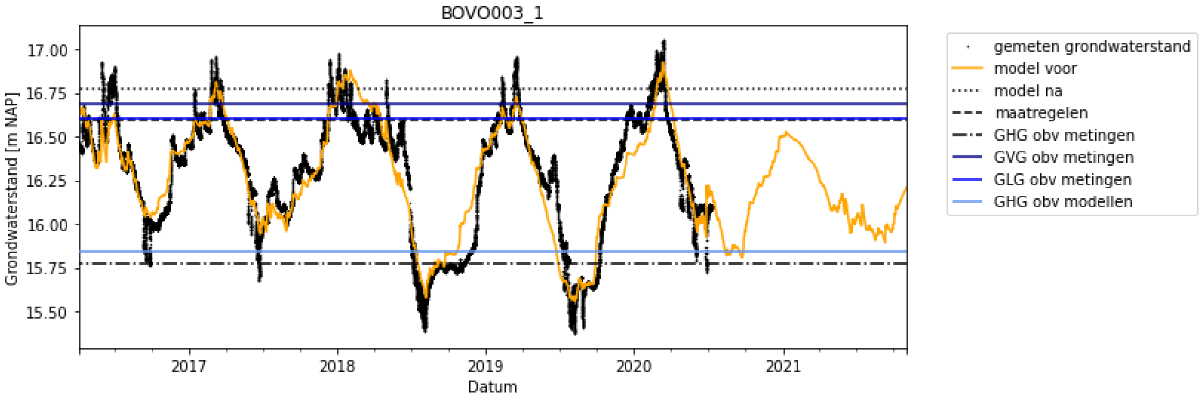

PEEL003_5_1
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen


PEEL012_G
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model na
maatregelen
GHG obv model
GVG obv model
GLG obv model

Donzel


B45E0352_001
Grondwaterstand [m NAP]
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen
GVG obv modellen
GLG obv modellen

Graspeel


BOVO003_1
Grondwaterstand [m NAP]
17.00
16.75
16.50
16.25
16.00
15.75
15.50
2017
2018
2019
2020
2021
Datum
gemeten grondwaterstand
model voor
model na
maatregelen
GHG obv metingen
GVG obv metingen
GLG obv metingen
GHG obv modellen

Appendix C: Model performance and ΔGxG values

Table C.1 The model performances and differences in GxG values as also shown in figure 3.1 for St Annabos

	Model before measures (%)	Model after measures (%)	Difference GLG	Difference GHG	Difference GVG
ANNA003_G	80	78	0.10	0.09	0.11
ANNA004_G	83	67	0.00	-0.09	-0.04
ANNA005_G	93	85	0.10	0.18	0.18
ANNA006_G	83	68	0.15	0.11	0.16
ANNA008_G	95	78	0.05	0.12	0.14
ANNA009_G	91	86	0.00	-0.05	0.00
ANNA010_1_G	92	76	0.04	0.01	0.05
ANNA010_2_G	88	82	0.03	0.01	0.06
ANNA010_3_G	92	74	0.03	0.01	0.05
ANNA011_1_G	87	82	0.02	0.03	0.06
ANNA011_2_G	89	92	0.12	0.06	0.07
B45G0269_001	67	79	-0.98	-1.02	-0.90
B45G0269_002	63	62	-0.04	-0.03	0.01
B45G0272_001	82	86	-0.11	0.16	0.14
B45G0272_002	74	75	0.15	0.02	0.08
B45G0273_001	90	85	0.00	-0.03	0.01
B45G0273_002	90	83	-0.03	-0.04	-0.01
B45G0273_003	91	82	-0.05	-0.06	-0.02
B45G0398_001	90	81	0.00	0.07	0.09
B45G1039_001	88	80	-0.59	-0.69	-0.61
REFV020_1_G	59	86	0.07	0.18	0.15
REFV020_2_G	85	82	0.00	0.05	0.11

Table C.2 The model performances and differences in GxG values as also shown in figure 3.2 for Venloop

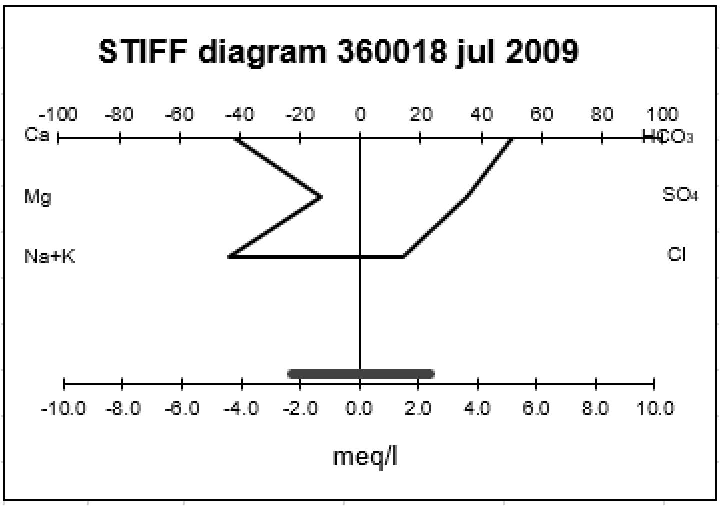
	Model before measures (%)	Model after measures (%)	Difference GLG	Difference GHG	Difference GVG
B45H0107_001	81	83	0.14	-0.14	-0.10
B45H0107_002	81	83	0.11	-0.13	-0.10
KARL001_G	88	93	-0.05	-0.19	-0.16
KARL002_G	87	95	-0.24	-0.03	0.05
KARL003_G	57	70	-0.19	-0.27	-0.19
KARL004_G	89	91	-0.10	-0.18	-0.10
MAAS003_G	78	79	0.17	-0.28	-0.20

