

Impact of local drought adaptation measures on groundwater levels and drought propagation

Weirs in the agricultural region of Breklenkamp in Twente, Eastern Netherlands

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Abstract

The accelerating impacts of climate change are intensifying hydrological cycles, resulting in more frequent and severe droughts across Europe. To prevent agricultural losses caused by these droughts, local drought adaptation measures were implemented in the agricultural region of Breklenkamp in Twente, Eastern Netherlands, focussing on storing and retaining of water. However, the hydrological effects of these local measures are largely unknown. Therefore, this study examines how this measure influences groundwater levels and drought propagation. Groundwater level time series of this new situation with the drought adaptation measure are compared with groundwater level time series of the situation before and without the implementation of the measure. To examine the influence of the measure on groundwater levels, groundwater signatures were determined for each time series. For the drought propagation analysis, the Standardised Groundwater Index (SGI) of each time series was determined and correlation coefficients with the Standardised Precipitation Index (SPI) with different accumulation periods were calculated. Groundwater levels have been observed to decrease over time. However, weirs have proven effective in maintaining higher groundwater levels during dry summer periods. In addition, the adaptation measure also better regulates high groundwater levels during wet periods. Correlation analysis between the SPI and SGI suggests that in the absence of weirs, the impact of precipitation deficits extends further into the system, affecting groundwater levels more significantly. Further analysis including delay times in groundwater response is needed to better assess the role of weirs in mitigating the propagation of meteorological droughts into groundwater droughts. Nonetheless, it is important to note that the effectiveness of weirs is limited under severe drought conditions.

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1. Introduction

1.1 Context

The impact of climate change has generally expedited hydrological processes, leading to faster onset and increased severity of droughts (Mukherjee et al., 2018). For example, the summers in Europe during 2018, 2019, 2020, and 2022 all experienced low precipitation rates and high temperatures, leading to widespread and severe droughts (KNMI, 2022; Philip et al., 2020; Rakovec et al., 2022). Droughts can have a profound effect on both terrestrial and aquatic ecosystems (Bartholomeus et al., 2011) as well as multiple sectoral water uses depended on both sufficient water quantity and quality (van Vliet et al., 2017; Wlostowski et al., 2021). For instance, low water levels hinder shipping operations (Vinke et al., 2022). Industries and energy sectors face limitations due to reduced summer flow and higher water temperature during droughts (Tobin et al., 2018). The drinking water industry faces challenges such as increased demand during dry seasons, higher salinisation and increased chemical concentrations (Delpla et al., 2009; Sjerps et al., 2017). And agriculture suffers from drought conditions and high salinity, resulting in decreased production (van Duinen et al., 2014). Failing to meet the water demand of different sectors can have significant economic consequences (Naumann et al., 2021). For example, the annual drought losses in the European Union and the United Kingdom combined could rise to more than €65 billion per year under the scenario of 4°C of global warming by 2100 and no adaptation measures. In comparison, the current annual losses are estimated at €9 billion per year. Therefore, it is generally the most expensive disaster in Europe (Guha-Sapir et al., 2016; Huang et al., 2021).

The Netherlands is one of the countries that was affected by the recent European drought events (Bakke et al., 2020) and climate projections show that the Netherlands is likely to experience more intense and frequent droughts in the future (Webber et al., 2018). A significant precipitation deficit was widespread in the Netherlands during the summers of 2018, 2019, 2020, and 2022, with the most pronounced effects in the southern, central, and especially the eastern regions of the country (Witte et al., 2020; Hendriks & de Louw, 2021; van den Eertwegh et al., 2021; KNMI, 2022). A reason for this is that approximately two-thirds of this area consists of higher and well-drained sandy soils that have a low water holding capacity. Besides that, in most of these regions in the eastern part of the Netherlands, no additional water could be brought in from the major rivers or the IJsselmeer. Therefore, an increased number of brooks and ditches dried up compared to usual conditions (Jansen et al., 2020).

The drought events especially have a large impact on the agricultural sector, since farmers are highly reliant on freshwater resources and manage over 60% of the total area of the Netherlands (Alberts, 2023). During a dry year, like in the recent warm European summers, the financial impact on the Dutch agricultural sector could reach €1.5 billion (Klijn et al., 2012; Van Bergeijk, 2024). As a result of the prolonged droughts, groundwater levels during each summer sank much deeper than in normal years. After that, winter precipitation often failed to replenish groundwater to its usual spring levels (Brakkee et al., 2022). Therefore, the growing season for vegetation consistently started with low groundwater levels. These water shortages can lead to reduced crop yields and quality, higher production costs and less income for agriculture (van Duinen et al., 2014).

The negative consequences of the recent years with droughts have led to the realisation that the current freshwater system is deficient (van den Eertwegh et al., 2021). Therefore, the focus should no longer be on discharging water to the sea as fast as possible, but retaining and infiltrating water in the soil. With that in mind, in numerous regions of the Netherlands, there is an effort at the local level to enhance drought resilience, especially in agricultural areas. Local measures play a crucial role in enhancing the quality of soil and water systems (Nikkels et al., 2023). Examples of measures include the improvement of soil structure, the use of dams and weirs, additional water supply and irrigation, and the use of other crops (Landbouw op Peil, 2014).

Ideally, the development, implementation and application of the local drought adaptation measures should consider other water users. The measures could have significant influences on ecosystems and various water-dependent sectors in the near and downstream area (Falkenmark, 2003). For instance, retaining water for agricultural use may cause a shortage of water for sectors in the downstream area. Furthermore, recent insights show that regional and local adaptation plans should aim to address the full spectrum of drought and flood challenges in a balanced manner (Bartholomeus et al., 2023). Enhancing the resilience of water systems to withstand hydrological and meteorological extremes, both droughts and floods, requires the implementation of strategies that can effectively mitigate risks associated with both these extremes. However, retaining water to mitigate drought can also prevent excess water from infiltrating sufficiently during a large rainfall event, resulting in an increased risk of flooding.

Various pilot projects have been initiated focusing on exploring measures for storing, retaining, and conserving water. One of these projects is the Upscaling Private and Collective Water Storage for Robust Agricultural Systems (UPWAS) project. In this project, research is conducted on possibilities to scale up sustainable water storage in the agricultural landscape (UPWAS, 2022). By combining knowledge from agricultural sciences, hydrology, law, and governance studies with practical expertise gathered from daily operations, the project aims to collaboratively develop insights and tools within and across various disciplines (WUR, 2022). These resources aim to assist farmers, Waterboards, Provincial Governments, and other relevant stakeholders in the Netherlands in scaling up both private and collective water storage methods to strengthen agricultural systems (UPWAS, 2022).

1.2 Research aim and questions

There is a focus on implementing local drought adaptation measures that can be taken quickly with the expectation that they will positively impact regional water management. However, the hydrological effects of local measures are largely unknown (Nikkels et al., 2023). Therefore, the main goal of this research is to study the local hydrological impact of drought adaptation measures. To reach this aim, the main question is:

“How do local drought adaptation measures affect drought propagation and alter hydrological signatures of groundwater levels?”

The sub-questions are:

-What are the trends and variations in groundwater levels in the study area, and how have they been altered after the implementation of the drought adaptation measure?

-How do the drought adaptation measures influence the occurrence, severity, and propagation of droughts?

1.3 Study area

This research focuses on the effects of the drought adaptation measures on groundwater levels and drought propagation in the agricultural area near Breklenkamp in Twente, which is one of the UPWAS project locations (Figure 1). This study area is suitable since it is located on elevated sandy soils, there is a lot of agricultural activity, the area is strongly affected by a water shortage and a drought adaptation measure has been implemented in the form of weirs (Figure 2).

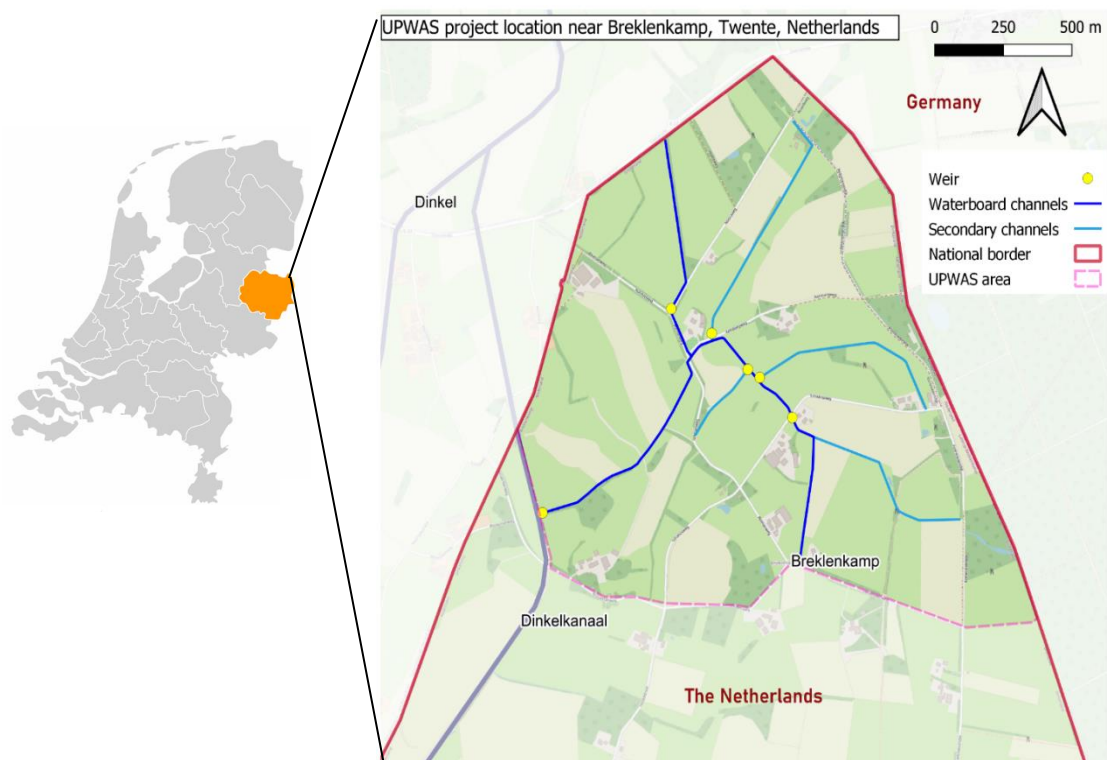


Figure 1: The location of the UPWAS project area near Breklenkamp in Twente, Eastern Netherlands, and the locations of the weirs.



Figure 2: Example of a weir.

1.4 Hypothesis

It is expected that the local drought adaptation measure will result in a signal of higher groundwater levels. Due to the presence of weirs, water is kept in the system at a local level and therefore ensures higher rates of groundwater recharge. Besides that, it is expected that due to the drought adaptation measure, these higher groundwater levels will result in a decline of the frequency, duration, and severity of hydrological groundwater droughts. Therefore, the meteorological drought would not be followed by (a large) hydrological groundwater drought. So, with the drought adaptation measure in place there would be less drought propagation towards a hydrological drought at a local level. However, it must be considered that the weirs can only hold back the water. When there isn't enough rainfall, there is no water to retain behind the weirs, leaving conditions similar to those in surrounding areas.

2. Theoretical framework

2.1 Definition of droughts and drought propagation

There is no universally accepted definition of drought, due to the complexity and non-uniformity of drought events (Lloyd-Hughes, 2013). In general, drought refers to an extended duration of below-normal water availability. They can occur anywhere in the world, and they have regionally varied spatial and temporal characteristics (Tallaksen & Van Lanen, 2004). Drought can be classified into various categories based on different aspects. In general, the three types of droughts that can be distinguished are: meteorological drought (section 2.1.1), soil moisture drought (also known as agricultural drought) (section 2.1.2) and hydrological drought (section 2.1.3).

Figure 3 represents the different categories of drought and their development. It shows that after meteorological droughts, soil moisture droughts can occur, since a lack of precipitation can lead to a decrease in soil moisture content. Eventually this can lead to hydrological droughts, since the precipitation deficiency and low soil moisture content can result in low discharge levels and low soil moisture content can lead to less recharge of groundwater, resulting in low groundwater levels. Consequently, droughts can propagate from a precipitation anomaly into a hydrological drought, impacting the deeper levels of this system (Peters et al., 2003; Van Loon et al., 2012). Moreover, the framework of Figure 3 shows that it is important to understand and consider the previous conditions and the connections between several factors when interpreting and explaining trends and variations in drought conditions.

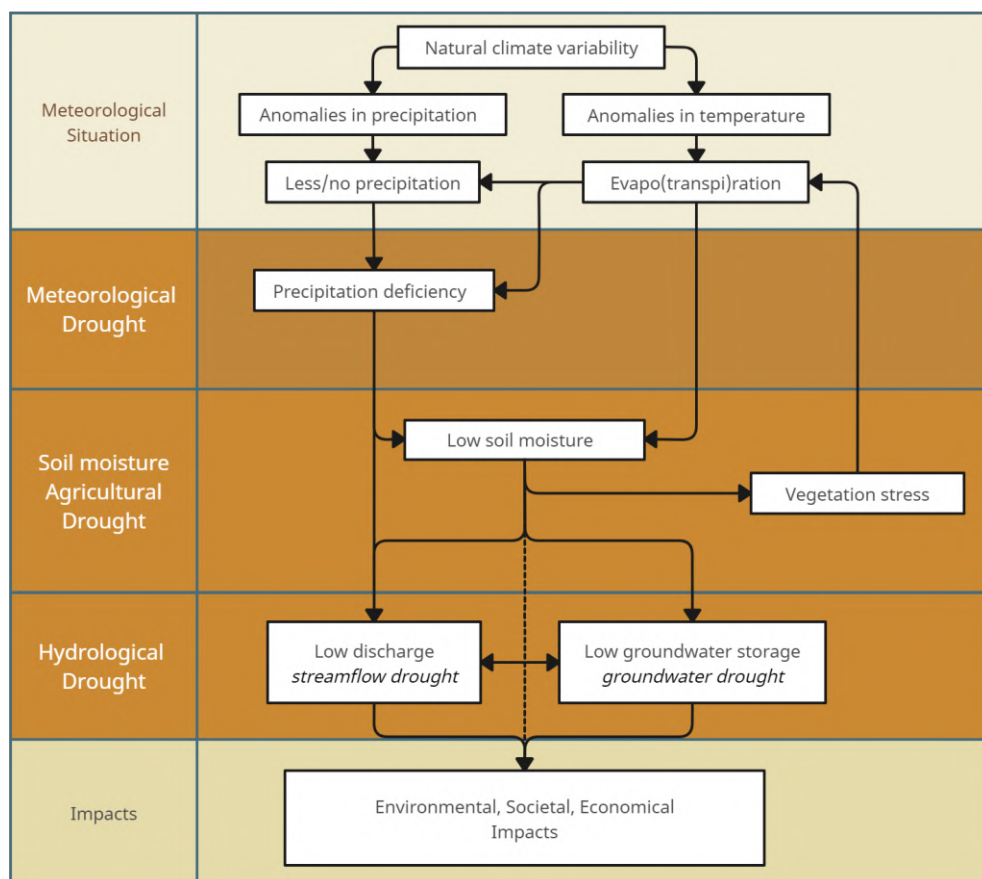


Figure 3: Types of droughts and their development (Adapted from Stahl, 2001; Van Loon, 2013)

2.1.1 Meteorological drought

Meteorological drought is characterised by a shortage of precipitation and is often combined with increased potential evapotranspiration (Van Loon, 2015). It occurs over a wide area and often lasts for a prolonged duration. As a result of climatic variability, anomalies in precipitation and temperature can occur that can be associated with large-scale atmospheric or ocean patterns like ENSO or the North Atlantic Oscillation (Kingston et al., 2015). Consequently, atmospheric processes, such as a blocking high-pressure system, can result in low precipitation rates and high temperatures (Fleig et al., 2010; Stahl & Hisdal, 2004). To assess this type of drought in the Netherlands, the KNMI uses precipitation deficit (KNMI, 2018). The KNMI keeps track of the continuous precipitation deficit every year from 1 April to 30 September. From October onwards, the KNMI assumes that precipitation again exceeds evaporation (KNMI, 2018). For determining the precipitation deficiency, the daily difference between calculated potential evaporation and measured precipitation is added up over the entire summer. When this precipitation deficit is greater than in most other years, a meteorological drought exists.

2.1.2 Soil moisture drought

Soil moisture drought is also known as agricultural drought (Van Loon, 2015). It is characterised by a below-average amount of water in the top layer of the soil. When the precipitation deficit is very high, the amount of water in the top layer of the soil also decreases significantly. This water is important for plants as this rootzone is where they get most of their moisture. Therefore, a large precipitation deficit can cause vegetation stress and has negative consequences for agricultural production (KNMI, 2018). The amount of soil moisture is also related to its antecedent condition, evapotranspiration of plants, evaporation from bare soil, runoff to streams and drainage to the groundwater (Van Loon, 2015). From these, the presence of vegetation is a very important factor in soil moisture feedback loops. This is because evapotranspiration rates may rise during a dry and warm weather period due to heightened radiation or wind speed, resulting in additional water loss from the soil (Teuling et al., 2005). In severe droughts, the scarcity of available soil moisture and plant wilting can constrain evapotranspiration, thus limiting further depletion of soil moisture content. However, this limitation may also hinder the generation of local precipitation, contributing to the maintenance of drought conditions (Dekker et al., 2007).

2.1.3 Hydrological drought

Hydrological drought is characterised by decreased levels of surface and subsurface water compared to average situations (Van Loon, 2015). A decrease in river discharge, lower water levels of surface waters and below-normal groundwater levels are examples of hydrological droughts. However, the below-normal discharge and groundwater levels are sometimes distinguished as streamflow drought (Feyen & Dankers, 2009) and groundwater drought (Mishra & Singh, 2010; Van Huijgevoort, 2014). A streamflow drought is a result of a decrease in discharge that can be caused by extended periods of low precipitation and high evaporation rates. A groundwater drought is a result of a decrease in groundwater levels. These actual groundwater levels are influenced by the initial conditions before an event occurs. Besides that, it is dependent on the speed at which the groundwater levels decrease during a dry event. This is determined by the balance between recharge and discharge rates and the storage properties of the aquifer (Van Loon, 2015). These recharge rates can be influenced by the depletion of soil moisture storage, as less soil moisture content could lead to less groundwater recharge. Since discharge is closely connected to storage (Van Lanen

et al., 2004), reduced groundwater levels can result in decreased groundwater discharge, which slows down the depletion of the aquifer. However, the primary source of streamflow during dry periods is through baseflow, the gradual release of groundwater. The fast pathways such as surface runoff and interflow, which are responsible for discharge during wetter conditions, are typically restricted during droughts (Van Loon, 2015). Therefore, reduced groundwater levels can lead to a decline in streamflow. Due to the delayed and gradual response of groundwater to climatic influences, groundwater droughts may not always develop. However, when they do occur, they frequently show extended durations of groundwater levels below normal (Van Loon, 2015). In addition, when there is sufficient access to open water or groundwater, farmers can utilise it to water their crops, thereby reducing the damaging effects of the meteorological and agricultural droughts (KNMI, 2018). However, this may also decline the surface and subsurface water levels resulting in hydrological drought conditions.