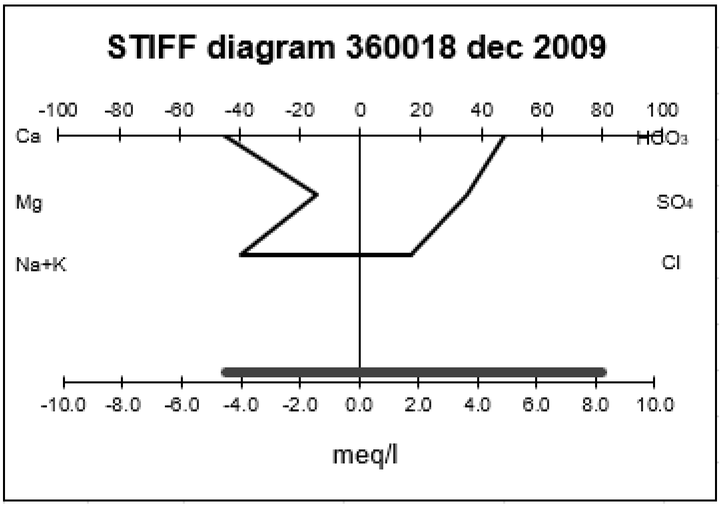
MAAS017_G	83	92	-0.02	-0.15	-0.10
MAAS018_G	76	93	-0.15	-0.12	-0.09
MAAS019_G	84	93	-0.05	-0.07	-0.02
MAAS020_G	82	94	-0.05	-0.06	-0.02
MAAS021_G	77	94	-0.05	-0.02	0.02
MAAS022_G	74	81	-0.60	-0.12	0.05
MAAS023_G	80	94	-0.02	-0.27	-0.24
MAAS024_G	82	82	-0.09	-0.19	-0.17

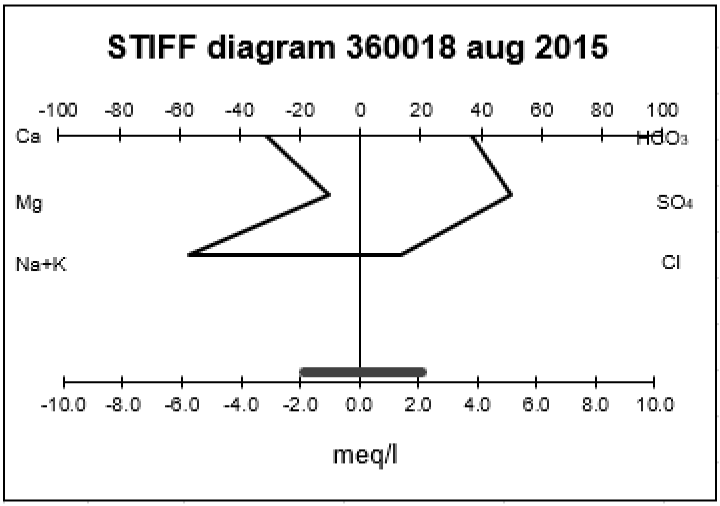
Table C.3 The model performances and differences in GxG values as also shown in figure 3.3 for Geeneneind

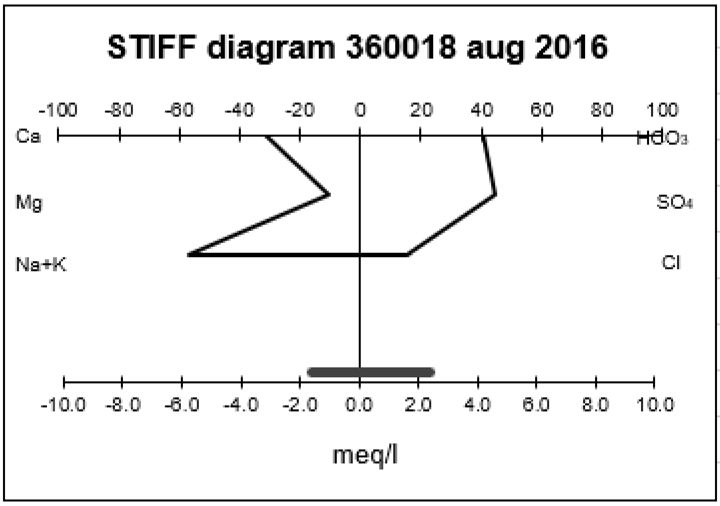
	Model before measures (%)	Model after measures (%)	Difference GLG	Difference GHG	Difference GVG
PEEL001_1_1	81	48	0.05	-0.06	0.00
PEEL001_1_2	82	54	0.07	-0.03	0.03
PEEL001_2_1	93	30	0.04	-0.04	0.00
PEEL001_3_1	95	62	0.09	0.05	0.11
PEEL001_4_1	92	63	0.01	-0.01	0.03
PEEL001_4_2	93	65	0.07	0.02	0.07
PEEL001_5_1	89	82	-0.17	-0.01	0.11
PEEL001_5_2	90	83	-0.06	0.01	0.18
PEEL002_1_1	75	76	0.04	0.13	0.19
PEEL002_1_2	75	74	0.05	0.12	0.19
PEEL002_2_1	71	80	0.05	0.10	0.16
PEEL002_3_1	64	73	0.08	0.14	0.22
PEEL002_3_2	64	70	0.08	0.12	0.20
PEEL002_4_1	88	76	0.11	0.08	0.21
PEEL002_5_1	87	75	0.20	0.32	0.45
PEEL002_5_2	88	74	0.09	0.17	0.31
PEEL003_1_1	90	77	0.19	0.11	0.19
PEEL003_1_2	88	76	0.17	0.08	0.17
PEEL003_2_1	87	91	0.01	0.02	0.08
PEEL003_3_1	82	77	0.07	0.07	0.12
PEEL003_4_1	74	79	0.03	0.09	0.08
PEEL003_4_2	73	79	0.03	0.10	0.09
PEEL003_5_1	50	26	0.12	0.07	0.15
B51F0096_001	86	75	0.02	-0.12	-0.02
B51F00432_001	61	65	0.15	0.00	0.09