2.2 Drought Indices

To understand the processes, effects, and propagation of droughts, it is necessary to identify key characteristics of drought, including the timing, duration, severity or intensity, and spatial extent of the drought event (Tallaksen & Van Lanen, 2004). To quantify this, drought indices are generally used (Bloomfield et al., 2015). There are different drought indices, and which is chosen and used is important to consider, since it influences the conclusions of research (Van Loon, 2015). However, there appears to be agreement among scientists that there is not a universally 'best' drought index (Hayes et al., 2011). The widely used drought indices can be broadly categorised into standardised indices and threshold-based indices (Van Loon, 2015). The standardised drought indices represent anomalies from a normal situation in a standardised manner. The threshold-based indices rely on predetermined threshold levels. When the variable falls below this threshold, the location is considered to be experiencing drought. In the context of this research, the standardised drought indices are used. The focus is on the impact of the drought adaptation measures throughout the year on the hydrological system in comparison with the normal situation at that time of the year. So, the severity of a drought event is expressed in relative terms. The Standardised Precipitation Index (SPI) is often used to characterise meteorological droughts (McKee et al., 1993) (section 2.2.1). The Standardised Groundwater Index (SGI) is the most-used groundwater drought index (Bloomfield & Marchant, 2013) (section 2.2.2).

2.2.1 Standardised Precipitation Index (SPI)

To quantify wet or dry conditions based on precipitation data, the SPI is developed by McKee et al. (1993). This meteorological drought index relies on long-term historical precipitation data. Given the notable spatial and temporal fluctuations in precipitation, meteorological drought indices often use monthly data. This data is adjusted to conform to a probability distribution using a gamma function for example (Lloyd-Hughes & Saunders, 2002). Subsequently, this distribution is converted into a normal distribution and the SPI is expressed as standard deviations from the long-term mean. This ranges from less than -2, which means extremely dry to +2 or more, which indicates extremely wet (McKee et al., 1993; Bloomfield & Marchant, 2013). The SPI can be calculated across various time intervals such as 1, 3, 6, or 12 months, thereby indirectly reflecting the impact of accumulating deficits in precipitation. The SPI offers several benefits, including the normalisation of values and the ability to calculate them over various time periods (Sheffield & Wood, 2011). However, the disadvantage of the SPI is that it only takes precipitation into

account, potentially overlooking the influence of other meteorological factors such as surface air temperature and evaporation (Dai, 2010). Moreover, the length of the precipitation dataset (Wu et al., 2005) and the selection of the appropriate probability distribution (Stagge et al., 2015) can greatly affect SPI values.

2.2.2 Standardised Groundwater Index (SGI)

The SGI is an index developed by Bloomfield and Marchant (2013) for standardising groundwater level data and it helps in quantifying groundwater droughts. The SGI builds on the SPI, but is specified for groundwater level data, which may have different patterns and characteristics than precipitation data. A statistical method, a non-parametric normal scores transform, is used to standardise the groundwater level data for each month of the year. So, it doesn't assume any specific distribution for the data and it aims to make the data conform to a standard normal distribution. The groundwater level data is analysed separately for each month of the year. These monthly estimates are combined to create a single, continuous index. This index provides a comprehensive overview of groundwater level variations over time, allowing for the identification and characterization of groundwater droughts. Since this SGI is comparable to the SPI and other variables of the terrestrial hydrological cycle, it can be a useful tool in drought propagation research (Kumar et al., 2016; Van Loon, 2015).

2.3 Hydrological signatures

Hydrologic signatures are quantitative metrics that describe statistical or dynamic characteristics of hydrologic data series, primarily streamflow. Numerous hydrologic signatures have been suggested, leading to various categorizations as outlined in the overview paper by McMillan (2020). The hydrological signatures enable us to derive significant insights about watershed dynamics from hydrologic/streamflow data. Signatures are also applied to other hydrologic data types. For example, to the characterization of groundwater dynamics, which is defined and quantified in several studies (Heudorfer et al., 2019; Von Asmuth and Klotters, 2004). Usually, the statistical characterization employs statistical parameters such as mean, highest and lowest groundwater levels (Von Asmuth & Klotters, 2004). In the context of the determination of the impact of the drought adaptation measures on groundwater levels in this research, the GWL5, GWL20, GWL50, GWL80, GWL95 are used. These represent the values below which 5, 20, 50, 80 and 95% of the data falls, respectively. Besides that, other groundwater signatures are useful to characterise groundwater level time series. For example, the slope of the duration curve, which is defined as the rate of change in groundwater levels as a function of time. The cumulative frequency of exceedance is plotted against the groundwater level (Oudin et al., 2010). The slope of this curve represents how quickly groundwater levels change with respect to time. A steeper slope indicates more rapid changes in groundwater levels, while a shallower slope suggests more gradual changes. Another groundwater signature is interannual variation, which is the average between the range in annually averaged three highest monthly values and the range in annually averaged three lowest monthly values ($s = ((\text{max_HW} - \text{min_HW}) + (\text{max_LW} - \text{min_LW})) / 2$) (Martens et al., 2013). A higher value indicates a more variable time series. Besides that, an average seasonal fluctuation can be determined, which is defined as the mean annual difference between the averaged three highest monthly heads per year and the averaged three lowest monthly heads per year ($s = \text{MHW} - \text{MLW}$) (Martens et al., 2013). A higher value indicates a more seasonal head. Furthermore, the mean annual maximum and minimum can be determined to characterise groundwater level time series (Clausen & Biggs, 2000).

3. Methodology

This chapter provides a detailed explanation of the data collection process and methods for this research. Figure 4 provides an overview of the methodological approach to address the research objectives. The first step is the data preparation of the collected raw data (section 3.1). Analysing the impact of the drought adaptation measure on drought propagation and changes in groundwater levels, requires groundwater level time series on long time scales which are undisturbed. However, generally time series of groundwater levels often have interruptions, have potential limitations in observations and/or have missing data. Therefore, it requires some preparation (section 3.2) before the data is suitable for analysis. The input data that is created within the first step, is analysed to gain an overall understanding of the influences of the drought adaptation measure on drought propagation and on the hydrological system in terms of groundwater levels (section 3.3). These results are interpreted and placed in a broader perspective in the discussion.

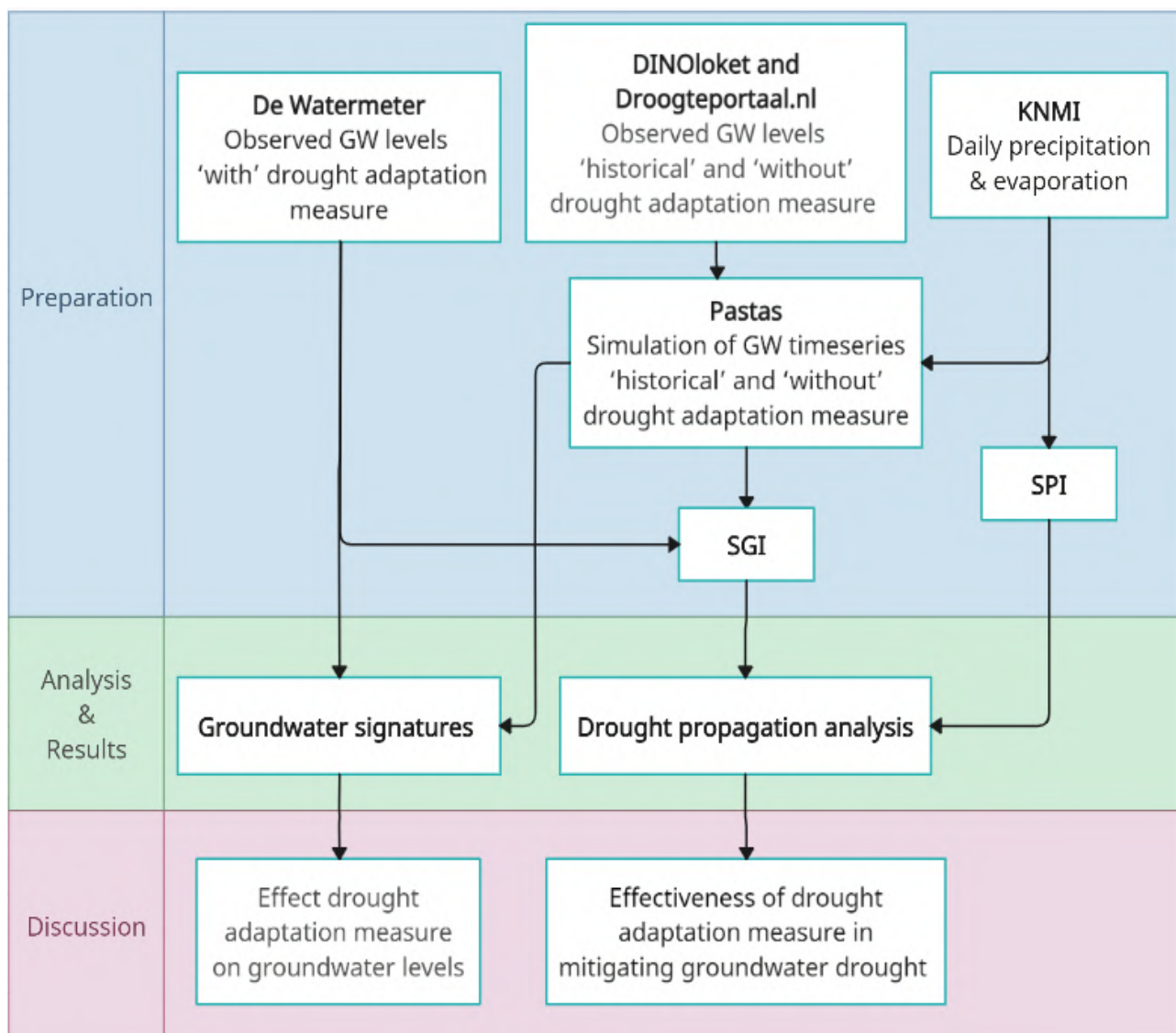


Figure 4: Overview of the methodological approach to address the research objectives.

3.1 Study area and raw data

Figure 5 shows the research area. This area is divided into study areas A and B. Study area A is the project location near Breklenkamp that is initialised, funded, and monitored by *Waterschap Vechstroom*. In this study area, weirs were implemented in 2021. Study area B is located south of Breklenkamp and has similar characteristics as area A; however, no drought adaptation measures were actively installed in this area. Figure 5 shows the locations of the groundwater monitoring wells used in this study. Table 1 presents an overview of these groundwater wells and the available observed time series. The observed groundwater level time series of area A after the implementation of the drought adaptation measure were retrieved from 'dewatermeter.nl' and were coded with GW01-GW05. Those of area A and B without drought adaptation measures were obtained from 'DINOloket.nl' and 'Droogteportaal.nl' and were coded with A1 and B1-B7. Besides that, daily evaporation and precipitation data were derived from the KNMI meteorological station Twenthe.

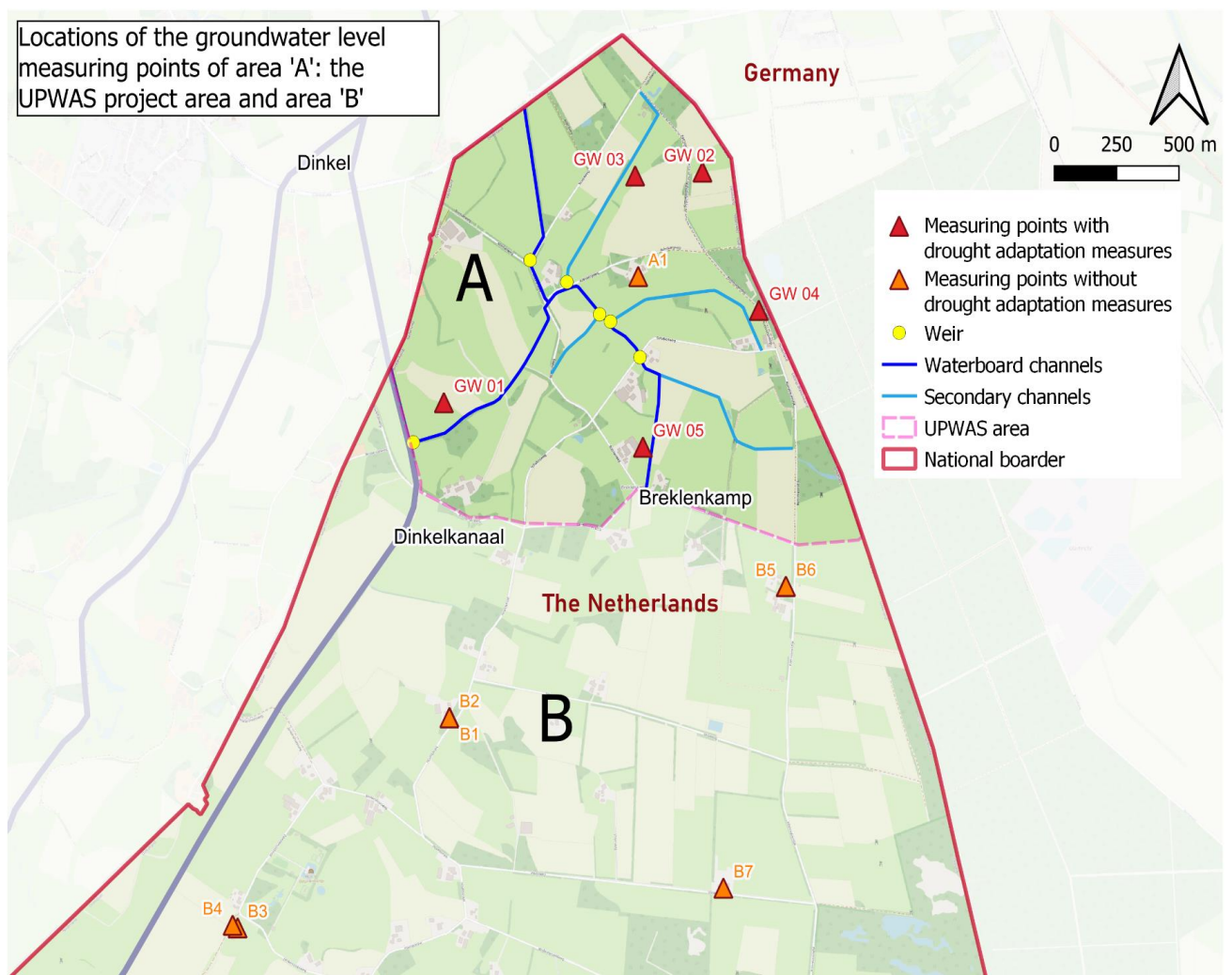


Figure 5: Locations of the groundwater measuring points with the observed groundwater level time series.

Table 1: Overview of the groundwater measuring points, their corresponding monitoring well code and their available data.

Groundwater measuring point	Monitoring well code	Available data
Area A		
GW 01-05		summer 2021- now
A1	B29A0156-001	1984-2007
Area B		
B1	B29A0730-001	2009-2020
B2	B29A0143-001	1984-2008
B3	B29A0103-001	2001-2007
B4	B29A0102-001	1960-2001
B5	B29A0057-001	1984-2007
B6	GLD000000037133	2000-now
B7	B29A0144-001	1984-1999

3.2 Input data

The observed groundwater level time series of groundwater measuring points GW01-GW05 were complete and formed the input data for the ‘*with*’ drought adaptation measure situation. To make a comparison of the effects of the drought adaptation measure on groundwater levels, groundwater level time series were created for a situation when the measure was not implemented. For this end, groundwater level simulations of groundwater measuring points A1 and B1-B7 (section 3.2.1) were used since these measuring points did not all have complete time series. The simulations were done for the after-implementation period that runs from 2021 until April 2024. These simulations formed the input data for the ‘*without*’ drought adaptation measure situation. Besides that, the simulations were performed for the period before the implementation of the drought adaptation measure. The before-implementation period runs from 1987-2021 and this formed the input data for the ‘*historical*’ period. Furthermore, the model and spatial uncertainty of the input data were calculated (section 3.2.2). Finally, for each time series, the SGI was determined (section 3.2.3). Besides that, the SPI (section 3.2.3) was determined. The SGI and SPI were used as input data in the drought propagation analysis.

3.2.1 Groundwater level simulations

The groundwater levels of the ‘*without*’ and ‘*historical*’ situation for groundwater measuring points A1 and B1-B7 were simulated with a time series model using the Pastas package in Python. The Pastas package, developed by Collenteur et al. (2019), is an open-source Python package designed for processing, simulating, and examining groundwater time series. With this method, the modelled groundwater level time series is based on the input of the meteorological data precipitation and evaporation.

The model for each measuring point was calibrated and validated to their observed groundwater level time series. Since the time series was calibrated and validated with observed data without the implementation of the drought adaptation measure, it was assumed that this simulated groundwater level time series does not take into account the measure implemented. For each calibration period, the first two-thirds of the observed groundwater level time series was used (Table 2). First, the model was solved for this calibration period to obtain a set of initial parameter values that are a good starting point. This was solved without including a noise model because this approach simplifies the parameter estimation process since there is less variability to account for. After obtaining an initial set of parameters, the model was solved with a noise model incorporated without re-initializing the parameters. This approach led to the highest R-squared correlation values (Table 2), which gives an indication of how well the simulated groundwater levels match their observed data. The remaining one-third of the observed groundwater level time series was used for the validation of the models (Table 2). An example of the modelled groundwater levels for groundwater measuring point A1 is given in Figure 6. The graphs of the model results of the other groundwater measuring points are in appendix A.

Table 2: Overview of the groundwater measuring points, their calibration and validation period and their corresponding R-squared values.

Groundwater measuring point	Calibration period	R2 Calibration	Validation period	R2 Validation
A1	16/04/1987-22/11/2000	0.81	22/11/2000-12/09/2007	0.69
B1	20/01/2009-17/10/2016	0.79	17/10/2016-31/08/2020	0.80
B2	16/04/1987-16/05/2001	0.86	16/05/2001-31/05/2008	0.85
B3	14/03/2001-03/07/2005	0.89	03/07/2005-28/08/2007	0.69
B4	16/04/1987-15/07/1996	0.85	15/07/1996-28/02/2001	0.74
B5	16/04/1987-22/11/2000	0.85	22/11/2000-12/09/2007	0.71
B6	13/01/2000-11/02/2016	0.79	11/02/2016-26/02/2024	0.68
B7	16/04/1987-14/09/1995	0.86	14/09/1995-29/11/1999	0.83

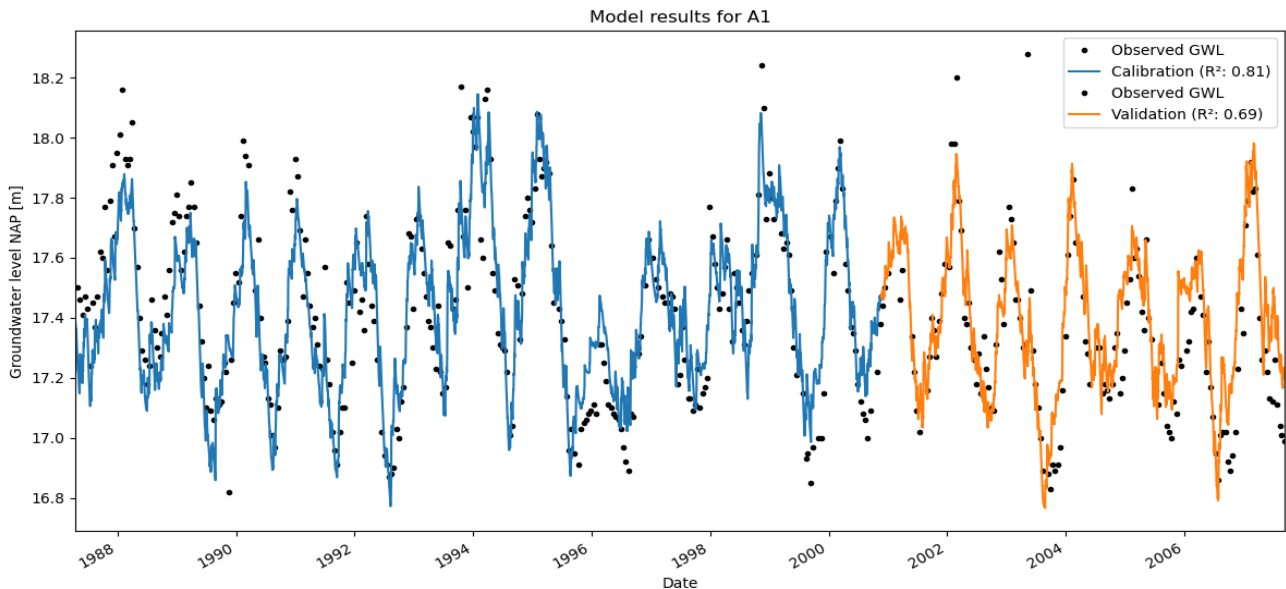


Figure 6: The observed groundwater levels for groundwater measuring point A1 indicated in black dots, its modelled groundwater levels during the calibration period in blue and the validation period in orange.

3.2.2 Uncertainties

Overall, the time series of A1 provided a good indication of how the groundwater levels respond to precipitation and evaporation in the study area A. The groundwater level time series of B1-B7 gave a good estimation of how the groundwater levels respond to precipitation and evaporation near the study area. In addition, model and spatial uncertainty were also taken into account. First, to compensate for differences in topography, the groundwater level time series were centralised around their mean. The average of the residuals of the observed groundwater level time series compared with its simulated time series formed an indication of this model uncertainty (Table 3). The absolute values of the residuals were taken before averaging to ensure that all the negative residuals did not outbalance the positive. The average of the residuals of the observed groundwater level time series of areas A and B for their overlapping time periods formed indications of the spatial uncertainty (Table 3).

Table 3: The model and spatial uncertainties in deviations from the mean (m) of each groundwater measuring point.

Groundwater measuring point	Model uncertainty	Spatial uncertainty
A1	0.11	0.00
B1	0.13	x
B2	0.12	0.13
B3	0.13	0.15
B4	0.17	0.17
B5	0.13	0.11
B6	0.20	0.10
B7	0.12	0.13

3.2.3 SPI and SGI

The SPI was computed using the SPI tool (si.spi) of the SPEI package in Python. The SPEI package, developed by Vonk (2024), is used to calculate drought indices for time series such as the SPI, Standardised Precipitation Evaporation Index (SPEI), and SGI. The precipitation data from 1987 until April 2024 was used to determine the SPI. This data is adjusted to conform to a probability distribution using a gamma function. It was computed for an accumulation period of 30 days (SPI-1), 90 days (SPI-3) and 180 days (SPI- 6) to reveal variations in drought occurrences for different time scales. It showed if droughts are present relative to the 'normal' situation of that month, season, and half of the year. In this way, the duration and frequency of drought events could be determined throughout the year. For example, a relatively dry winter can also be recognised with the use of these shorter accumulation periods as used in SPI-1. The SGI was computed for each time series using the SGI tool (si.sgi) of the SPEI package in Python. This computation of the SGI is based on the description in Bloomfield and Marchant (2013). The SGI-1 was determined for the time series of the 'with' and 'without' situation since it captures short-term variability in groundwater levels. Thereby, it allows for the detection of short-term fluctuations and trends throughout the year. However, the 'with' and 'without' period is short, with 3 years of data. Therefore, the SGI was based on the 'historical' period since it provided a more robust and representative baseline against which to compare whether the situation is drier or wetter than normal. This extended timeframe captures a broader range of natural variability and information about average drier and wetter conditions. This approach ensures that short-term anomalies do not skew the analysis.

3.3 Data analysis and results

For the analysis of the influence of the drought adaptation measure on groundwater levels, groundwater signatures were used to characterise the groundwater level time series of the 'historical', 'with' and 'without' situations (section 3.3.1). Besides that, a correlation analysis of the SGIs and the SPIs with different accumulation periods was performed to determine drought propagation for the situation 'with' and 'without' the drought adaptation measure implemented (section 3.3.2). In addition, t-tests of the results were performed to determine whether the differences between the 'historical', 'without' and 'with' groups were statistically significant.

3.3.1 Groundwater signatures

To compare the behaviour of the groundwater level in the study area, the groundwater time series was centred around the mean to compensate for the differences in topography. The influence of the drought adaptation measure on groundwater levels was characterised by determining groundwater signatures for each time series. The lowest to highest groundwater levels were calculated in Python. This was done using the GWL5, GWL20, GWL50, GWL80 and GWL95. These signatures were chosen, since the GWL5 and GWL20 gave information about the low levels of the groundwater level time series, whereas the GWL80 and GWL95 provided information about the high levels. Besides that, five other groundwater signatures were determined by using the signatures module in the Pastas.stats sub-package. One of these was the slope of the duration curve. It was calculated after Oudin et al. (2010). It was used, since it provided information about how gradually groundwater levels change over time. Moreover, the interannual variation was calculated after Martens et al. (2013). Besides that, the average seasonal fluctuation was determined after Martens et al. (2013). These two signatures were chosen to characterise variations between and throughout the years.

Furthermore, the mean annual maximum and minimum were calculated after Clausen and Biggs (2000), to provide more information about the high and low peak water levels of the time series.

3.3.2 Drought propagation analysis

A drought propagation analysis can give insight in the effectiveness of the drought adaptation measure in mitigating hydrological groundwater droughts. To examine drought propagation, an analysis between the SPI-1, SPI-3 and SPI-6 with SGI-1 was performed. It provided the relationship between rainfall patterns and groundwater levels for different timescales. To quantify this relation, the Spearman correlation was conducted to examine whether the two variables were correlated with one another, since it uses ranks instead of assumptions of normality like the Pearson test, for example (De Winter et al., 2016). As noted by Kumar et al. (2016), the propagation of precipitation signals to groundwater is non-linear, so the Spearman correlation is more appropriate when comparing SPI and SGI. A higher correlation value indicates more drought propagation. This correlation analysis was done for each time series of the 'with' and 'without' situations, to determine the effect of the drought adaptation measure on drought propagation. In addition, the SGI of each time series of the 'with' and 'without' situations was used to determine the number of days with drought conditions. This was performed with a threshold of 0, which indicates mild drier conditions than normal and with a threshold of -1, which indicates moderately drier conditions. Furthermore, the number of droughts was determined by calculating how often continuous days of drought conditions were present. The average duration of these droughts was determined by calculating their average length in days. Besides that, their average deficit was determined by calculating the average of the surface areas below the thresholds. These four variables were compared to characterise the effect of the drought adaptation measure on groundwater droughts.

4 Results

4.1 Groundwater levels during the ‘historical’ period

Figure 7 shows the simulated groundwater level time series for the period 1987-2021, before the implementation of drought adaptation measures. Each time series is centralised around their mean for better comparison. The overall trend shows a small decline in groundwater levels. Besides that, the seasonality is present with summer periods which are characterised by lower groundwater levels with a deviation of around -0.5m from the mean compared to the winter periods that are characterised by higher groundwater levels with a deviation of around 0.5m from the mean. However, there are also outliers. For example, the 1996 winter period has a low deviation from the mean of about 0.25m and thus a relatively low groundwater level. Besides that, periods with the highest groundwater levels are present in 1994, 1995, 1999, 2000, 2002 and 2007. Furthermore, periods with the lowest groundwater levels occurred in 1992, 2003, 2006, 2010, 2016, 2018, 2019 and 2020.

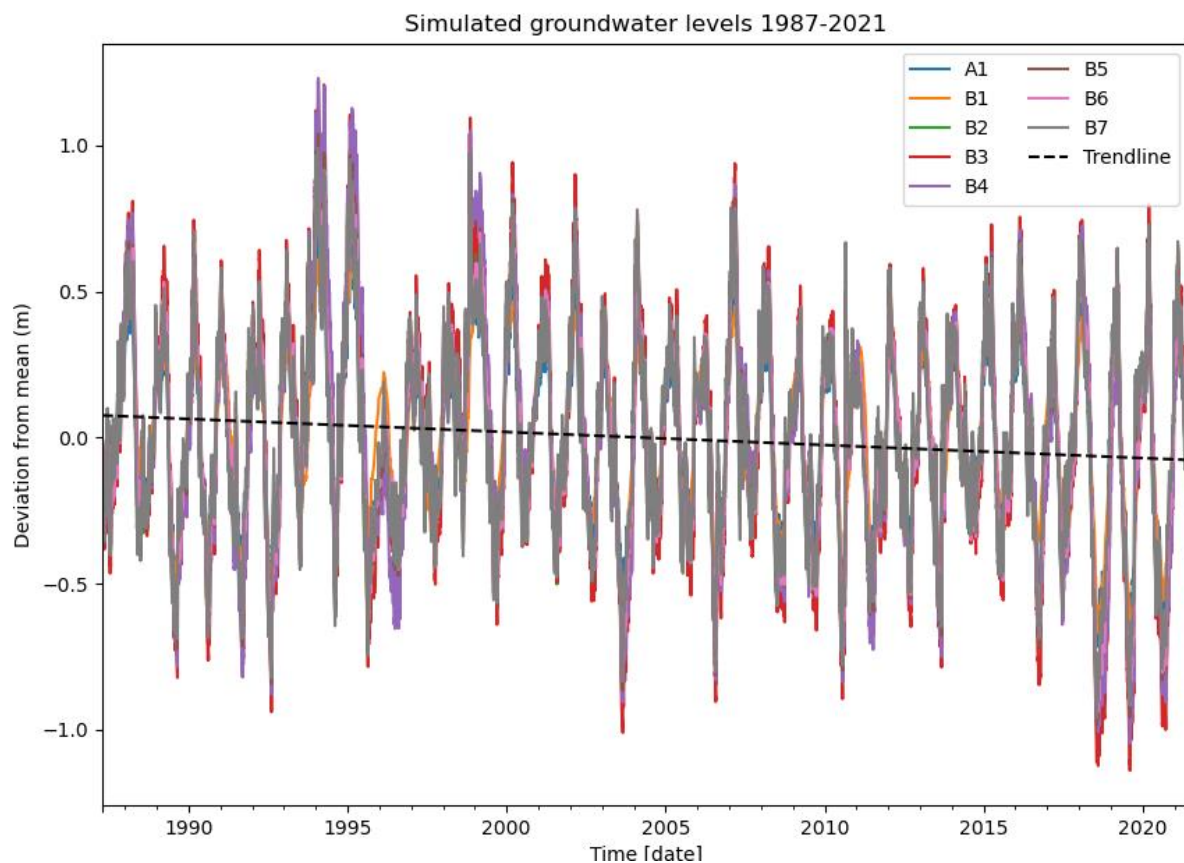


Figure 7: The simulated groundwater levels of groundwater measuring points A1 and B1-B7 for the ‘historical’ period. The deviation from the mean is plotted against the time in years. Besides that, the overall trendline of the measuring points together is included.

4.2 Groundwater levels of the ‘with’ and ‘without’ drought adaptation measure situation

Figure 8 shows the simulated groundwater level time series for the period 2021-2024. GW01-GW05 are solid lines that represent the ‘with’ drought adaptation measure situation. A1 and B1-B7 are dotted lines, and they represent the ‘without’ situation. Overall, it shows that mostly the groundwater levels of the ‘with’ group are a bit higher and have more fluctuations on small timescales of weeks for example. Figure 8 also shows that during the summer of 2021, the groundwater levels decline from around 0.15m towards -0.5m deviations from the mean for the ‘without’ situation and from 0.35m towards -0.35m in the ‘with’ situation. After that, the groundwater levels for both groups increase towards a deviation from the mean of around 0.75m until the end of the winter period. In summer 2022, the groundwater levels in the ‘without’ situation have declined to around -1.2m deviations from the mean, while those of the ‘with’ situation decline more gradually towards a deviation from the mean of around -0.6m. The groundwater levels of the ‘with’ group stay around that value until November 2022, while those of the ‘without’ are increasing and show higher values. After that, the groundwater levels increase towards a deviation from the mean of around 0.45m until May 2023 for both groups. Thereafter, they decrease towards -0.45m for the ‘without’ situation and show a more varying pattern with mostly higher values of those of the ‘with’ situation. After summer 2023, the groundwater levels increase towards a deviation from the mean of around 1m. From the beginning of 2024 until May 2024, the groundwater levels of the ‘without’ situation are overall higher than those ‘with’.

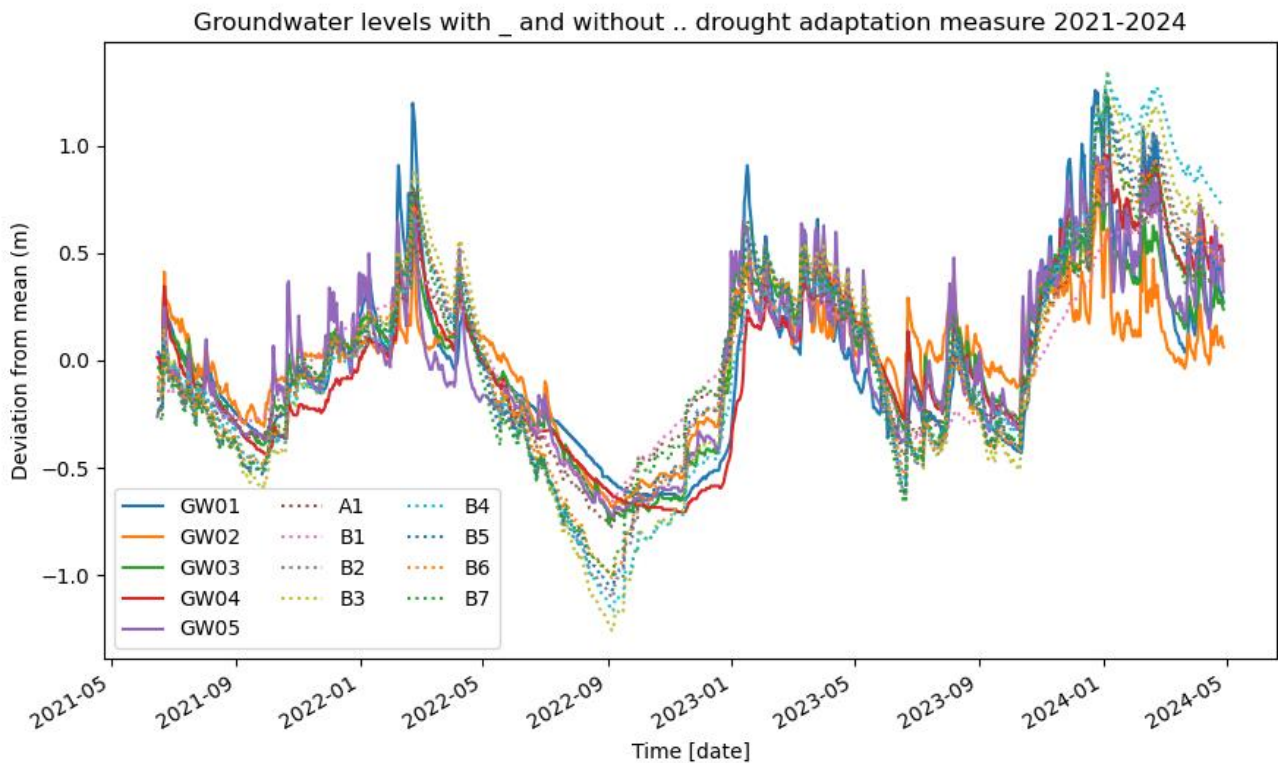


Figure 8: The groundwater levels of GW01 - GW05 ‘with’ drought adaptation measure implemented in solid lines. Besides that, the groundwater levels of A1 and B1-B7 for the ‘without’ situation in dotted lines. The deviation from the mean is plotted against the time.

To check whether the groundwater level differences between the ‘with’ and the ‘without’ groups fall out of range of the model and spatial uncertainty, the time series of the ‘without’ group are plotted with its uncertainty bands. As an example, Figure 9 shows a closer look at the ‘with’ group and the time series A1 of the ‘without’ group. This comparison is shown, since groundwater measuring point A1 is in the same area as the groundwater measuring points of the ‘with’ group (Figure 5). In summer periods, the ‘with’ group shows higher groundwater levels than A1 including its uncertainty band. Besides that, the ‘with’ group shows lower values from September 2022 until the end of 2022. Furthermore, the ‘with’ group has during the winter periods more comparable or lower values than A1.

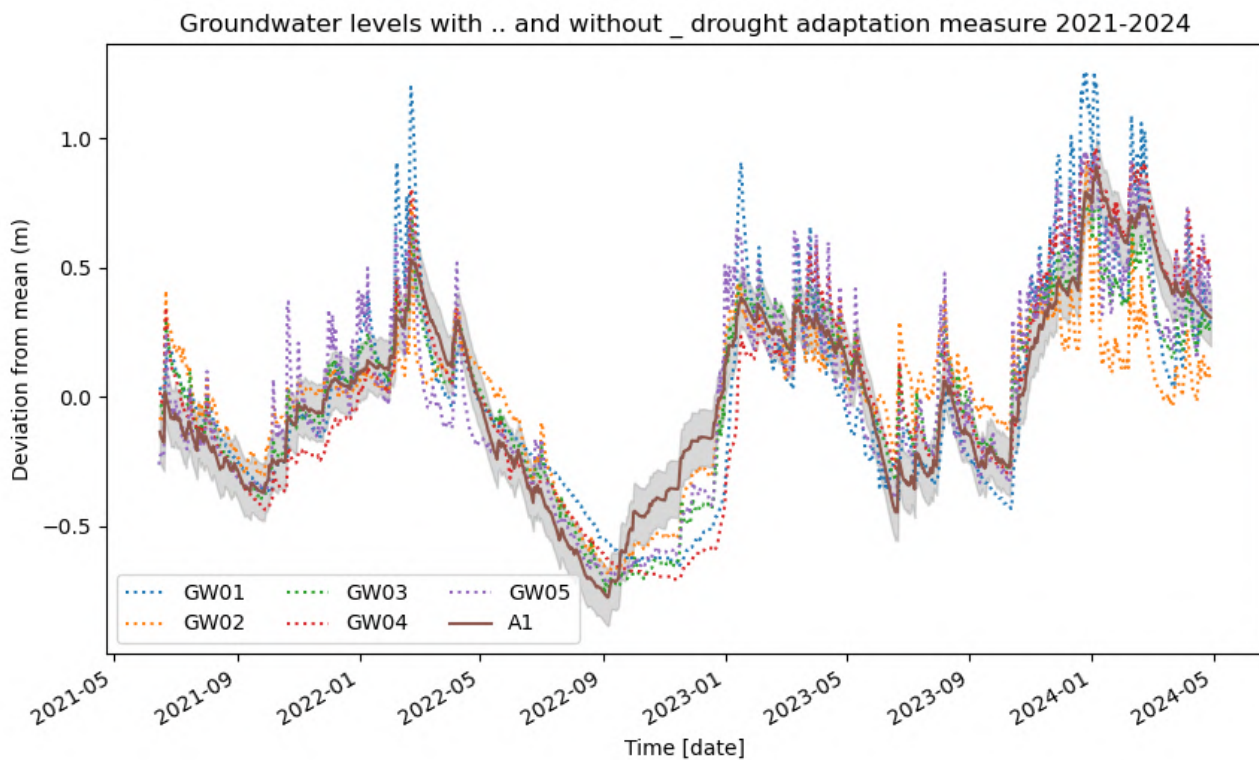


Figure 9: The groundwater levels for the period 2021-2024 of GW01 - GW05 for the ‘with’ drought adaptation measure group in dotted lines. Besides that, the groundwater level of groundwater measuring point A1 for the ‘without’ group is represented in a solid line. In grey the uncertainty band of A1. The deviation from the mean is plotted against the time.