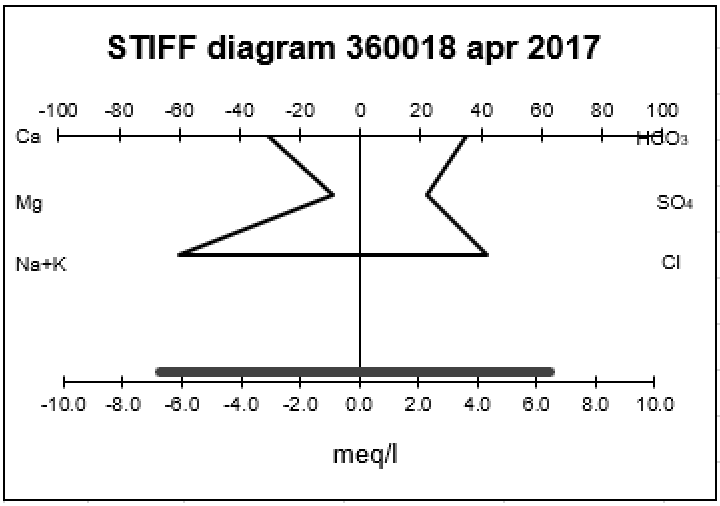
Appendix D: Stiff diagrams St Annabos








STIFF diagram 360018 aug 2016
-100 -80 -60 -40 -20 0 20 40 60 80 100
Ca
Mg
Na+K
HCO3
SO4
Cl
-10.0 -8.0 -6.0 -4.0 -2.0 0.0 2.0 4.0 6.0 8.0 10.0
meq/l


STIFF diagram 360018 apr 2017
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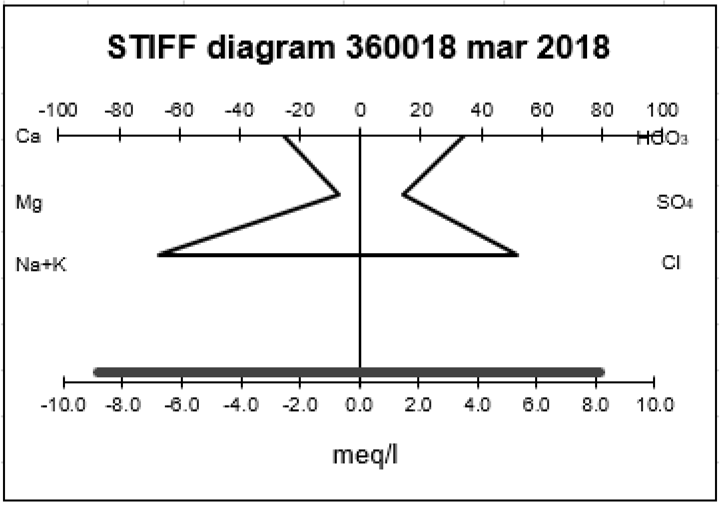
Ca
Mg
Na+K
HCO3
SO4
Cl
-10.0 -8.0 -6.0 -4.0 -2.0 0.0 2.0 4.0 6.0 8.0 10.0
meq/l


STIFF diagram 360018 mar 2018
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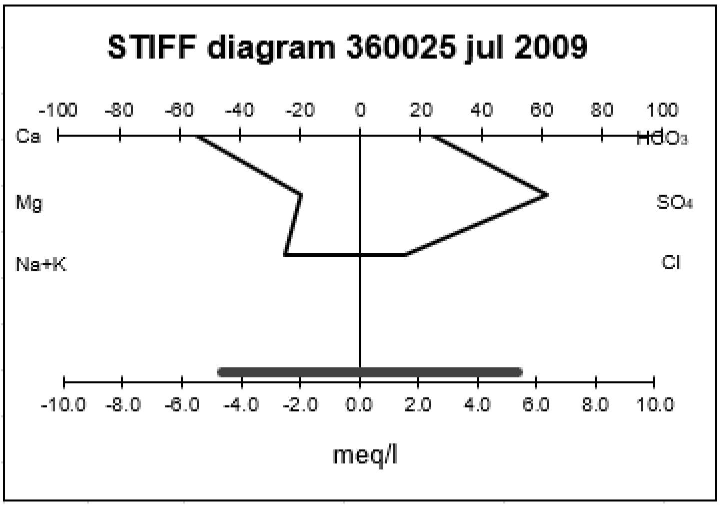
Ca
Mg
Na+K
HCO3
SO4
Cl
-10.0 -8.0 -6.0 -4.0 -2.0 0.0 2.0 4.0 6.0 8.0 10.0
meq/l