As another example, Figure 10 shows a closer look at the ‘with’ group and time series B6 of the ‘without’ group. This comparison is made, since groundwater measuring point B6 has available observation data until the beginning of 2024 (Table 1) and is close to the same area as the ‘with’ group (Figure 5). In the summer periods, the ‘with’ group has on average slightly higher values in comparison with B6 including its uncertainty band. Especially towards the end of the summer of 2022, the deviation of the mean is around -1m in the ‘without’ situation, while those of the ‘with’ are more around 0.5m. Besides that, the ‘with’ group has during the winter periods lower values than B6, especially in 2024.

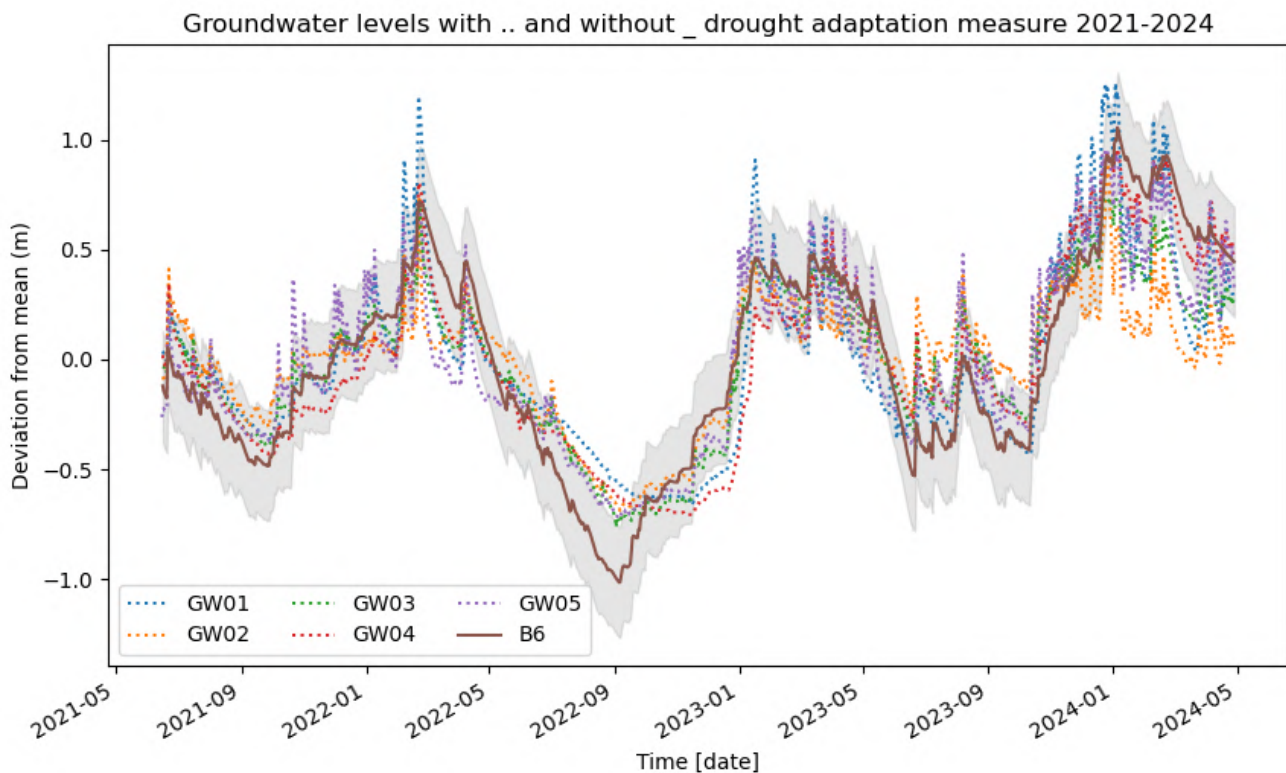


Figure 10: The groundwater levels for the period 2021-2024 of GW01 - GW05 for the ‘with’ drought adaptation measure group in dotted lines. Besides that, the groundwater level of groundwater measuring point B6 for the ‘without’ group is represented in a solid line. In grey the uncertainty band of B6. The deviation from the mean is plotted against the time.

The groundwater levels of the other groundwater measuring stations of the ‘without’ group with their uncertainty bands compared to the groundwater levels of the ‘with’ group are in appendix B.

4.3 Groundwater signatures

Figure 11 and Figure 12 show the results of the groundwater signatures, which are used to characterise the groundwater level time series of the 'historical', 'without' and 'with' groups.

The GWL5 and GWL20 (Figure 11) of the 'historical' period show higher values than the 'without' group. This indicates that the 5 and 20% lowest groundwater levels that are present during the 'without' period are lower than these during the 'historical' period. However, the GWL5 and GWL20 of the 'with' group are higher than the 'without' group, which indicates less low groundwater level values for the 'with' group. Besides that, the 'with' group shows the lowest spread in these signatures. The GWL50 (Figure 11) is for the three categories approximately the same by median values of -0.01m, -0.04m and -0.05m deviations from the mean. The GWL80 and GWL95 (Figure 11) show the lowest values for the 'historical' period. The 'without' group shows the highest values and those of the 'with' group are in between. This indicates that the highest groundwater levels that were present during the 'historical' period are lower than those during the 'without' and 'with' periods. Nevertheless, the highest groundwater levels of the 'with' group have lower values than those of the 'without' group. However, the spread of the three groups for the GWL95 is large. Overall, these GWL results show values for the 'with' group that are more similar to the 'historical' situation compared to the 'without' group. In addition, the groundwater levels of the 'historical' and 'with' group are less fluctuating.

The slope of the duration curve (Figure 12) for the 'historical' period has a median value of -0.8. However, for the 'without' group, this signature has a more negative value indicating a steeper decline. The 'with' group demonstrates a less steep slope, although influenced by a high outlier. In terms of inter-annual variation (Figure 12), the 'historical' group has a median value of 0.8. For the 'without' situation, this value is higher and showing greater variability. Contrarily, the 'with' group shows less variation compared to the 'without' group. When examining average seasonal fluctuations, minor differences emerge between the groups. The median values of the mean annual maximum and minimum (Figure 12) of the 'historical' group are 0.6m and -0.6m deviation from the mean respectively. The 'without' group presents higher results for both signatures. The 'with' group shows the highest values but these are also influenced by the presence of outliers.

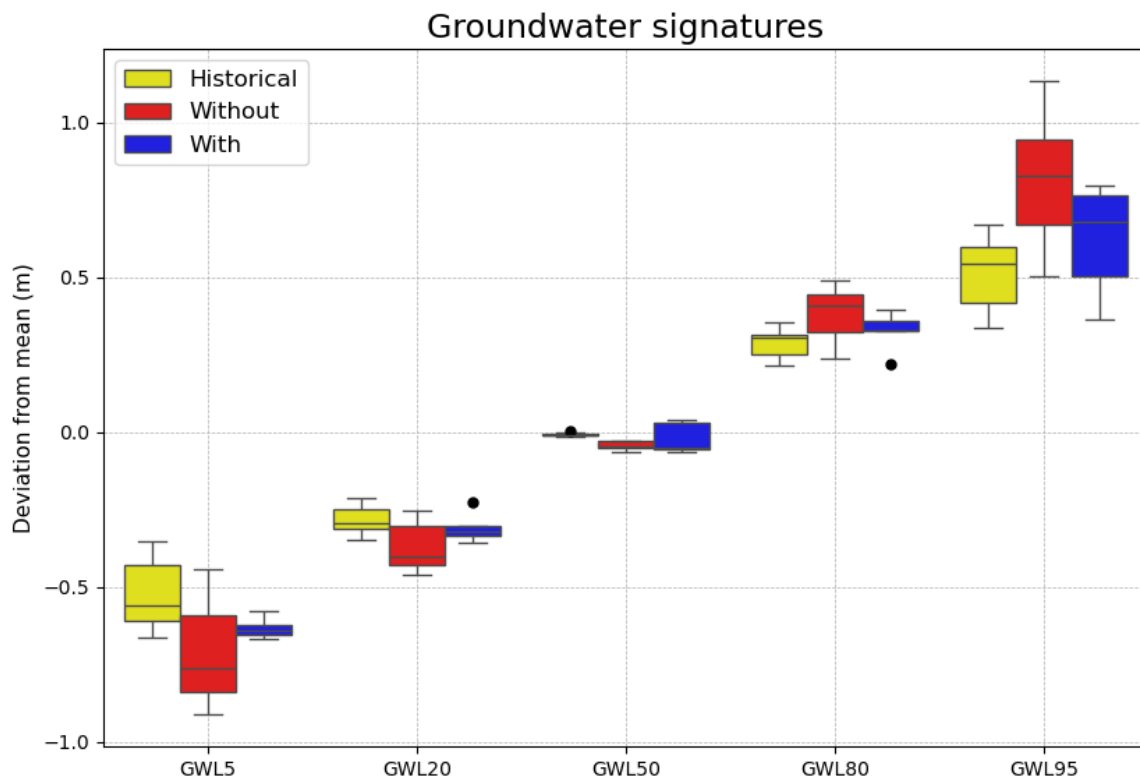


Figure 11: Boxplots of the GWL groundwater signatures of the 'historical', 'without' and 'with' group.

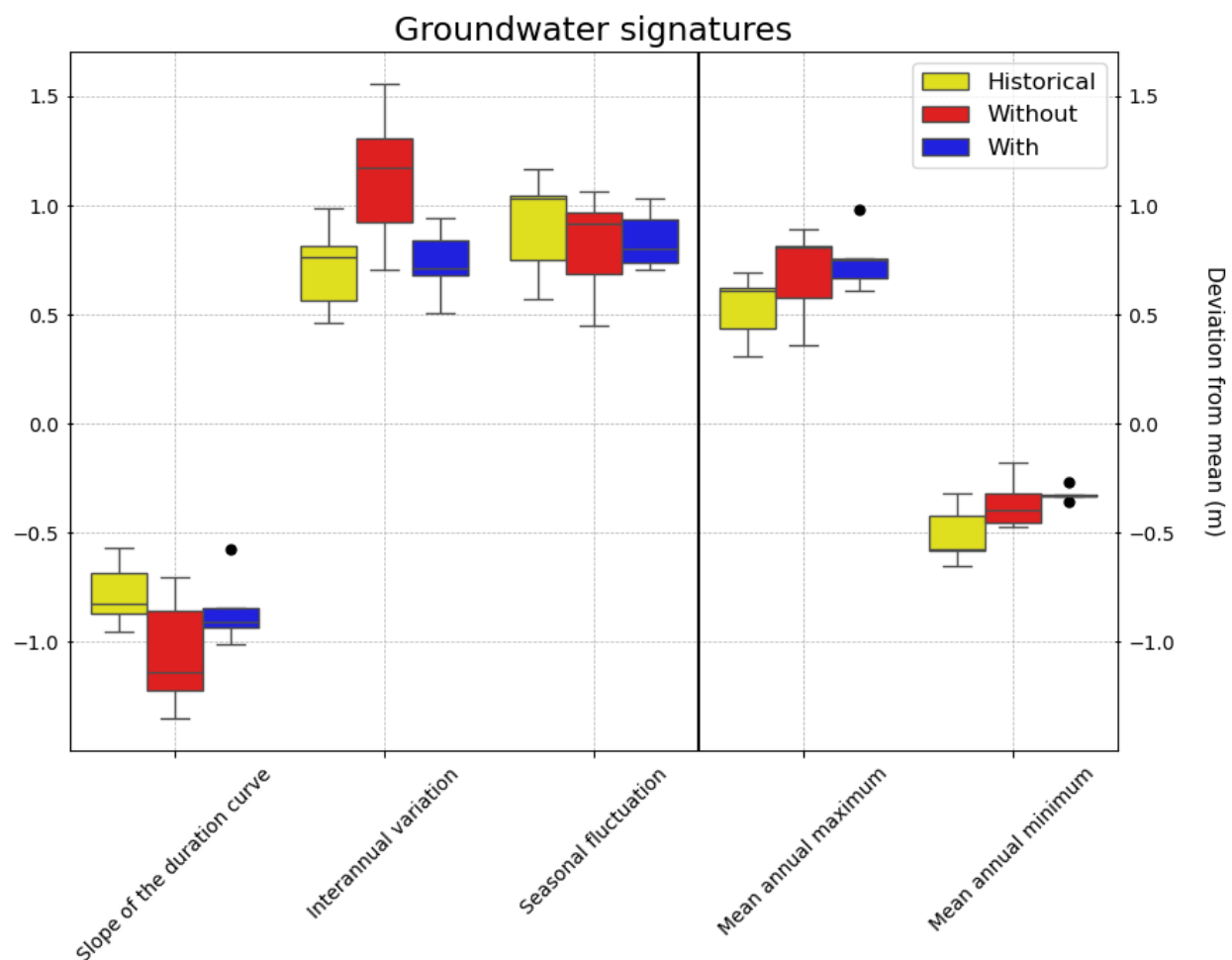


Figure 12: Boxplots of the groundwater signatures of the 'historical', 'without' and 'with' group.

The t-test results (Table 4) show that the differences between the 'with' and the 'without' group are not statistically significant, except the interannual variation. However, the p-values of especially the GWL20, GWL 95 and the slope of the duration curve come close to the 0.05 value indicating statistical significance. The groundwater signatures of the 'historical' compared with the 'without' group all show statistically significant differences, except the seasonal fluctuation and mean annual maximum. The p-values comparing the 'historical' with the 'with' group show much higher p-values, indicating that the outcomes of these variables are more similar.

Table 4: T-test results of the groundwater signatures. The p-values comparing each group with each other is given. ** Indicates statistically significant with $p < 0.05$. * Indicates weak statistically significant with $p < 0.1$.

	p-value		
	'Historical' and 'Without'	'Historical' and 'With'	'Without' and 'With'
GWL5	0.010**	0.071*	0.250
GWL20	0.005**	0.340	0.094*
GWL50	0.000**	0.482	0.201
GWL80	0.012**	0.231	0.236
GWL95	0.002**	0.246	0.097*
Slope of the duration curve	0.003**	0.360	0.079*
Interannual variation	0.002**	0.952	0.012**
Seasonal fluctuation	0.312	0.414	0.884
Mean annual maximum	0.060*	0.015**	0.546
Mean annual minimum	0.012**	0.003**	0.347

4.4 SPI

Figure 13 shows the SPI-1, SPI-3 and SPI-6 from summer 2021 until April 2024. Negative SPI values indicate periods of drier conditions than normal at the monthly, seasonally and half year level, respectively. The more negative, the drier the situation. The SPI-1 shows periods of a negative SPI in 2021 in September-October (towards -1.7) and in December - February 2022 (-0.7). Besides that, in 2022 the SPI is negative in April (-1.5), May-June (-2.5), July-October (-2.9), November (-1.4) and in December (-1.4). In 2023 the SPI is negative in March (-1) and in August (-2.8) and in 2024 in March (-1). In contrast with the SPI-1, the SPI-3 and SPI-6 do not have many periods with a negative SPI. However, those negative periods are longer. The SPI-3 has a period of a negative SPI from September 2021 until January 2022 (-1.1) and from June 2022 until January 2023 (-2.9). The SPI-6 is negative in September-October 2021 (-0.3) and from November 2021 until March 2023 (-2.5). Since the end of 2023, all these SPIs show high positive values towards 2 and higher.

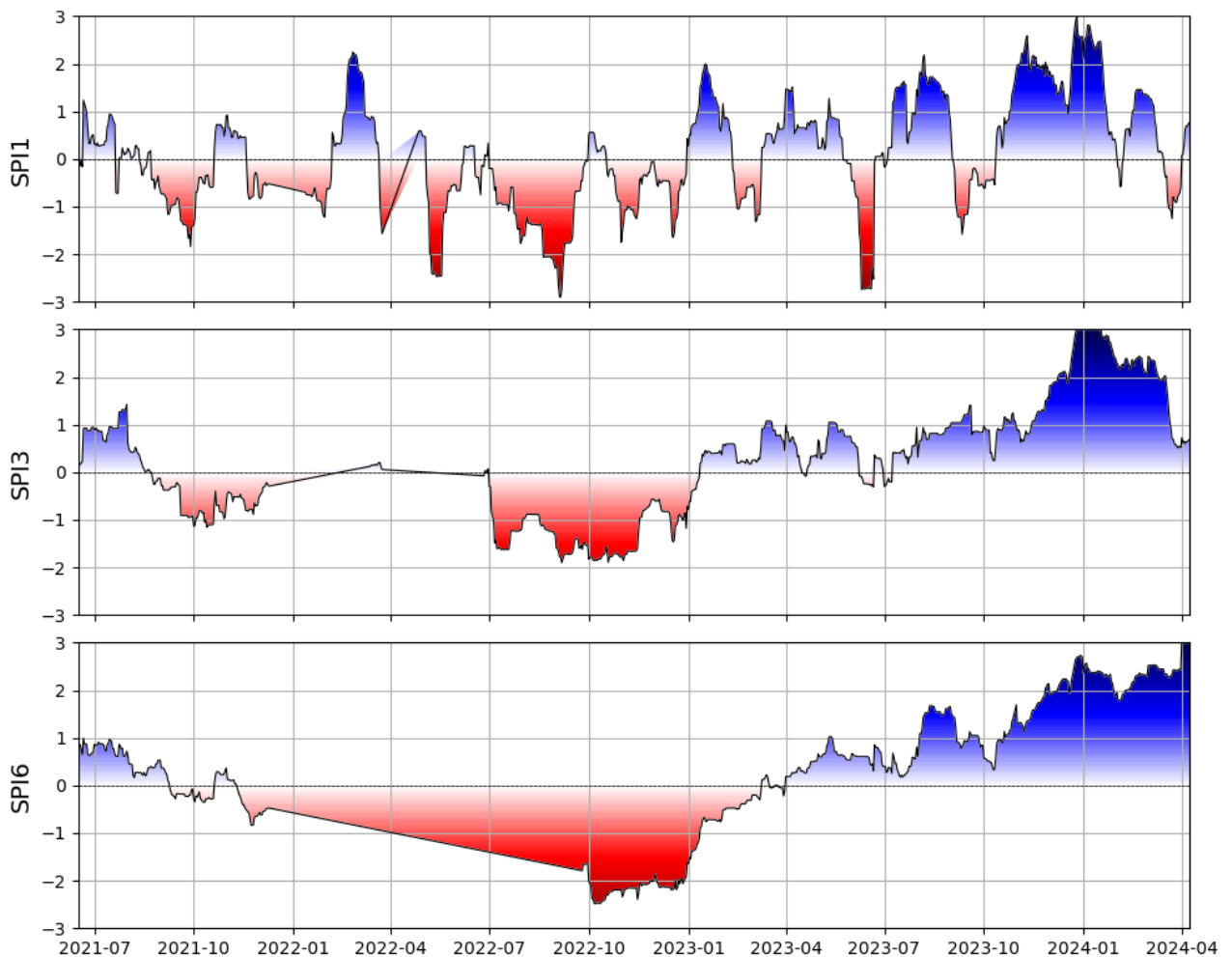


Figure 13: The SPI-1, SPI-3 and SPI-6 for summer 2021 until April 2024 based on the precipitation data of meteorological station Twenthe.

4.5 SGI

Figure 14 shows the SGI of groundwater measuring point GW02 as an example of the 'with' group and of A1 as an example of the 'without' group. The SGI graphs of the other measuring stations are in appendix C. For GW02, periods with a negative value for the SGI are present in 2021 in September (-0.4) and November 2021 until February 2022 (-1.8). Besides that, in 2022, February (-1.8), February-March (-1.6), June (-1), July-December (-3). In 2023, periods with a negative SGI are present in March (-1), April (-0.8) and May (-0.5). In 2024, in January-February (-1.1) and February-March (-2). For A1, the periods with a negative SGI value are present in 2021 in September-November (-1), November (-0.5) and December until February 2022 (-1.3). In 2022 they are present in March (-1) and from May until January 2023 (-3). In 2023 in February-March (-0.9) and May-July (-3) and September-October (-1). Overall, the periods with a negative SGI are longer for the 'without' group.

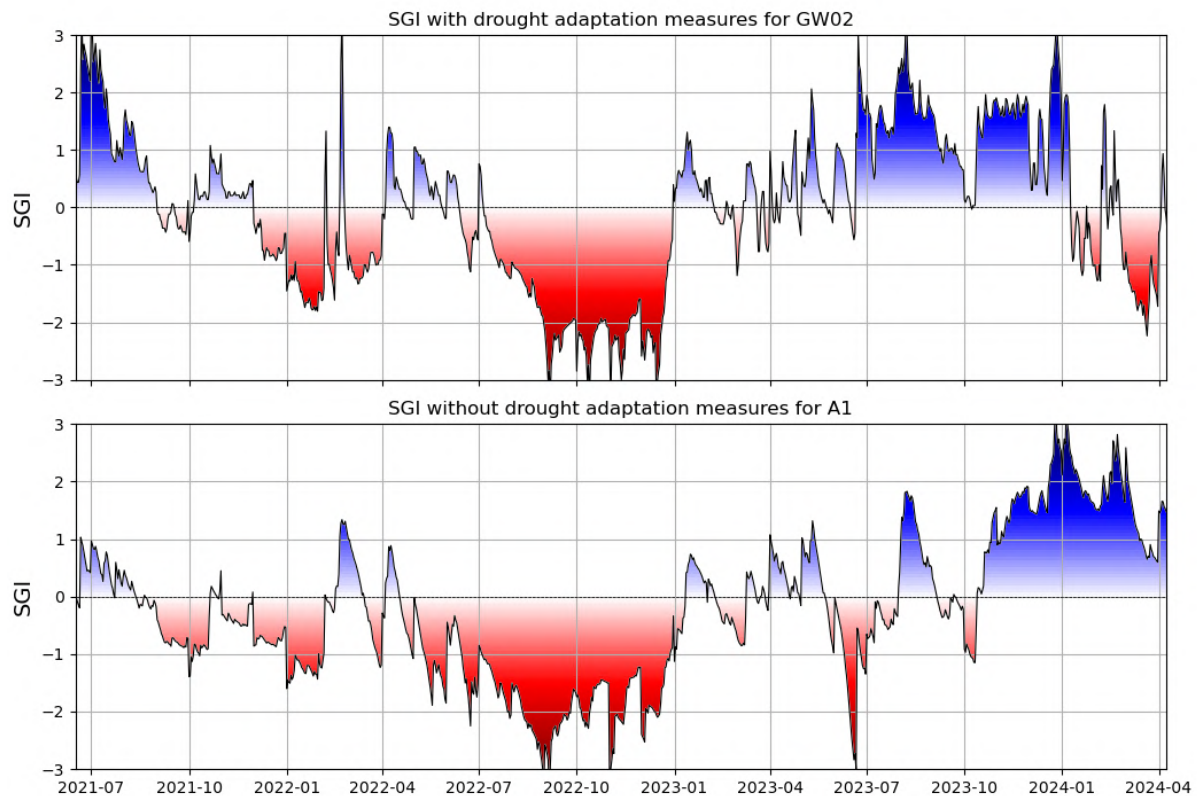


Figure 14: The SGI of groundwater measuring point GW02 of the 'with' group and the SGI of groundwater measuring point A1 of the 'without' group.

4.6 SPI-SGI correlation

Figure 15 shows the Spearman correlation values between the SPIs with the SGIs. The SPI-1, SPI-3 and SPI-6 are correlated with the SGI of each groundwater measuring point of the 'without' and 'with' group. The SPI with the highest correlation values with the measuring points is SPI-3. Furthermore, the 'with' group shows overall lower correlation values than the 'without' group. The correlation values of the 'without' group are around 0.74 with SPI-1, 0.86 with SPI-3 and 0.83 with SPI-6. In comparison, those of the 'with' group are around 0.66 with SPI-1, 0.74 with SPI-3 and 0.67 with SPI-6.

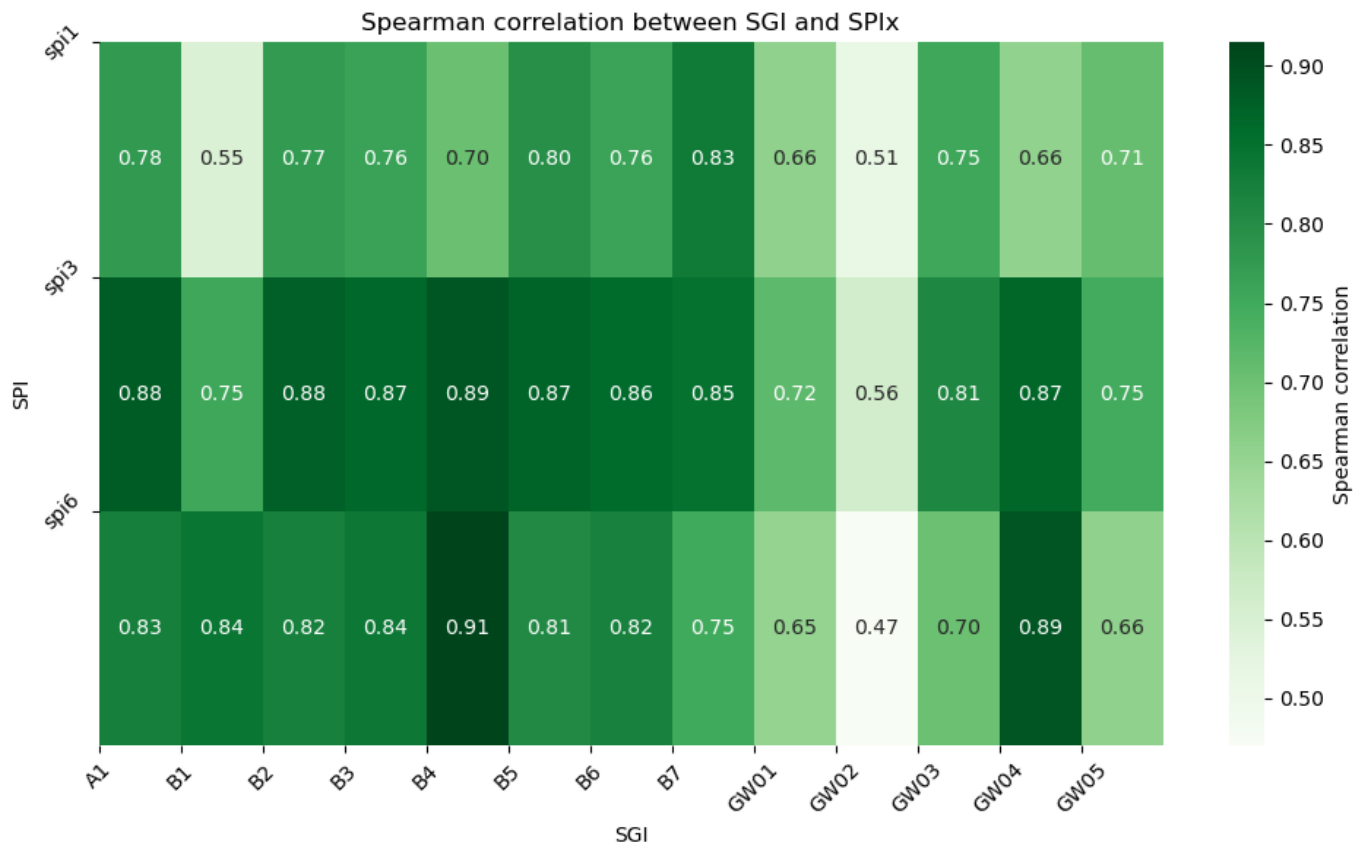


Figure 15: The Spearman correlation between the SPI-1, SPI-3 and SPI-6 with the SGI of each groundwater measuring point of the 'without' (A1, B1-B7) and 'with' (GW01-GW05) group.

4.7 Groundwater drought characteristics ‘without’ and ‘with’ drought adaptation measure

Figure 16 shows the groundwater drought characteristics for the ‘without’ and ‘with’ group when a threshold of 0 is used of the SGI-1. The results show that there are less days with drought for the ‘with’ group (median value is 538 out of 1028 days) in comparison with the ‘without’ group (640 out of 1028 days). However, the median number of droughts for the ‘with’ (22) group is higher than the ‘without’ group (17). Nevertheless, the average duration of the droughts for the ‘with’ group (22 days) is lower than for the ‘without’ group (38 days). Moreover, the average drought deficit is also lower for the ‘with’ group (24) than of the ‘without’ group (41). However, the spread of the average duration and drought deficit for both groups are large. The t-test results (Table 5) show that only the number of days with drought are statistical significantly different using $p < 0.05$ comparing the ‘without’ and ‘with’ group.

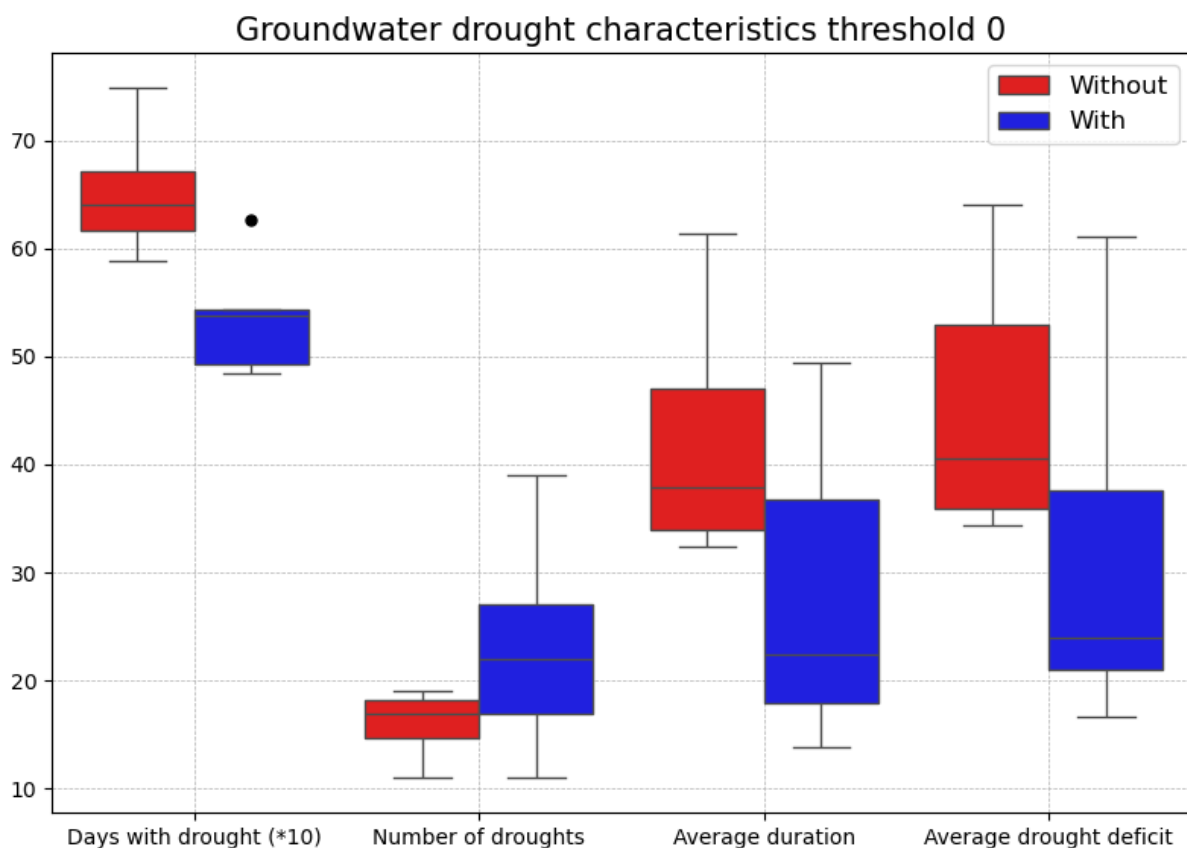


Figure 16: The groundwater drought characteristics with threshold 0 of SGI-1 of the ‘without’ and ‘with’ group.

Table 5: T-test results of the variables of the groundwater drought characteristics with threshold 0, comparing the ‘without’ and ‘with’ group. ** Indicates statistically significant with $p < 0.05$. * Indicates weak statistically significant with $p < 0.1$.

	p-value
Days with drought (*10)	0.003**
Number of droughts	0.100
Average duration	0.077*
Average drought deficit	0.137

Figure 17 shows the groundwater drought characteristics for the 'without' and 'with' group when a threshold of -1 standard deviations is used of the SGI-1. There are less days with drought for the 'with' group (median value of 255 out of 1028 days) than for the 'without' group (290 out of 1028 days). Furthermore, the number of droughts for the 'with' group is comparable (15) with the 'without' group (16). In addition, the average duration of a drought has a more spread distribution for the 'with' group. Their median values are approximately the same with around 19 days. Moreover, the average drought deficit of the 'with' group (16) has a larger distribution and is slightly higher than the 'without' group (14). The t-test results (Table 6) show that all variables are not statistical significantly different comparing the 'without' and 'with' group. The p-values of the variables are higher with threshold -1 in comparison with threshold 0.

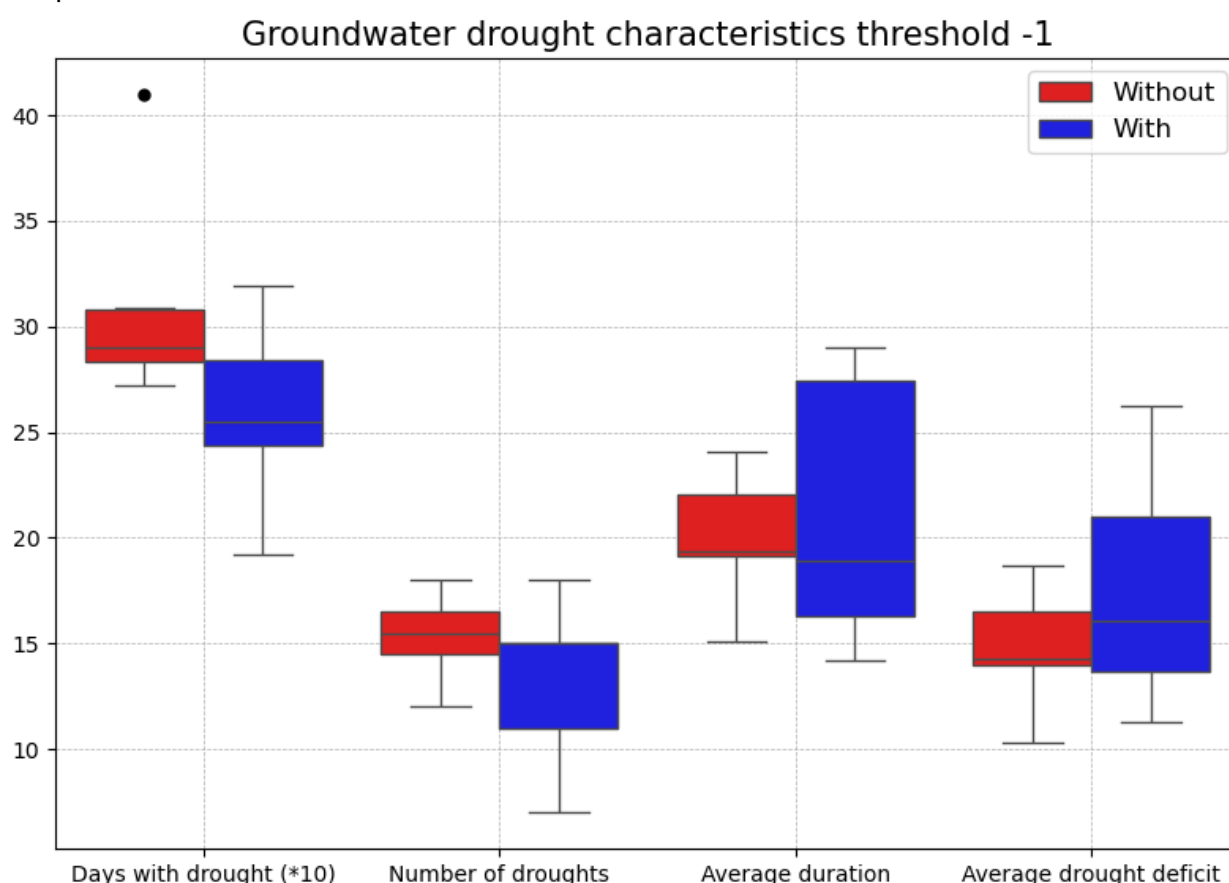


Figure 17: The groundwater drought characteristics with threshold -1 of SGI-1 of the 'without' and 'with' group.

Table 6: T-test results of the variables of the groundwater drought characteristics with threshold -1 comparing the 'without' and 'with' group. * Indicates weak statistically significant with $p < 0.1$.

	p-value
Days with drought (*10)	0.100*
Number of droughts	0.242
Average duration	0.688
Average drought deficit	0.286

5. Discussion

5.1 Influence of drought adaptation measure on groundwater levels

The implementation of a drought adaptation measures in the form of weirs, has had a significant impact on groundwater levels. In the situation with weirs, groundwater levels have been more comparable to those observed during historical periods. This indicates that the adaptation measures have been effective in maintaining groundwater levels similar to times when such drought adaptation measures were less necessary. While the differences between the situation with and without the drought adaptation measure might not be statistically significant across all groundwater signatures, the differences in groundwater levels are visible in the time series data and their corresponding uncertainties.

In summer periods, the results of the situation with weirs showed consistently higher groundwater levels compared to the situation without. This suggests that the drought adaptation measure has been successful in retaining precipitation within the area, thereby enhancing groundwater levels during dry periods. This effectiveness of the weirs is further demonstrated by groundwater signatures such as the GWL5 and GWL20, which indicate that the lowest groundwater levels observed were higher in the situation with weirs. This trend is also confirmed by the mean annual minimum groundwater levels, which were higher for the situation with weirs. This shows that at the local level, the use of weirs near agricultural land is effective in mitigating the effects of drought by maintaining higher groundwater levels during dry summer periods. This observation is consistent with other studies where drought adaptation measures are implemented focussing on the retaining of water. For example, the optimization of the spread and height of drains and water regulation in the ditches in the south-west of the Netherlands help to prevent the loss of groundwater lenses in dry periods (Tolk, 2012). Besides that, the findings are consistent with measures taken by the Aa en Maas Waterboard, such as implementing higher surface water levels (Waterschap Aa en Maas, 2022).