STIFF diagram 360025 jul 2009
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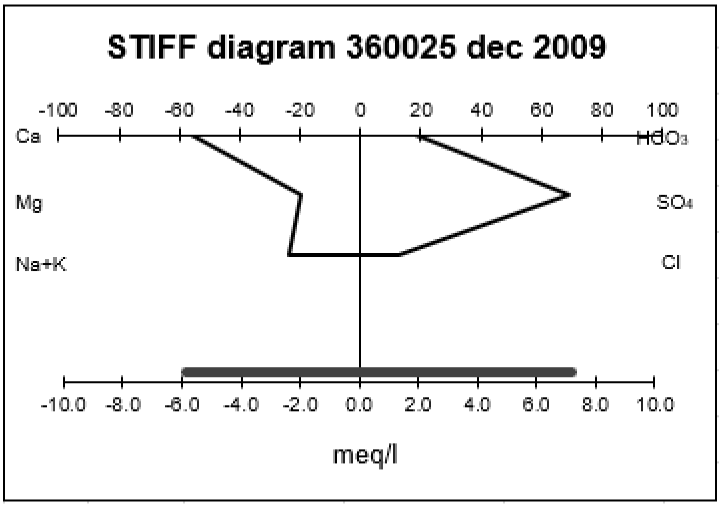
Mg
Na+K
HCO3
SO4
Cl
-10.0 -8.0 -6.0 -4.0 -2.0 0.0 2.0 4.0 6.0 8.0 10.0
meq/l


STIFF diagram 360025 dec 2009
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Mg
Na+K
HCO3
SO4
Cl
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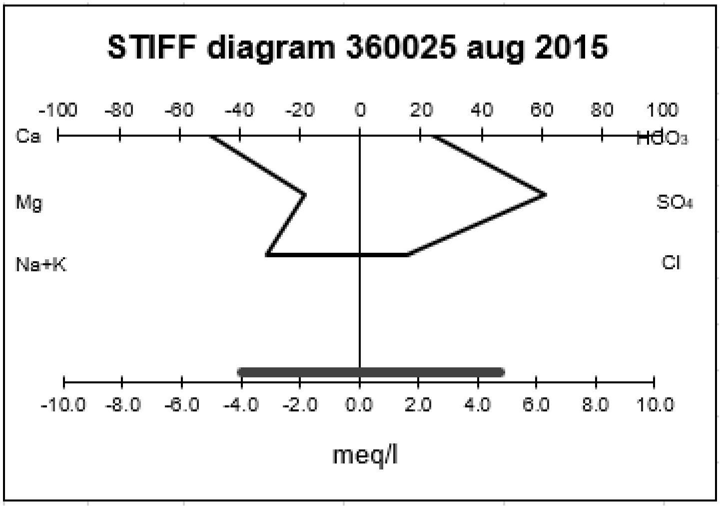
meq/l


STIFF diagram 360025 aug 2015
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Mg
Na+K
HCO3
SO4
Cl
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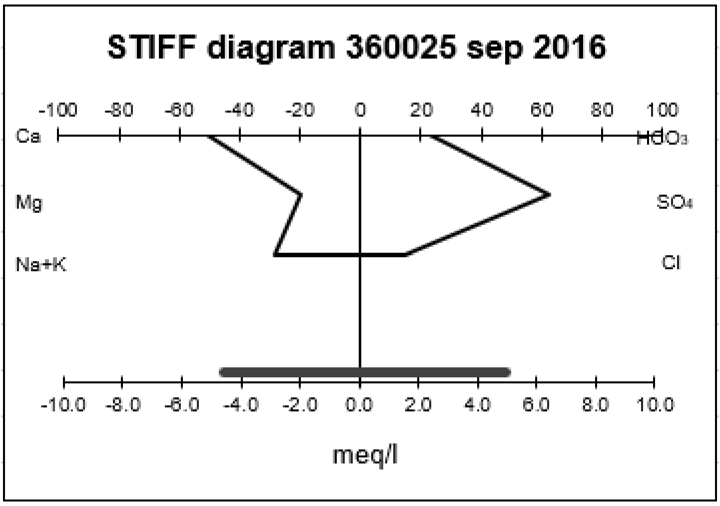
meq/l


STIFF diagram 360025 sep 2016
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Mg
Na+K
HCO3
SO4
Cl
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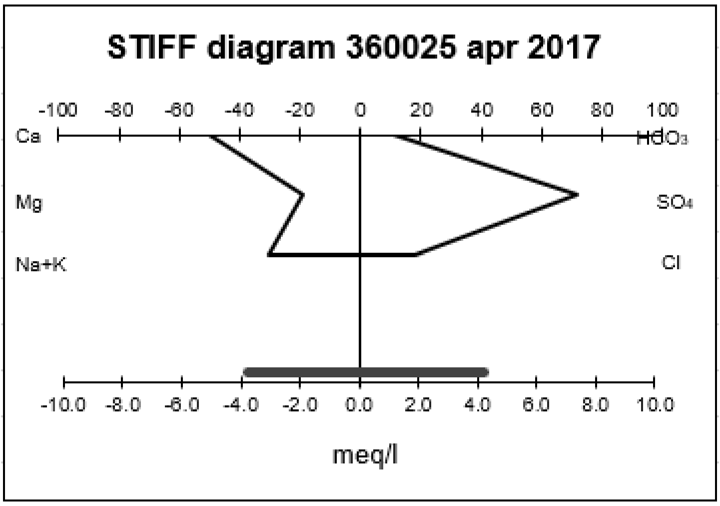
meq/l


STIFF diagram 360025 apr 2017
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Ca
Mg
Na+K
HCO3
SO4
Cl
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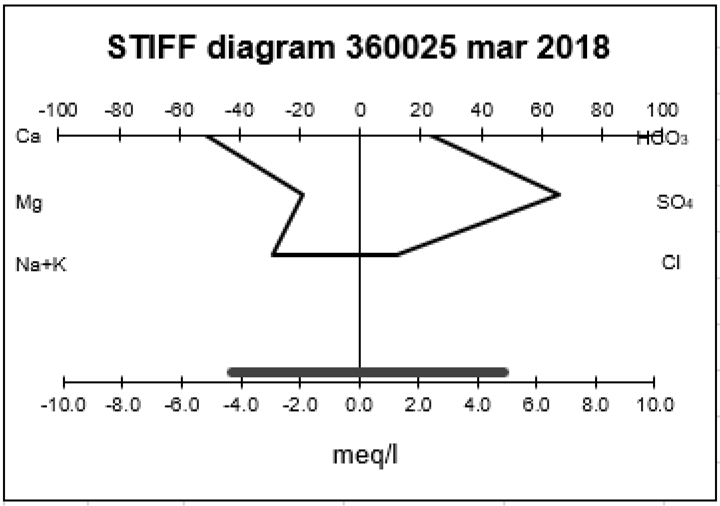
meq/l


STIFF diagram 360025 mar 2018
-100 -80 -60 -40 -20 0 20 40 60 80 100
Ca
Mg
Na+K
HCO3
SO4
Cl
-10.0 -8.0 -6.0 -4.0 -2.0 0.0 2.0 4.0 6.0 8.0 10.0
meq/l

Appendix E: Spatial distribution of iron concentration and groundwater temperature in management area

Fluctuations in iron concentration and groundwater temperature at Geeneneind are shown in figure E.1. The variation seen in these graphs emphasises the need to measure these parameters more than once a year or choose the same month every year while being aware of these variations. Figure E.2. shows a spatial map using the iron concentration and the groundwater temperature, showing the heterogeneity in the measurements, likely caused by the different measurement moments.

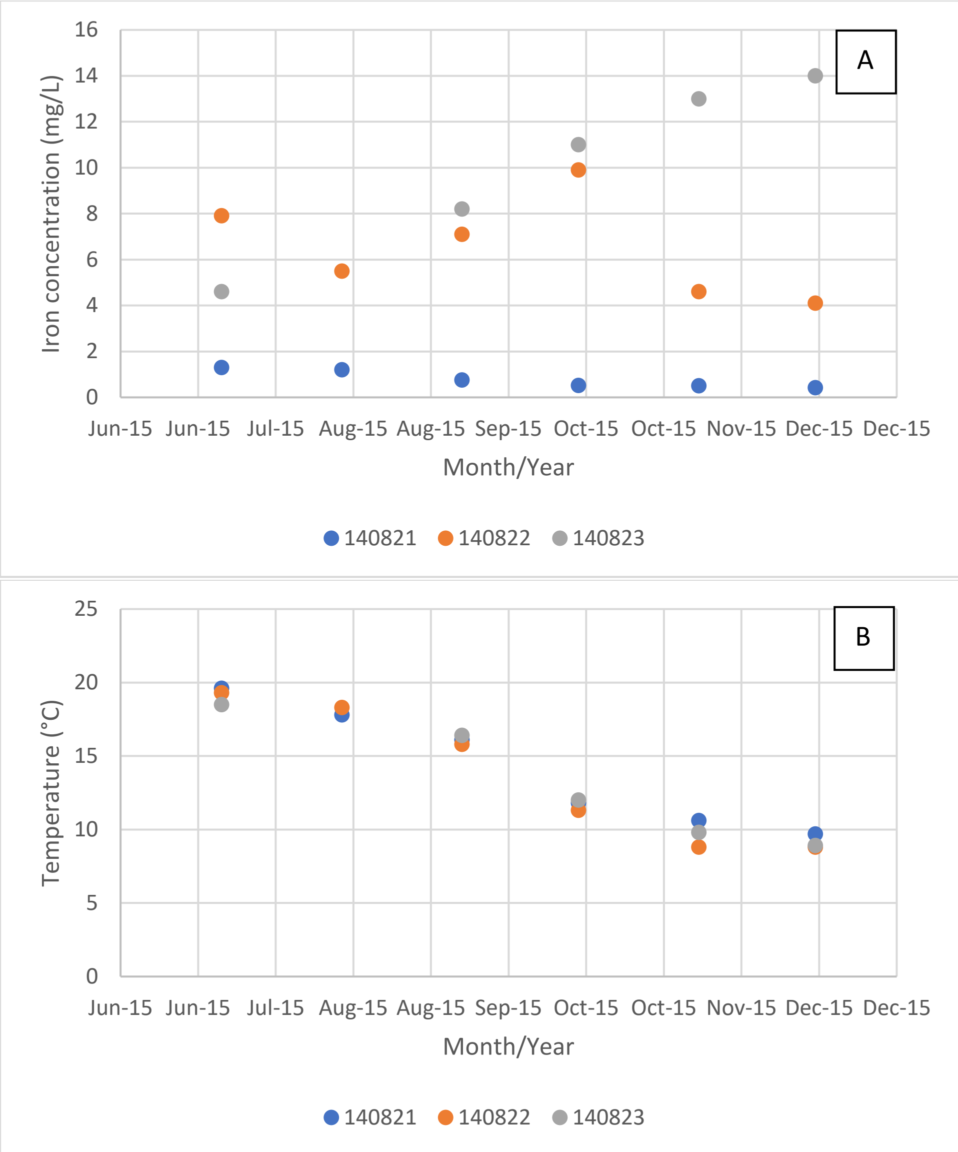


Figure E.1. Time series showing the seasonal fluctuation of the iron concentration (A) and temperature (B) at Geeneneind.

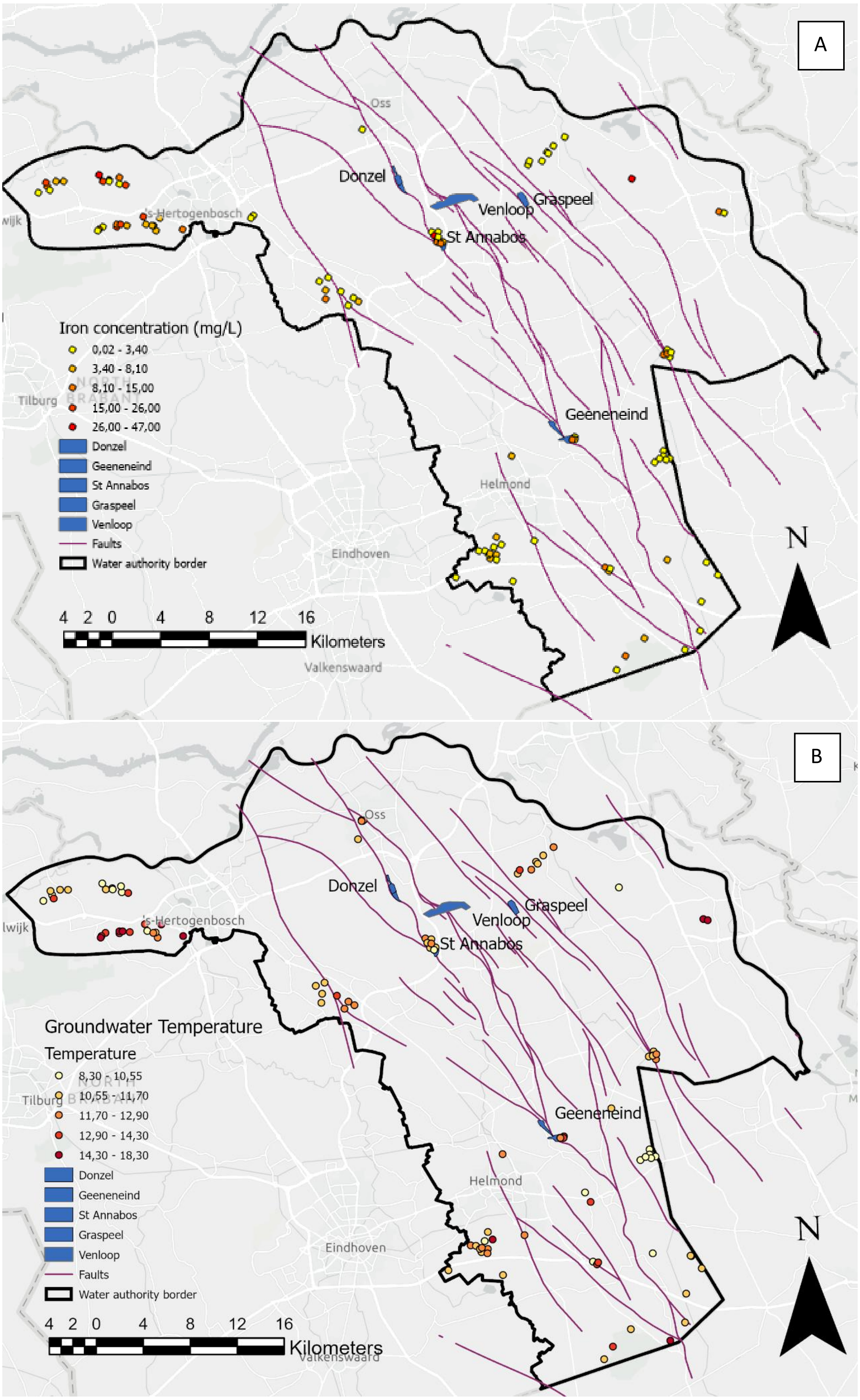


Figure E.2. Map of iron concentration (mg/L) (A) and temperature (°C) (B) in the management area of the water authority.

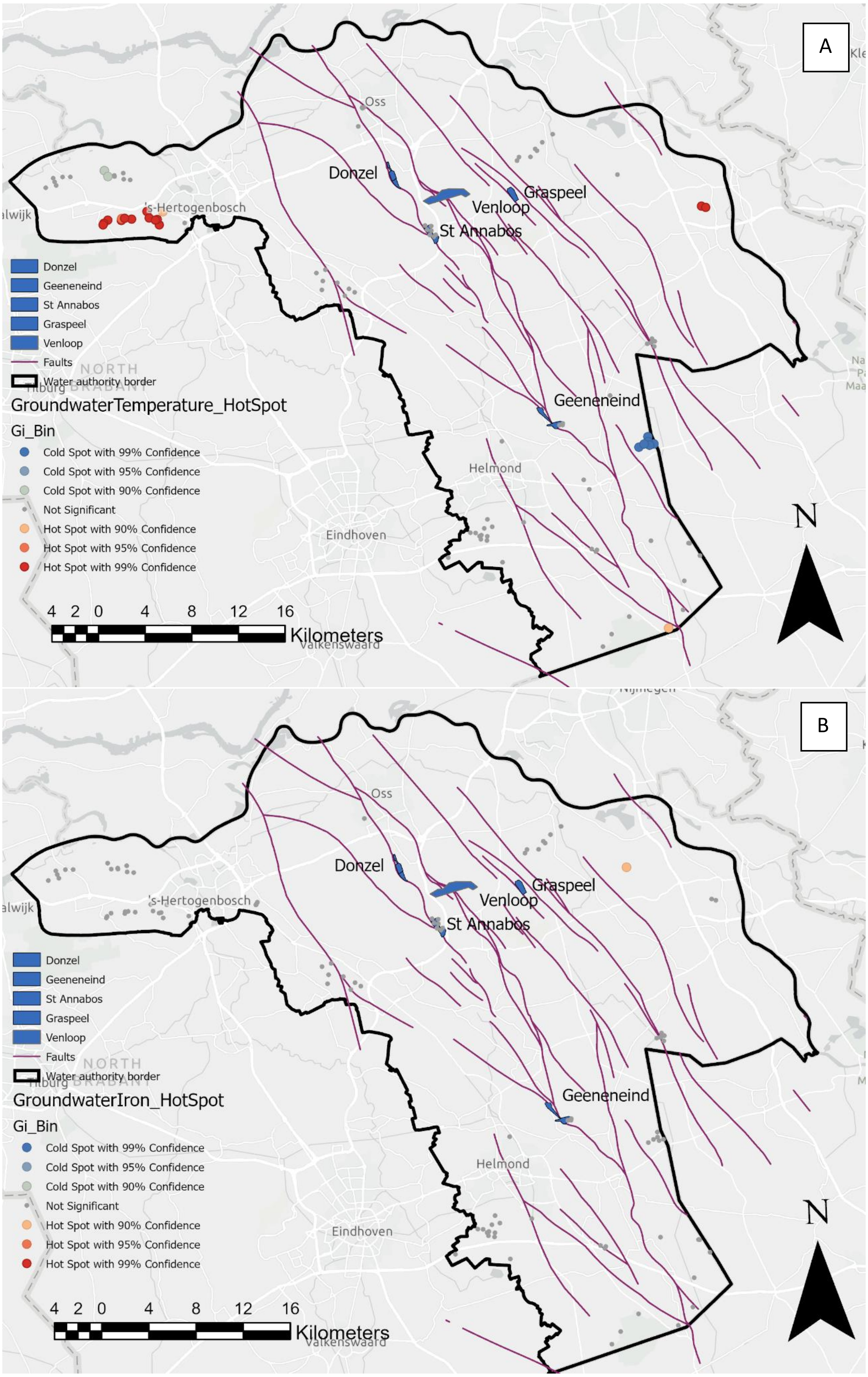


Figure E.3. Optimized hot spot analysis output maps for temperature (A) and iron concentration (B).

The values in figure E.3. that are within a 90% confidence interval are not shown, meaning that only the outliers are shown in these types of maps. After performing this optimized hotspot analysis in ArcGIS Pro it was clear that the potentially higher temperature at the project areas was not detectable (Fig. E.3.). This result seems to agree with the maps in figure E.2. The higher values are situated around 's-Hertogenbosch and most of the other values do not show a spatial pattern.

Next to the temporal analysis, also a spatial analysis with the groundwater temperature and the iron concentration were conducted. The patterns in figures E.2 and E.3 do not show any significant raised values around the project areas. The values near 's-Hertogenbosch are higher, likely the urban environment here has caused these high temperatures (Epting & Huggenberger, 2013). However, the measurements are not taken in the same seasons. Annual fluctuations for both parameters can be expected. Higher temperatures are measured in summer and iron concentration is dependent on this fluctuation in temperature, warmer water can dissolve more iron (Nelson, 2002). These flucutations are also seen in figure E.1.

Appendix F: Species present in the project areas

Table F.1. Presence species St Annabos

Dutch name	Latin name	Before 2009	After 2009
Weidebeekjuffer	Calopteryx splendens		X
Waterral	Rallus aquaticus		X
Spotvogel	Hippolais icterina	X	X
Putter	Carduelis carduelis	X	X
Pluimzegge	Carex paniculata subsp. paniculata	X	X
Pinksterbloem	Cardamine pratensis	X	X
Oranjetipje	Anthocharis cardamines	X	X
Nachtegaal	Luscinia megarhynchos		X
Klimopwaterranonkel	Ranunculus hederaceus		X
Kleine watersalamander	Lissotriton vulgaris	X	X
Kleine karekiet	Acrocephalus scirpaceus	X	X
Icarusblauwtje	Polyommatus icarus	X	X
Hooibeestje	Coenonympha pamphilus		X
Holpijp	Equisetum fluviatile	X	X
Gewone pad	Bufo bufo	X	X
Echte koekoeksbloem	Silene flos-cuculi	X	X
Gewone dotterbloem	Caltha palustris subsp. palustris	X	X
Bruine kikker	Rana temporaria	X	X
Bosrietzanger	Acrocephalus palustris	X	X
Blauwborst	Luscinia svecica		X
Bittere veldkers	Cardamine amara	X	X
Bandheidelibel	Sympetrum pedemontanum		X

Table F.2. Presence species Venloop

Dutch name	Latin name	Before 2016	After 2016
Wezel	Mustela nivalis		X
Weidebeekjuffer	Calopteryx splendens	X	X
Spotvogel	Hippolais icterina	X	X
Putter	Carduelis carduelis	X	X
Pinksterbloem	Cardamine pratensis	X	X
Oranjetipje	Anthocharis cardamines	X	X
Nachtegaal	Luscinia megarhynchos		X
Kleine watersalamander	Lissotriton vulgaris	X	X
Kleine karekiet	Acrocephalus scirpaceus	X	X
Kamsalamander	Triturus cristatus	X	X
Icarusblauwtje	Polyommatus icarus	X	X
Hooibeestje	Coenonympha pamphilus	X	X
Holpijp	Equisetum fluviatile	X	X
Heikikker	Rana arvalis	X	X
Gewone pad	Bufo bufo	X	X
Echte koekoeksbloem	Silene flos-cuculi	X	X
Bunzing	Mustela putorius		X

Bruine kikker	Rana temporaria	X	X
Bosrietzanger	Acrocephalus palustris	X	X
Beekoeverlibel	Orthetrum coerulescens		X
Bandheidelibel	Sympetrum pedemontanum	X	X

Table F.3. Presence species downstream Geeneneind

Dutch name	Latin name	Before 2016	After 2016
Weidebeekjuffer	Calopteryx splendens	X	X
Spotvogel	Hippolais icterina	X	X
Putter	Carduelis carduelis	X	X
Pinksterbloem	Cardamine pratensis	X	X
Oranjetipje	Anthocharis cardamines	X	X
Kleine watersalamander	Lissotriton vulgaris	X	X
Kleine karekiet	Acrocephalus scirpaceus	X	
Icarusblauwtje	Polyommatus icarus	X	X
Hooibeestje	Coenonympha pamphilus	X	X
Holpijp	Equisetum fluviatile	X	X
Heikikker	Rana arvalis		X
Gewone pad	Bufo bufo	X	X
Gewone dotterbloem	Caltha palustris subsp. palustris	X	X
Gewone Bronlibel	Cordulegaster boltonii	X	X
Echte koekoeksbloem	Silene flos-cuculi	X	
Bunzing	Mustela putorius		X
Bruine kikker	Rana temporaria	X	X
Bosrietzanger	Acrocephalus palustris	X	
Beekoeverlibel	Orthetrum coerulescens		X
Bittere veldkers	Cardamine amara	X	
Bandheidelibel	Sympetrum pedemontanum	X	X

Table F.4. Presence species upstream Geeneneind

Dutch name	Latin name	Before 2016	After 2016
Wezel	Mustela nivalis	X	
Weidebeekjuffer	Calopteryx splendens	X	X
Waterral	Rallus aquaticus		X
Spotvogel	Hippolais icterina	X	X
Putter	Carduelis carduelis	X	X
Pluimzegge	Carex paniculata subsp. paniculata		X
Pinksterbloem	Cardamine pratensis	X	X
Oranjetipje	Anthocharis cardamines	X	X
Nachtegaal	Luscinia megarhynchos	X	X
Kleine karekiet	Acrocephalus scirpaceus	X	X
Icarusblauwtje	Polyommatus icarus	X	X
Hooibeestje	Coenonympha pamphilus	X	X
Gewone pad	Bufo bufo	X	X

Echte koekoeksbloem	Silene flos-cuculi		X
Bunzing	Mustela putorius		X
Bruine kikker	Rana temporaria	X	X
Bosrietzanger	Acrocephalus palustris	X	X
Blauwborst	Luscinia svecica	X	X
Bittere veldkers	Cardamine amara		X
Bandheidelibel	Sympetrum pedemontanum	X	X