The weirs are also found to be effective in winter periods. The results of the situation with weirs show lower groundwater levels during winter, especially in 2024. This indicates that the presence of this drought adaptation measure helps to reduce high groundwater levels during wet periods. This observation is supported by lower GWL80 and GWL95 values, showing that the highest groundwater levels were generally lower when the weirs are in place. However, despite the lower general groundwater levels, the mean annual maximum groundwater level is higher in the situation with drought adaptation measures. This anomaly is partially due to high outliers in the data and the fact that the mean annual maximum is influenced by short-lived peaks in groundwater levels. These brief peaks do not significantly affect the top 20% and 5% of the highest groundwater levels, which are captured by the GWL80 and GWL95 signatures. Similar effects in lower groundwater levels during wet winter periods are found with the implementation of other drought adaptation measures focussing on storing and retaining water in the Netherlands. For instance, the drought adaptation measures in the south-west of the Netherlands are also effective in preventing damage from flooding (Van Duinen et al., 2014).

The weirs provide more regulation options allowing more control over too high and too low water levels. Besides that, the use of weirs has resulted in a more gradual change in groundwater levels over time, indicated by the higher slope of the duration curve for the situation with the drought adaptation measure. This is further supported by the lower inter-annual variation in groundwater levels for the situation with the weirs, indicating a more stable and balanced groundwater level pattern with fewer extremes in both low and high groundwater levels.

5.2 Influence of drought adaptation measure on drought propagation

The higher correlation between the SPI and SGI in the situation without the drought adaptation measure, indicates a strong link between precipitation deficits and changes in groundwater levels. This suggests that without drought adaptation measures, drought propagates more visibly (Bloomfield and Marchant, 2013). Research of Holtus (2021) investigated these correlations between the SPI and SGI in the province of Gelderland. It was stated that these relations indicate a direct propagation of meteorological drought through the hydrological cycle.

The group with drought adaptation measures showed lower correlations between SPI and SGI. Research by Wendt et al. (2020) also found lower correlations between different SPI accumulation periods and SGI in the UK. In their study, a lack of strong correlation between SPIs and SGI was seen as evidence of human impact on the hydrological system. This is because the effects of groundwater usage on groundwater drought are asymmetric in human-modified environments. Besides that, Khan et al. (2008) investigated the correlations between the SPI and fluctuations in shallow groundwater levels in the Murra-Darling Basin in Australia. The results showed high correlations of the SPI with groundwater level fluctuations, but low correlation coefficients where irrigation practices were, and therefore the recharge of groundwater was complex. In addition, Secci et al. (2021) stated that anthropogenic factors, such as irrigation purposes, can affect groundwater levels in different ways along the year, influencing the SGI and the correlation coefficient with the SPI.

The SPI-3 and the SGI give the highest correlation values. Several authors (Bloomfield and Marchant, 2013; Kumar et al., 2016; Van Loon et al., 2017) believe that the variations in correlation values between the different accumulation periods of the SPI with the SGI is determined by the characteristics of the aquifers including its type of recharge. The high correlation values of the SPI-3 and SGI indicate that the groundwater levels in the study area are responsive to relatively short-term precipitation patterns. Therefore, it is suggested that there is a moderately fast interaction between surface water and groundwater. This can be assigned to the sandy soils which are present in the study area, which are known to be well drained (Jansen et al., 2020). Besides that, it can be caused by the relatively shallow water table that is present, since the water table is perched (Van Gorp, 2016).

Despite the relatively fast interaction of the groundwater levels on precipitation, it still takes some time before a change in precipitation propagates further into the hydrological system. As a result, a change in precipitation represented by the SPI is relatively fast, but not necessarily directly visible as a change in groundwater level represented by the SGI. Therefore, a correlation analysis by considering delay times is recommended to draw firmer conclusions about the influence of drought adaptation measures on drought propagation. For example, as research conducted by Babre et al. (2022), where the correlations between SGI

and hydrometeorological indices at different time lags were determined. Besides that, for example, the cross-correlation between SGI and SPI was analysed to find the time delay between meteorological and groundwater droughts in the US by Guo et al. (2021).

However, the drought characteristics derived from the SGI reflect that the use of weirs mitigates drought conditions, since with a threshold of 0 and a threshold of -1 standard deviations, fewer days with dry conditions are observed in the situation with weirs. However, with a threshold of 0, the number of dry periods is larger for the situation with weirs. This indicates that the adaptation measure is not effective in mitigating drought conditions. Nevertheless, those periods are shorter and have a lower drought deficit on average. In the situation without weirs, the number of dry periods is smaller. However, those periods are longer and have a higher drought deficit on average. This aligns with research of Wendt et al. (2020) which shows that aquifers subject to worse drought and abstractions tend to show fewer droughts but longer and with larger magnitude.

The influence of weirs on drought mitigation is limited. With a threshold of -1 of the SGI of the situation with weirs, the number of days with drought conditions and the number of dry periods are lower. However, the average duration of a dry period is about the same and the average drought deficit is greater. This shows that the mitigating impact of the drought adaptation measure decreases when the drought conditions become more severe. This could be caused by the fact that a prolonged lack of precipitation results in a shortage of the water that can be held in the area using weirs.

5.3 Human impact and potential trade-offs of weir use

The more balanced groundwater level pattern in a situation with weirs installed could be driven by the fact that due to the presence of the UPWAS project in the agricultural area near Breklenkamp, there is more cooperation and communication between the farmers and the Waterboard, enabling more efficient water management throughout the area. The farmers in the area determine when the weirs open or close. With this, human choices have an impact on the retention and release of water from the system and changing groundwater levels. Mistakes in this water management can be caused by a lack of information, miscommunication, or delayed action for example.

While weirs offer significant benefits in managing groundwater levels and mitigating the impacts of drought, they also give potential trade-offs that need to be considered. The excessive release of water undermines the benefits of the weirs during dry periods. The retaining of water could lead to increased flood risk in certain areas, if not managed properly (Barendrecht et al., 2024). Especially when periods without drought are followed by extreme wet conditions. The capacity of weirs to store water is finite and during large precipitation events, they can quickly reach their limit. If water is not released in a controlled manner, there is a risk of overflow, which can lead to flooding or waterlogging of soils. Subsequently, this can also affect agricultural productivity. Moreover, the retention of water behind weirs can result in decreased water flow downstream (RangeCroft et al., 2019). Different water users, such as other farmers, municipalities, nature and drinking water companies for example, may have competing interests regarding water retention and release.

5.4 Other factors impacting groundwater levels and drought propagation

Another factor that could have an influence on the different trends and variations in groundwater levels and drought propagation, besides the use of the weirs, is the use of different other crop types. The choice of crop types has a significant impact on groundwater levels through variations in water use, root depth, and seasonal water demand for example (Yang et al., 2015). If other crop types are used in the same period the weirs were installed, this could also have an influence on the groundwater level pattern.

The type of irrigation could also have influenced the differences in groundwater levels and drought propagation. The method of irrigation affects the amount of water applied to crops and subsequently the groundwater recharge and depletion (Fawen et al., 2023). Besides that, the timing and frequency of the irrigation could impact changes in groundwater levels. If other irrigation methods are used in the same period the weirs were installed, this could also have an influence on the groundwater levels.

5.5 Limitations of the research

The research has some limitations. It is based on a relatively short observation period for the situation with weirs implemented. This might not adequately capture long-term trends and seasonal variations. Besides that, errors and uncertainties in the measurement of groundwater levels, precipitation and evaporation can affect the outcomes of the research. In addition, the results may be specific to the local context and may not apply to other regions with different soil types, topography and people. Besides that, the choice of the groundwater signatures and the drought indices with their accumulation periods might not capture all the complexities of groundwater levels and especially with their interaction with precipitation. Although the model results were sufficient, the assumptions and parameters used in the models not perfectly reflect the real-world conditions.

6. Conclusion

The influence of drought adaptation measures on groundwater levels and drought propagation is investigated. Hereby, the effectiveness of weirs in local water management and drought mitigation is determined. The higher groundwater levels during dry summer periods and the overall reduction in the number of days with dry conditions of the 'situation with the drought adaptation measure show their role in sustaining groundwater levels. This situation has groundwater levels that closely resemble those from the period before the implementation, since 1987, when such measures were on average less necessary. This indicates the success of weirs in retaining precipitation and thereby mitigating dry conditions in the subsurface. In addition, the lower groundwater levels of the situation with the drought adaptation measure during wetter periods, mainly during winter, suggest that weirs can also help better regulate high groundwater levels. Therefore, the weirs can provide a buffer against both drought and flood conditions. Potentially caused by better water management in the area, driven by more corporation and communication between the people in the area.

In terms of drought propagation, the higher correlations observed between SPI and SGI in scenarios without drought adaptation measures suggest a more direct propagation of meteorological drought into the groundwater system. So, in the absence of weirs, precipitation deficits have a more pronounced and immediate impact on groundwater levels, increasing drought conditions. However, an analysis including considerations of delay times is needed to understand the full impact of weirs on drought propagation.

The effectiveness of weirs in reducing drought conditions in the subsurface is limited, particularly under more severe drought conditions. While the overall number of dry days and periods were lower in the areas with weirs, the severity and duration of droughts increased as the conditions became more extreme. During extended periods of low precipitation, the ability of weirs to mitigate the impact of dry conditions decreases, since the retention of water is limited in this situation.

In conclusion, the drought adaptation measure in Breklenkamp shows significant potential for mitigating drought impacts and more balancing groundwater levels. However, other factors, such as changing vegetation types during the period the weirs were installed, also need to be taken into account in studying the influence on changing groundwater levels. Besides that, the efficacy of the weirs is subject to careful management driven by human choices. Especially, during periods without drought or with extreme precipitation events, the use of weirs needs to be considered.

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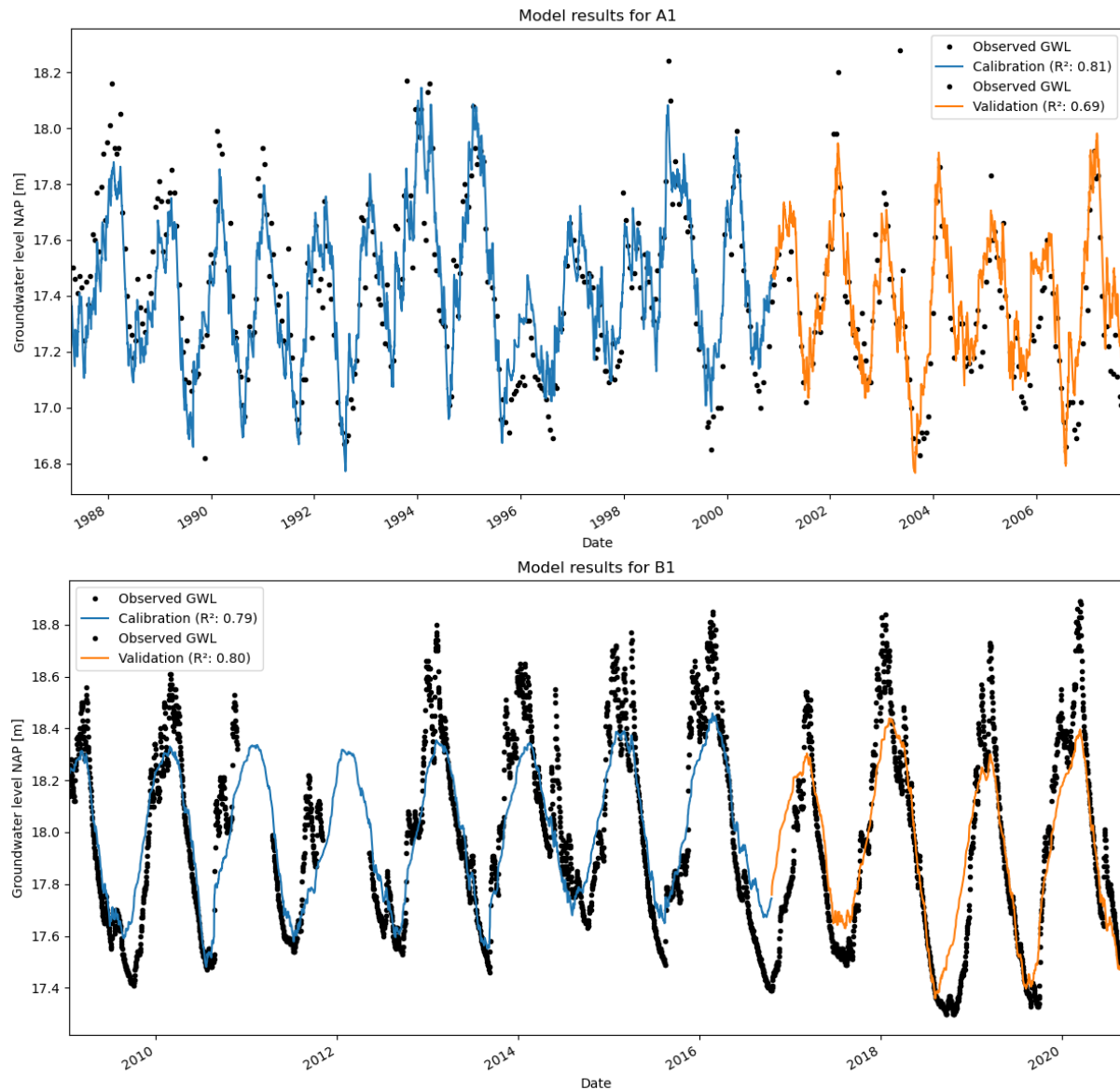
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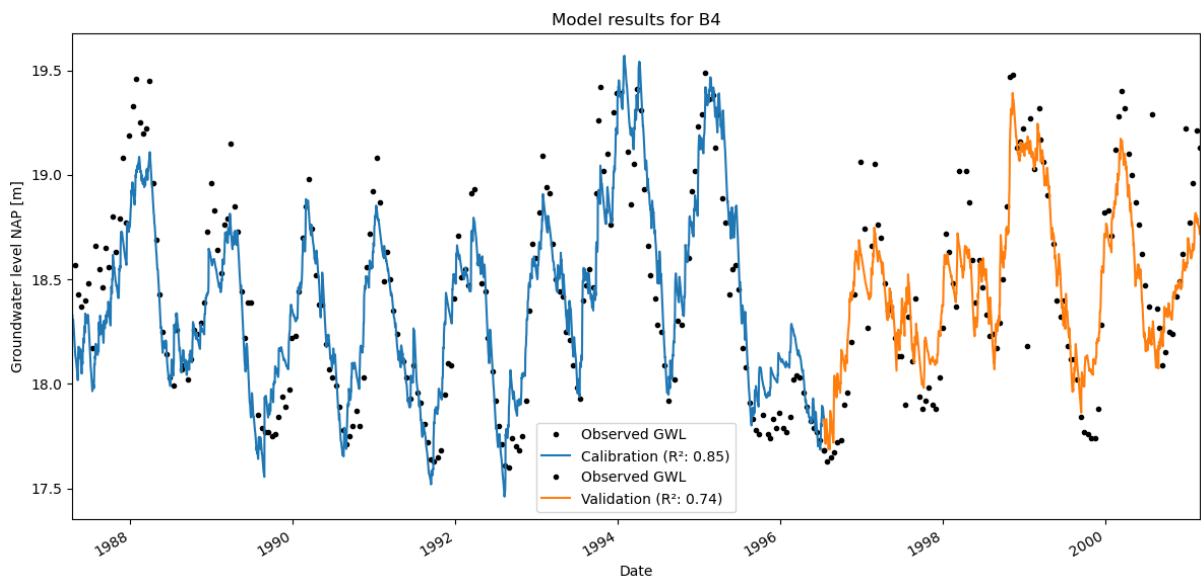
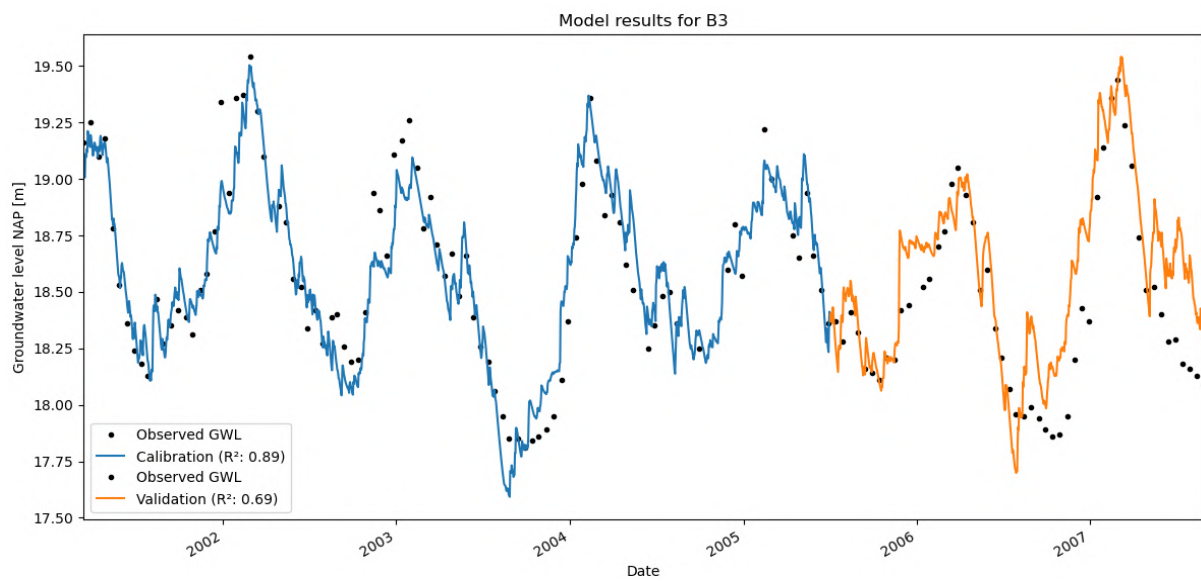
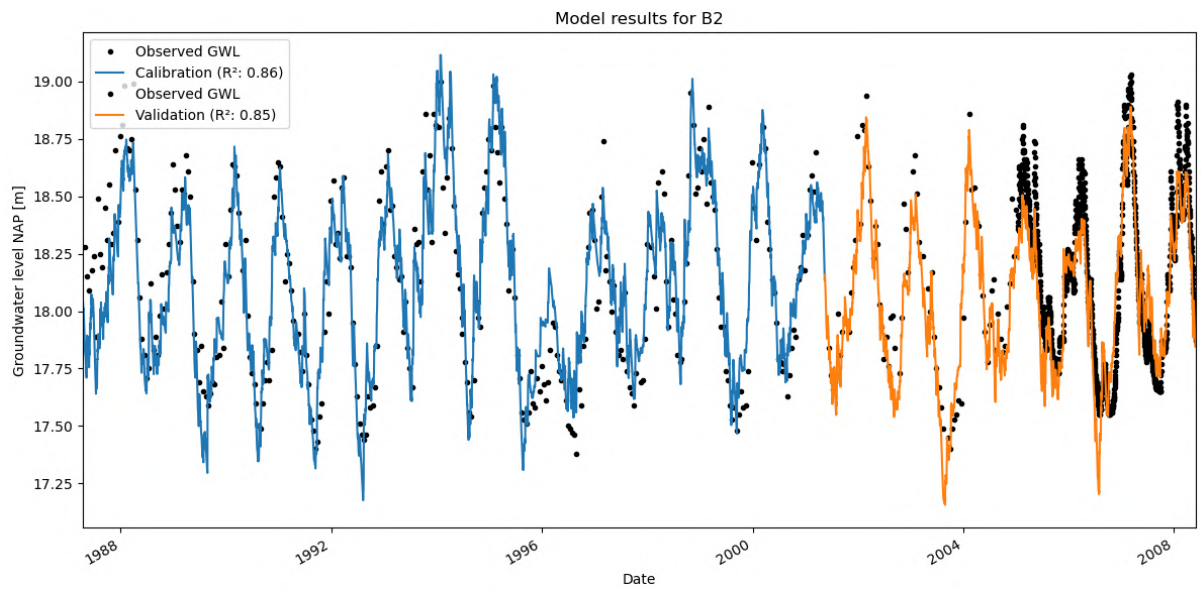
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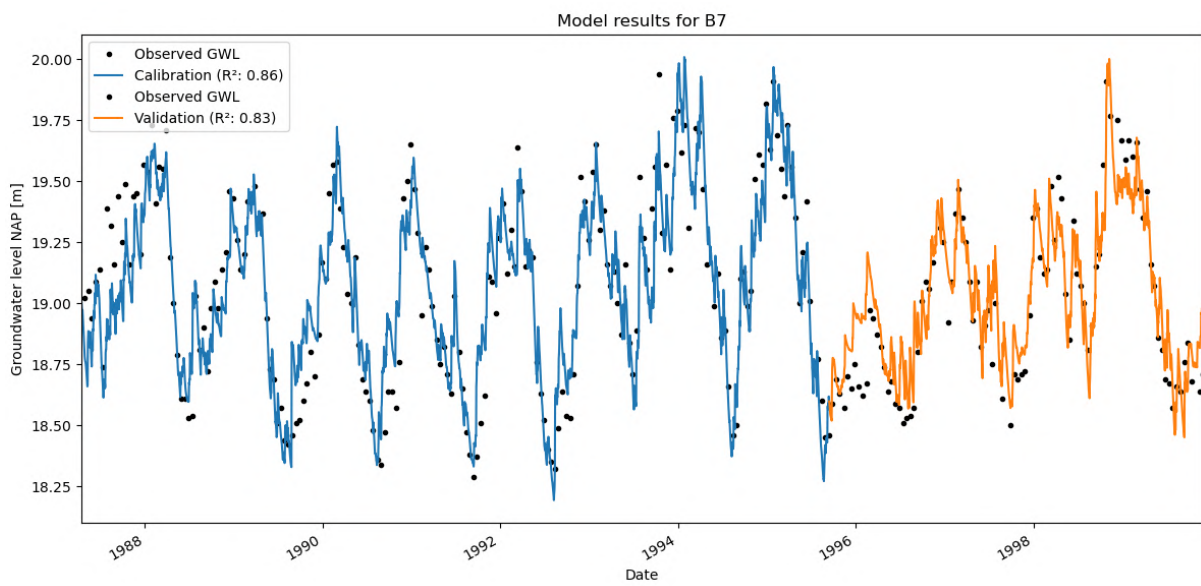
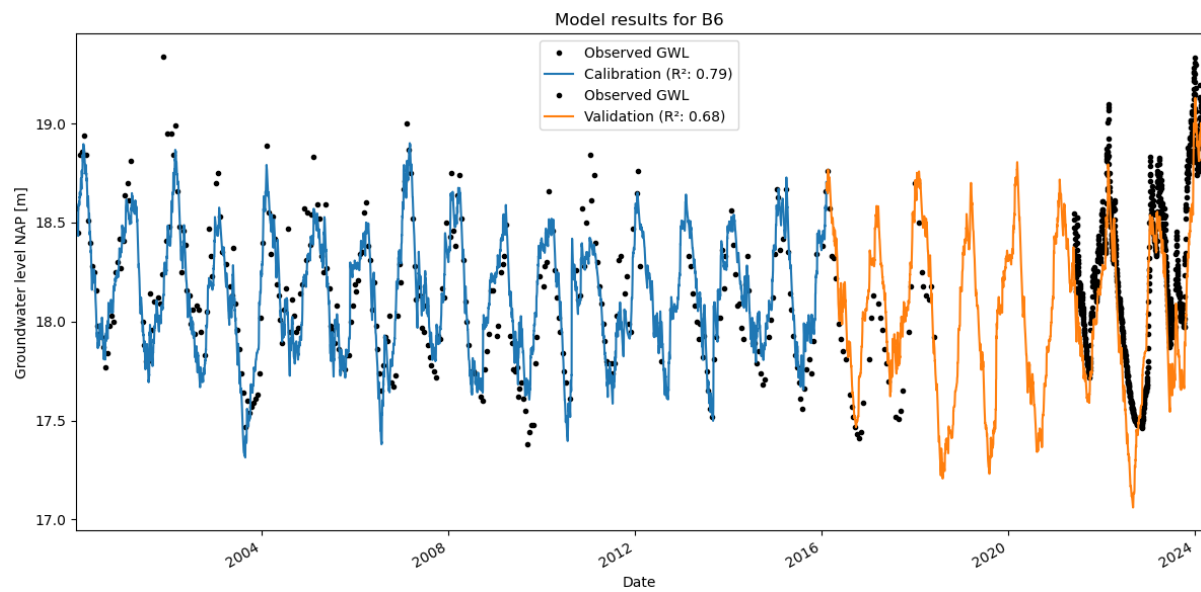
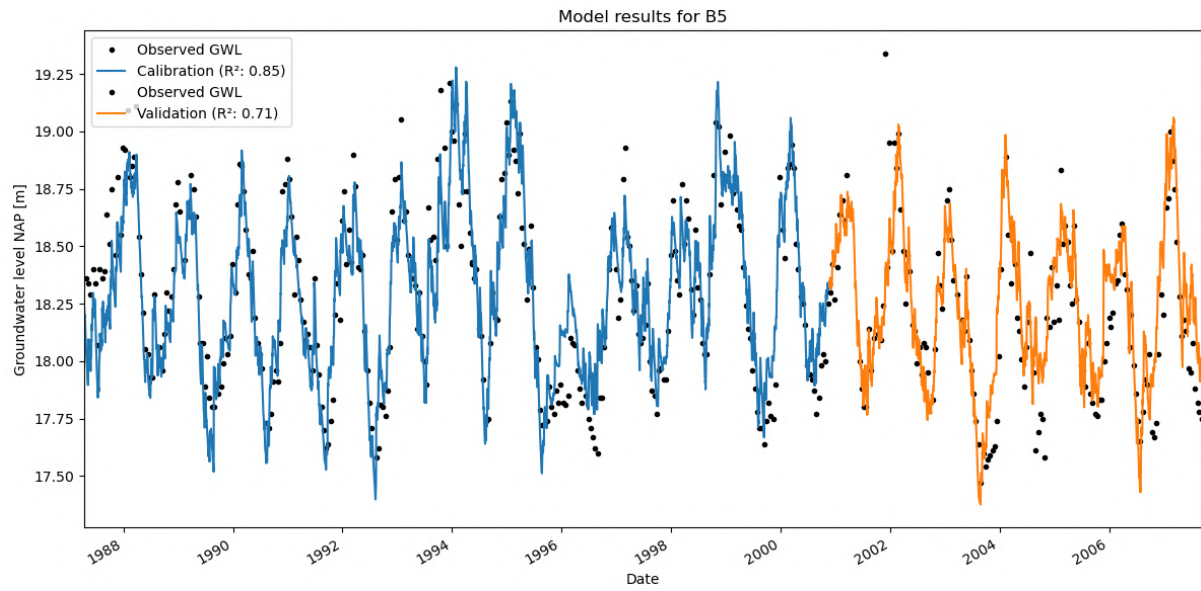
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Appendix A

Model results for the groundwater measuring points. The observed groundwater levels for each groundwater measuring point indicated in black dots, their modelled groundwater levels during the calibration period in blue and the validation period in orange.

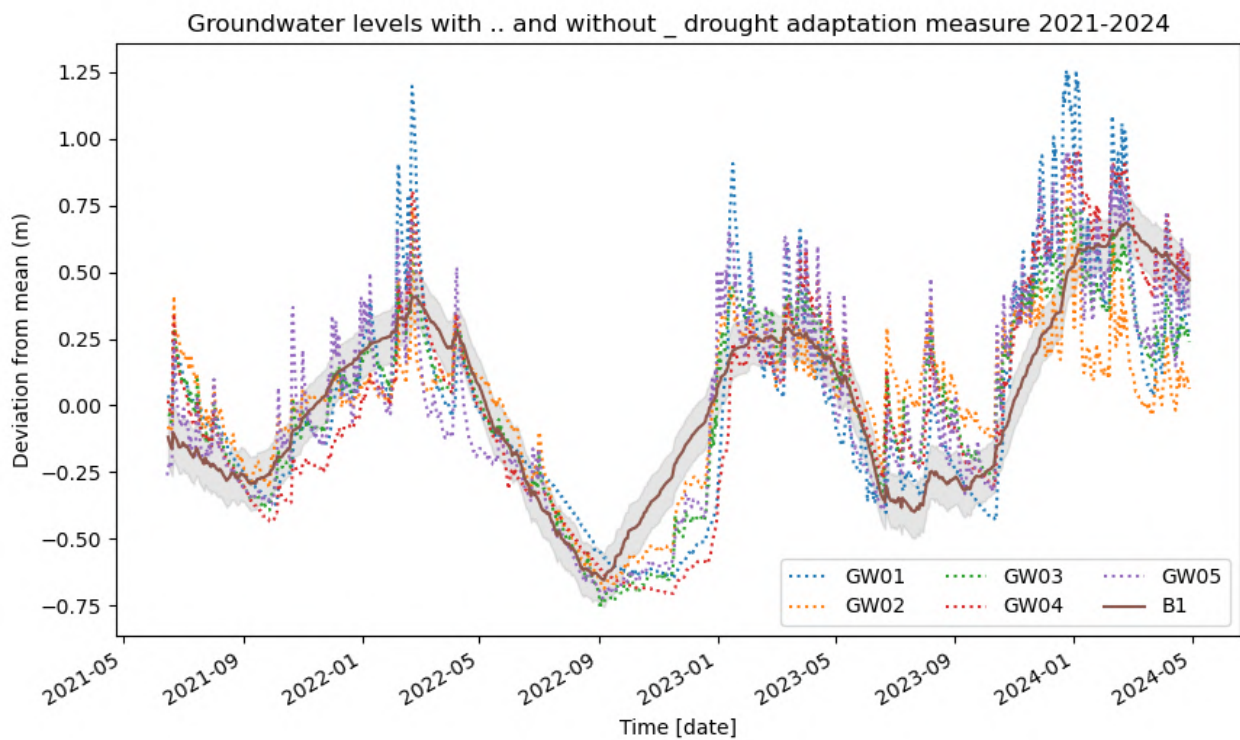
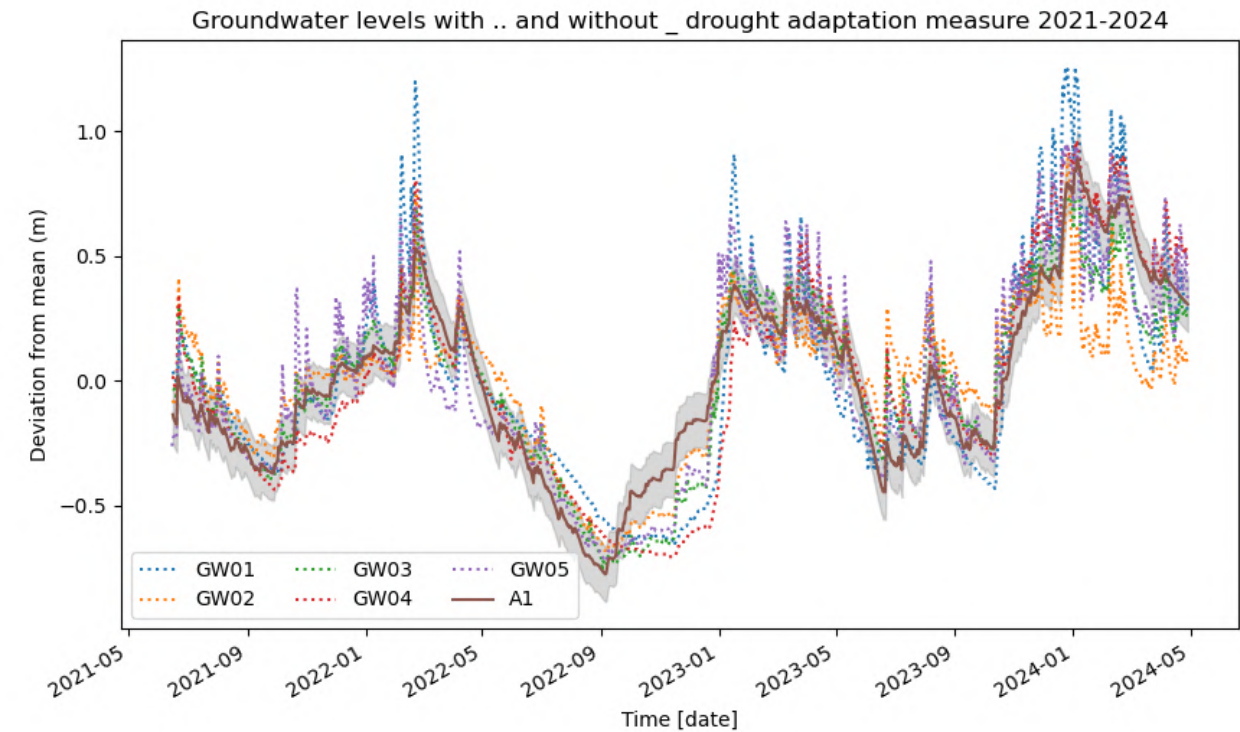


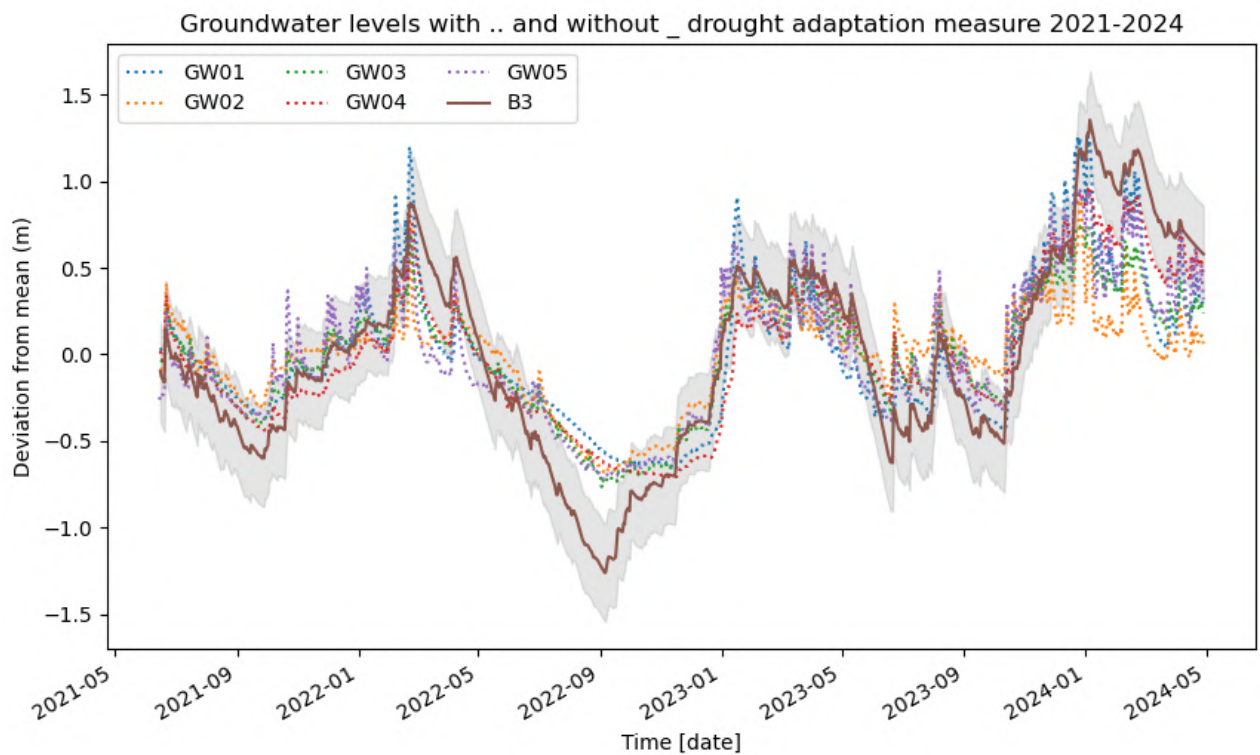
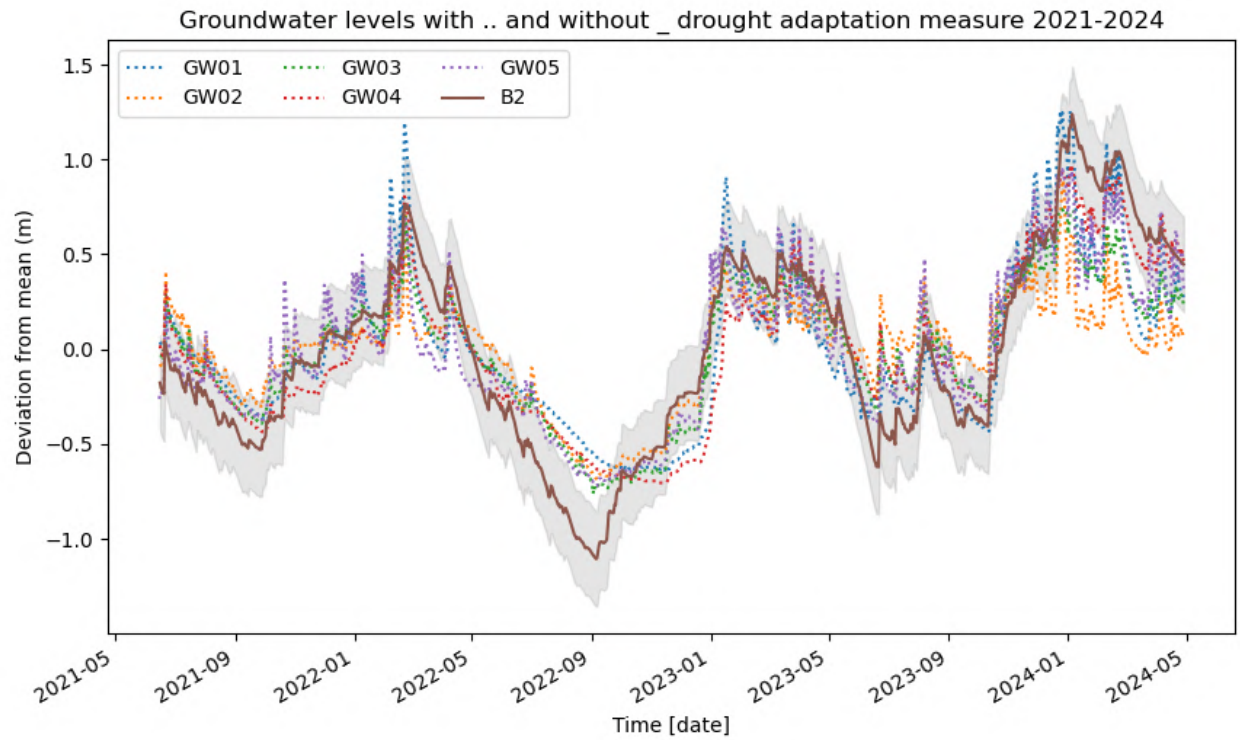


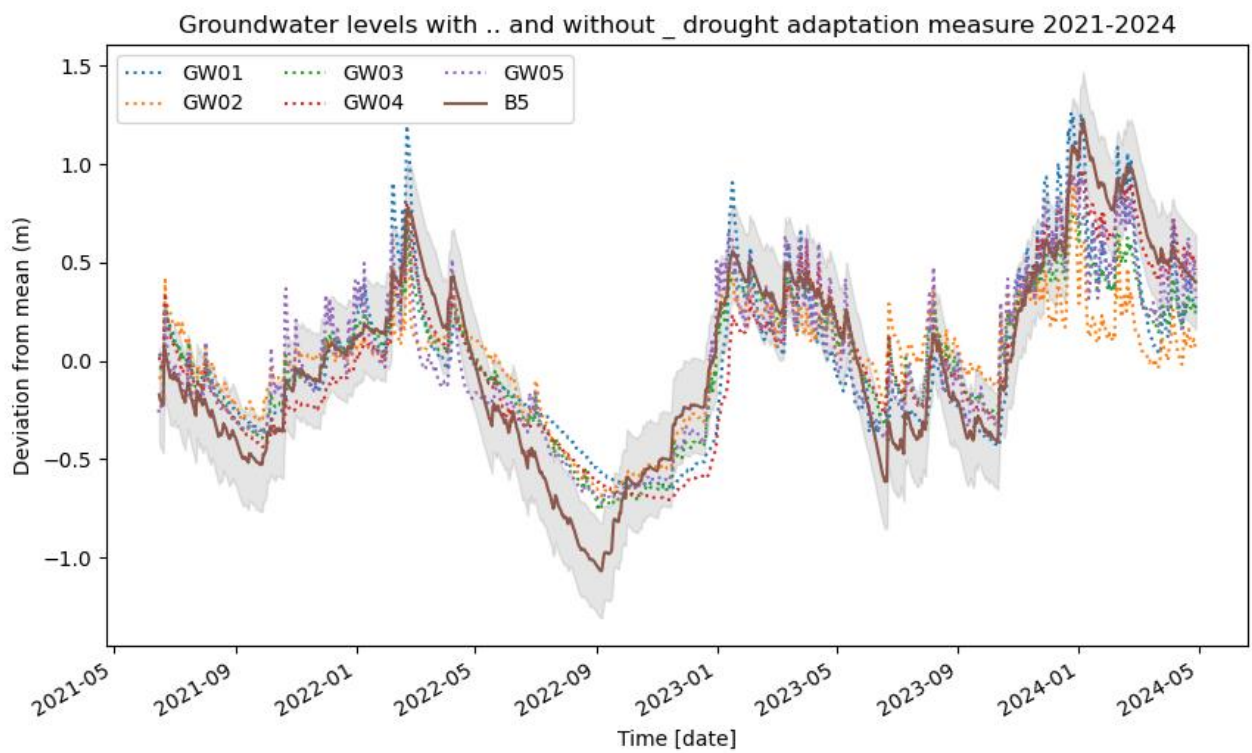
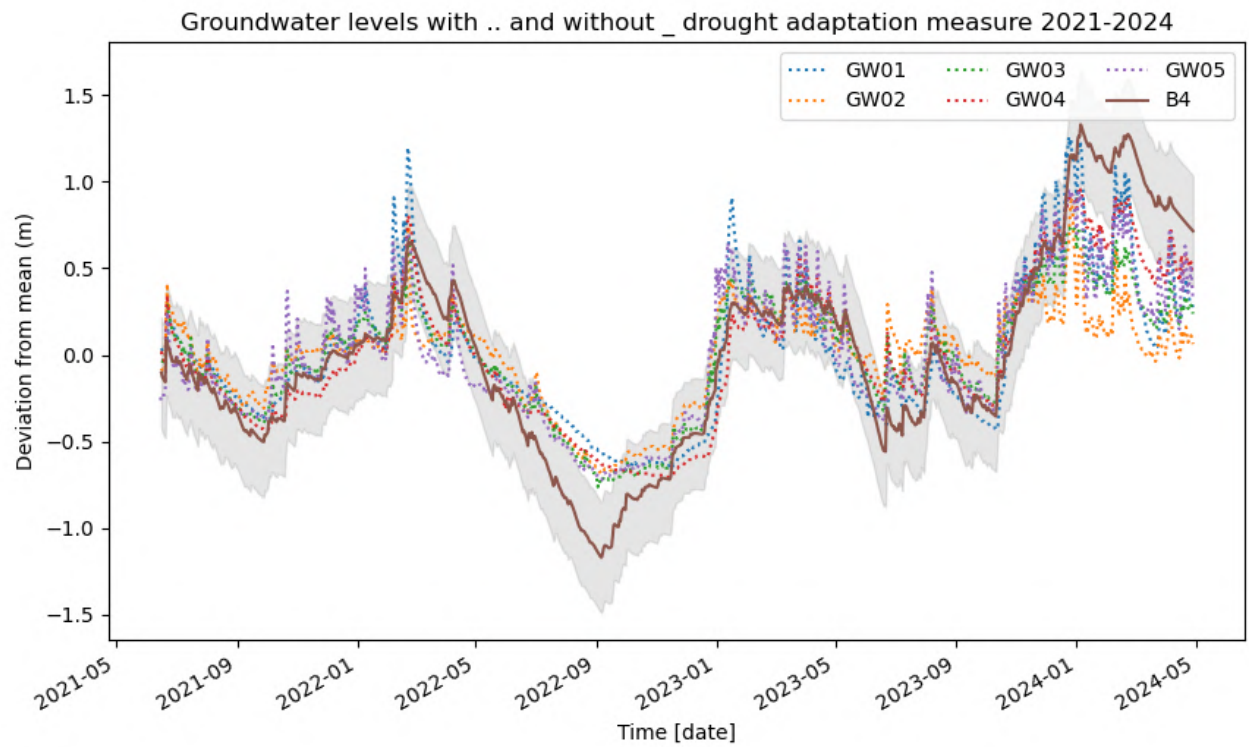


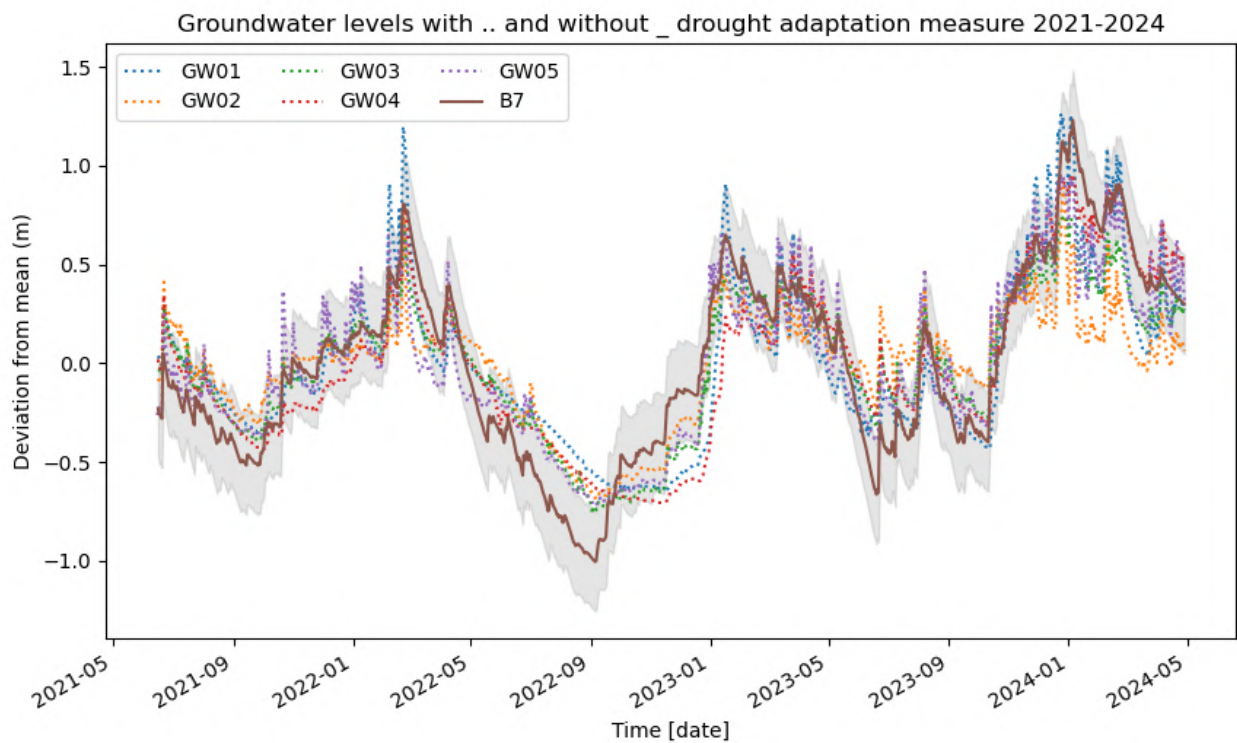
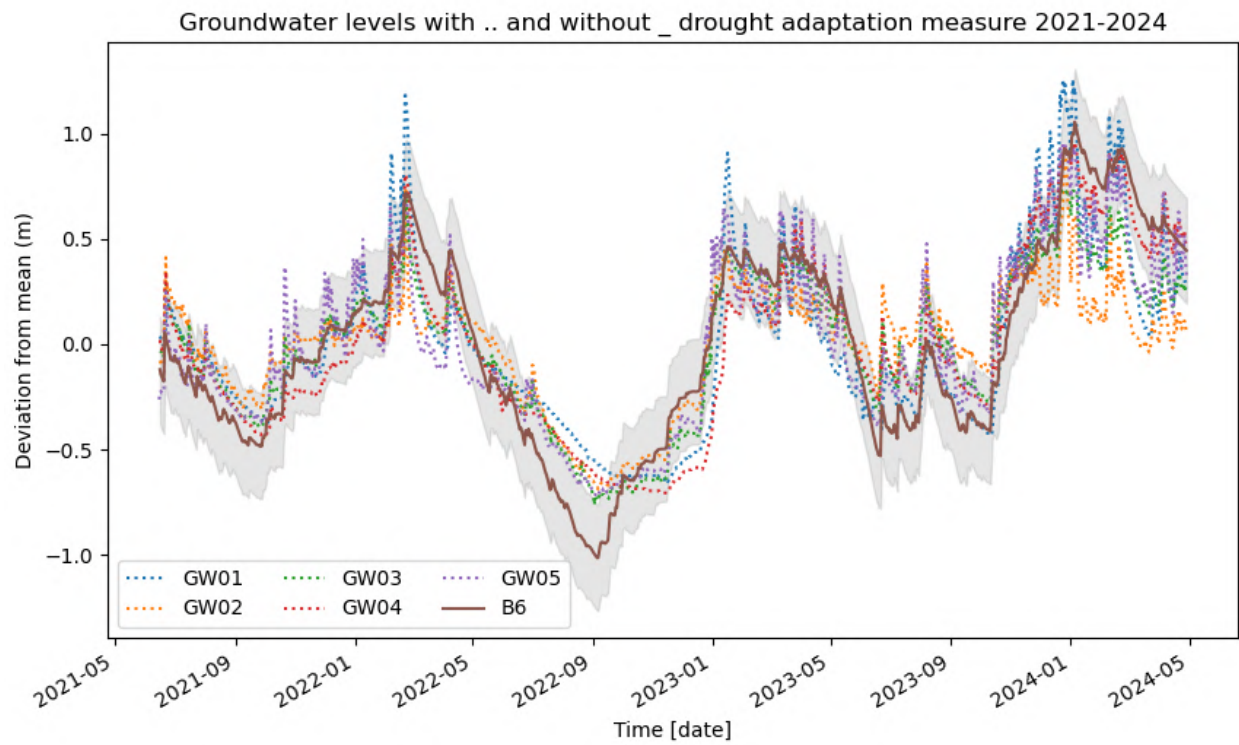
Appendix B

The groundwater levels for the period 2021-2024 of GW01 - GW05 for the 'with' drought adaptation measure group in dotted lines. The groundwater levels of the groundwater measuring points of the 'without' group are represented in solid lines. In grey their uncertainty bands. The deviation from the mean is plotted against the time.



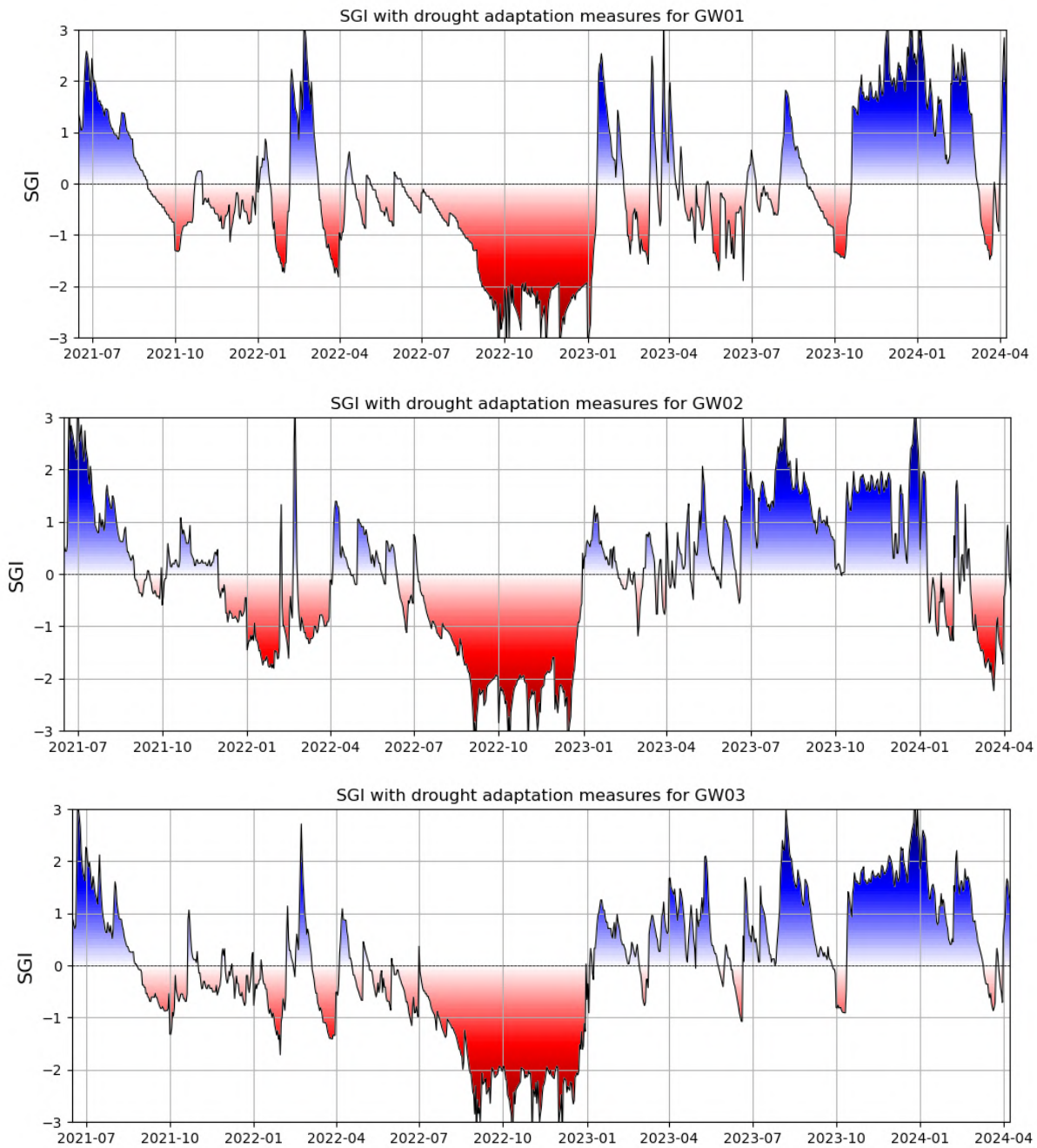


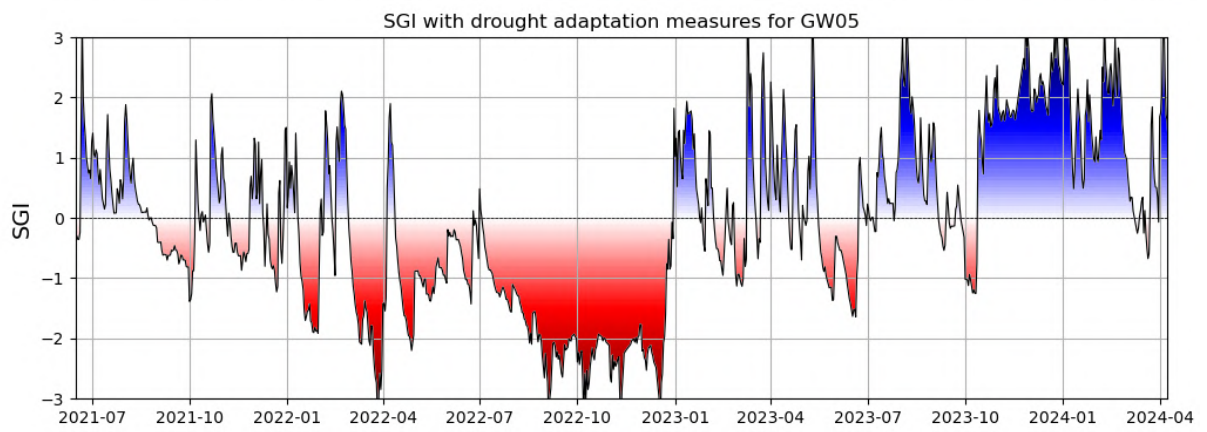
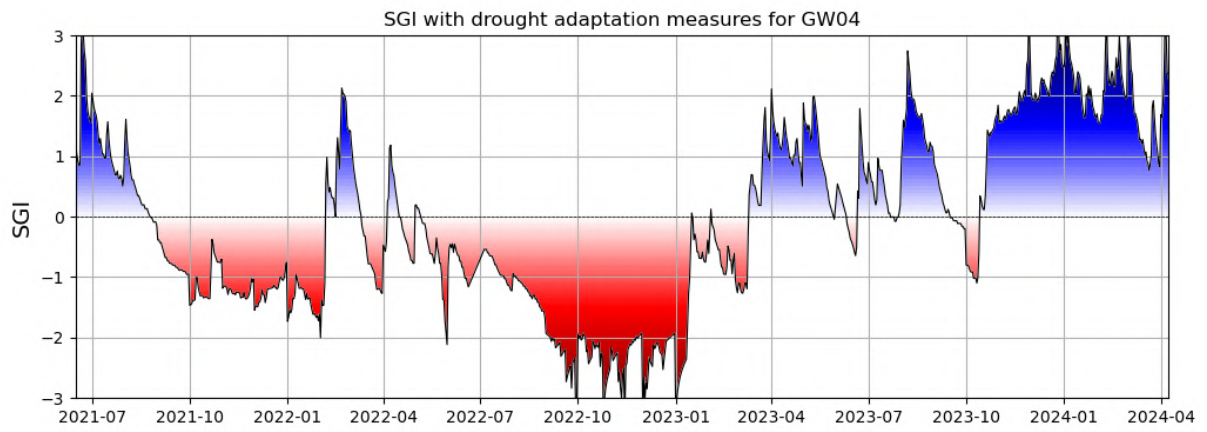




Appendix C

SGI with drought adaptation measure based on historical period:





SGI without drought adaptation measure based on historical period:

