MASTER THESIS

Effects of human landscape interventions on groundwater drought

Image of De Doorbraak

UNIVERSITY OF TWENTE.

Pim Ratering
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Master Thesis

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Author:
P. (Pim) Ratering p.ratering@student.utwente.nl

Supervised by:
Dr. Ir. M. (Michiel) Pezij
Dr. Ir. D.C.M. (Denie) Augustijn

University of Twente,
Department of Civil Engineering,
Water engineering and Management

Photo cover page: Gonny Sleurink via https://landschapoverijssel.nl/twente/doorbraak

Preface

As I stand on the brink of completing my degree in civil engineering, I look back on a wonderful student time. The journey to this point has been both challenging and rewarding, as I have had the opportunity to find out where my interests lie in the field of civil engineering. I am glad that I chose to follow the master track water engineering and management, as I learned a whole lot about this interesting topic.

This thesis is the result of months of hard work and dedication. I have conducted this research in a specific area of water engineering and management related to groundwater, gaining a greater understanding of the subject and the challenges it poses. The findings and recommendations provided in this thesis represent additional information to the research field and I hope they will be of great value to researchers and other interested parties.

Throughout this journey, I have had the support and guidance of my supervisors Michiel Pezij and Denie Augustijn. I have experienced their guidance as pleasant and instructive and would like to thank them for this. I would also like to express my gratitude to friends and family, who have supported and helped me in various occasions. A special thanks to my girlfriend, who helped me through the difficult periods of the research.

I am looking forward to using my gained knowledge in the work field.

Enschede, 2023

Summary

Groundwater drought is an unwanted phenomenon with multiple negative effects on society. Groundwater drought is defined as a decrease in groundwater levels from normal conditions in groundwater levels. Due to climate change and growing water demands, it is receiving increasing attention. Groundwater levels, and therefore groundwater droughts, are influenced by nature-based human interventions, which can be described as water-related anthropogenic adjustments in landscapes. These interventions are constructed with various objectives and in spatially different environments in terms of area characteristics, resulting in varying impacts on groundwater levels and droughts.

The purpose of this study is to investigate the effects of three different types of interventions on groundwater drought. The first intervention was a peat restoration project for the nature area Korenburgerveen. The second intervention was a newly constructed waterway called De Doorbraak near Almelo and the last intervention was a newly constructed side channel and lowered flood plains known as the Scheller and Oldeneler buitenwaarden near Zwolle. Analysing the effects of such interventions is of great value and provides relevant information to decision-makers for future interventions or adjustments to existing ones. Additionally, the results of this research can be used to validate geohydrological models applied before the construction of the intervention, increasing the accuracy of these models.

To achieve the objective of this study, a data-driven model technique is used based on transfer function noise modelling. This model is applied with the open-source Python package Pastas, which is widely used to perform time series analysis. For this study, Pastas is implemented to model groundwater levels in the presence of intervention and without the presence of an intervention. Comparing these two series for various locations near the intervention provides information about the temporal and spatial impact of the intervention on groundwater levels and drought.

The research showed varying impacts on groundwater droughts between the different interventions, over space and time for the specific interventions. First, the peat restoration resulted in a strong decrease in the duration and intensity of groundwater droughts inside the area, and a smaller decrease outside the area. Second, De Doorbraak resulted in increased and decreased groundwater droughts close to the new stream, but further away no impact was observed. Third, the Scheller and Oldeneler buitenwaarden increased the groundwater recharge groundwater which decreased the duration and intensity of groundwater drought in general. However, the impact varies spatially. Overall, it is highly recommended that decision-makers perform detailed preliminary investigations on hydrology, geology and other area characteristics to increase understanding of the area. This positively contributes to accuracy in forecasting the effects of interventions on groundwater droughts.

Contents

1 Introduction

This Section starts with a brief background of the study. Subsequently, we discuss the context and state the research objective and questions for the study.

1.1 Background

Groundwater dynamics form a complex phenomenon and play an important role in the hydrological cycle, as more than 30% of earth's freshwater reserves occur as groundwater and the availability of groundwater is essential for drinking water, industry, livestock and irrigation (Brands et al., 2016). These man-induced influences can have a significant impact on groundwater fluctuations, next to the groundwater dynamics under natural conditions. When groundwater levels decrease from normal conditions for more than months, it is called a groundwater drought. Normal conditions are defined as groundwater levels above a certain average threshold based on historical groundwater levels. Groundwater droughts can arise and terminate after long periods. This depends on various spatial characteristics, which makes them an unwanted phenomenon with multiple effects. Examples of these effects are the drying-up of wells, brooks and rivers, increased pumping costs, intrusion of saltwater (in coastal areas) from surface water or deeper soil layers, increased land subsidence, rotten pile foundations, changes in water quality and loss of crop yield (Famiglietti, 2014; Peters, 2003). The impacts of groundwater droughts are different for each function and stakeholder over space and time, which makes interpretation difficult. Multiple indices are developed to enable better comparison over time and space to create a better understanding of drought.

This study focuses on the effects of human landscape interventions on groundwater drought. Such interventions are defined as water-related anthropogenic adjustments in landscapes. For this research, the focus is on nature-based (non-urban) landscapes, like peat restoration measures or the construction of a new waterway. This excludes constructions like bridges, buildings or traffic roads. These nature-based human interventions affect various processes in the hydrological cycle, enhancing deviations in the contributions of precipitation, evapotranspiration and surface water to groundwater fluctuations. Various research is available related to the effects of these human activities in landscapes on changes in the hydrological cycle. Van Huijgevoort et al. (2020) addressed the significant effect of pumping on the groundwater table and Han et al. (2017) acknowledged the importance of recharge estimation before the various anthropogenic modifications to landscapes and validation of this (actual) recharge after the modifications. This research aims to investigate the anomalies in groundwater drought over time and space induced by the intervention.

1.2 Problem context

Geohydrological models are often used to simulate groundwater level dynamics and groundwater droughts prior to the construction of human landscape interventions and validate the impact of the intervention. This study analyses the impact of interventions on groundwater levels and droughts over both time and space is yet to be analysed for three study areas. These study areas are:

1. Korenburgerveen (a nature restoration project)
2. Doorbraak (construction of a new waterway)
3. Scheller and Oldeneler buitenwaarden (construction of a bypass river channel)

First, for nature restoration at Korenburgerveen, a time-series analysis has already been performed by Simmelink et al. (2021) focusing on the groundwater levels inside the nature reserve. This research indicated an increase in groundwater levels due to the intervention. However, research on spatial impact is still required. Second, for de Doorbraak a time-series analysis has been executed before the construction of the stream by Snepvangers (2003), but not yet for the effects after a few years. This research showed a varying impact of the intervention on groundwater levels, depending on the area characteristics. Last, for the Scheller en Oldeneler buitenwaarden, no time-series analysis has been found in the literature.

Investigating the effects of such an intervention can be of great additional value. Time-series analyses of monitored groundwater levels and droughts provide relevant information for future interventions, as it gives insight into the effect of the interventions. Additionally, the results of the time-series analyses can be used to validate geohydrological models, increasing the accuracy of these models. More knowledge on the effects of nature-based human interventions on the groundwater table and droughts contributes to decision-makers for water authorities, consultancies, and other related parties, as changes in groundwater levels can be forecasted with higher accuracy.

1.3 Research dimensions

1.3.1 Research objective and questions

The objective of this research is:

To investigate the effect of nature-based human interventions on groundwater drought by analysing groundwater level time-series in the vicinity of the interventions.

The research questions are:

1. *What is the autonomous spatiotemporal behaviour of the groundwater level?*
2. *How has the intervention changed the spatiotemporal behaviour of the groundwater level?*
3. *What relations between groundwater levels and auxiliary data can be found?*
4. *How did the intervention affect spatiotemporal groundwater drought?*

1.3.2 Thesis outline

The structure of the thesis is as follows. Groundwater and groundwater drought are elaborated on in the theoretical background (Section 2). Next, the modelling instrument is described (Section 3). Then the method is explained (Section 4). This includes a description of the case studies and interventions, and how the model will be used to obtain useful and confident results. Next, the results are provided per case study (Sections 5, 6 and 7). Afterwards, the discussion the interpretations and explanations of the results are discussed in the context of the research question and general remarks are made related to the model and this research (Section 8). In the end, a conclusion is drawn and recommendations to researchers and policy makers are made (Sections 9 and 10). Additional figures, tables and information are provided in the appendices (Sections 12-16).

2 Theoretical background

The theoretical background is elaborated on in this Section. Section 2.1 elaborates on the general concept of groundwater and the related processes and section 2.2 defines groundwater drought.

2.1 Groundwater

Groundwater forms the largest reservoir of freshwater after the polar ice caps and plays an important role in the hydrological cycle (Brands et al., 2016). Precipitation, confined aquifers and surface waters like rivers, streams and lakes are the water sources that replenish the phreatic water table. Replenishing of groundwater can also be done artificially, with the use of ponds and infiltration basins or through injection wells. On the other hand, groundwater is widely abstracted for irrigation and as a freshwater supply (Peters et al., 2005; Famiglietti, 2014).

2.1.1 Groundwater in the hydrological cycle

Groundwater is defined as the water that exists in saturated underground voids. Peters (2003) presented a schematic view of the hydrological cycle under natural conditions with the term 'Saturated' indicating groundwater, see Figure 1. The unsaturated zone is the zone above the groundwater table, where the pores not only contain water but also air. The thickness of the unsaturated zone differs spatially, as for arid zones this zone can be hundreds of meters and for marshes no unsaturated zone is present.

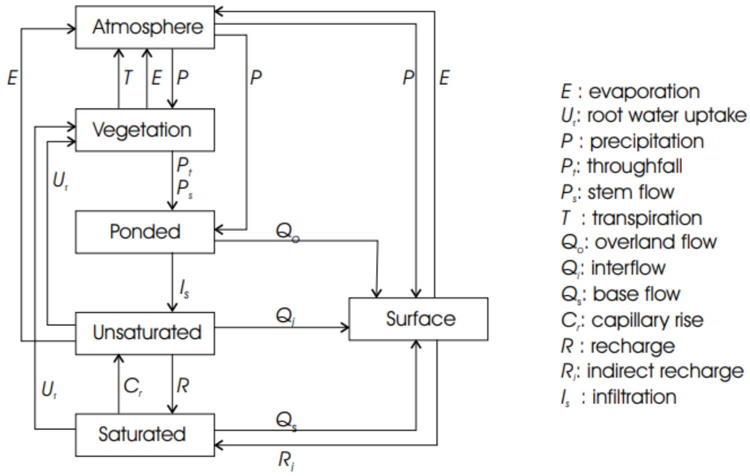

Figure 1: Schematic view of the hydrological cycle (Peters, 2003)

Natural groundwater dynamics depend on five factors:

- Recharge (direct vertical percolation of water);
- Indirect recharge;
- Baseflow;
- Root water uptake;
- Capillary rise;

First, recharge is defined as the direct vertical percolation of water, which is influenced by precipitation and evapotranspiration, which makes those processes major factors that impact groundwater replenishment. In areas close to rivers, recharge can also be significantly influenced by the water levels in the river. Low infiltration capacities, caused by soil characteristics, land use, vegetation type, sloping surfaces, or frozen topsoils, can decrease the direct recharge of groundwater. Second, indirect recharge is defined as recharge from rivers, canals, and lakes. Within a catchment, an indirect recharge will seldom be a process, that causes or aggravates drought, as this contribution is minimal compared with direct recharge (Peters, 2003). Third, baseflow is described as the flow towards and from the surface water. At last, root water uptake and capillary rise can play an important role in groundwater dynamics in vegetated areas with shallow groundwater tables, like the Netherlands (Peters, 2003). At last, as mentioned before, additional man-induced causes like pumping or artificial recharging of the groundwater can have a significant influence on groundwater droughts (Famiglietti, 2014).

In Figure 2 a schematization of the recharge process is shown, including a pumping well, an unconfined aquifer and two confined aquifers. The residence time of water in the ground varies spatially and depends greatly on the hydraulic conductivity of the soil (Usowicz and Lipiec, 2021). In this schematization, the surface water stream acts as a gaining waterway as it receives water from the groundwater system (Winter et al., 1999). The other way around, the stream is referred to as a losing stream, as it recharges the groundwater table.

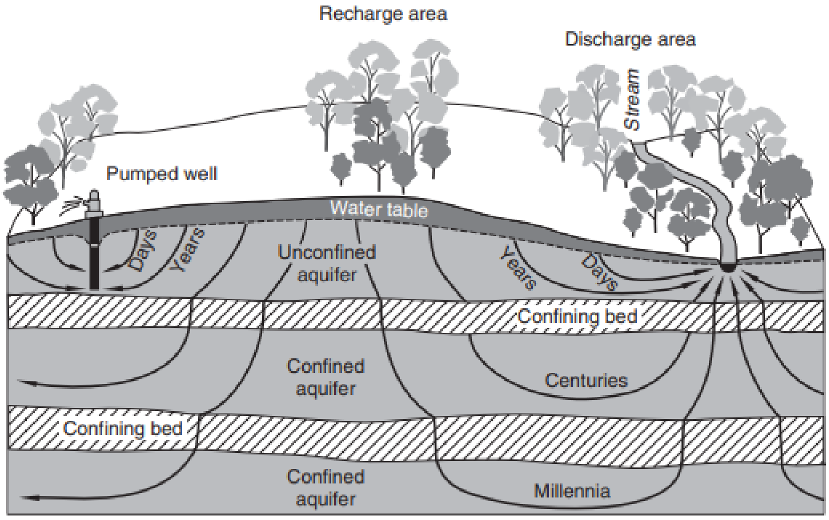

Figure 2: Groundwater system showing generalized flow paths of groundwater movement and the relative age of the water since the time of recharge (Alley et al., 2005)

Also, climate change induces more extreme precipitation events, higher evapotranspiration rates and shifts in precipitation patterns which, enhance groundwater droughts (Famiglietti, 2014; Schreiner-McGraw and Ajami, 2021).

2.2 The various stages of drought

Droughts are widely known environmental disasters and are recognized as complex phenomena (Zhu et al., 2019). Several reasons indicate its complexity. Firstly, drought is often referred to as a creeping phenomenon as the impacts of droughts can slowly accumulate over the years. Secondly, no general definition of drought is drafted. Thirdly, the impact of droughts is difficult to quantify compared to other hazards, like earthquakes or dike breaches, as their impact is non-structural and spread over large geographical areas. Lastly, human activities can enhance drought, for example via, excessive irrigation or deforestation (Diani et al. 2019; Mishra and Singh, 2010; Wilhite and Glantz, 1985).

Droughts can occur in regions with both high and low precipitation intensities. Their occurrence is mostly related to periods of reduced precipitation (Mishra and Singh, 2010). Wilhite and Glantz (1985) suggested four categories for the definition of drought: meteorological, agricultural, hydrological, and socio-economic. In their categorization, groundwater droughts are part of hydrological droughts. However, Mishra and Singh (2010) described groundwater drought, as an own type of drought, separately from hydrological drought, as shown in Figure 3. Hydrological drought refers to the reduction of water levels in streamflow, reservoirs, and wetlands from normal conditions.

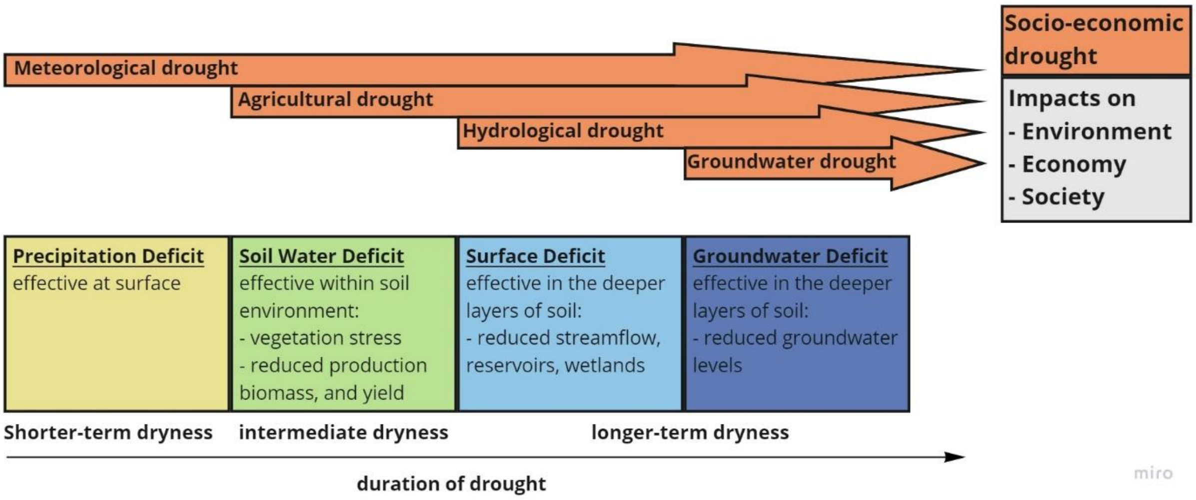

Figure 3: Types of drought: meteorological, agricultural, hydrological, groundwater and socio-economic drought with their major triggers and impacts (Crocetti et al., 2020)

Mishra and Singh (2010) defined groundwater drought as a decrease from normal conditions in groundwater level, groundwater storage and groundwater recharge. Over time, groundwater droughts do appear more often because the climate is changing and the population is increasing, enhancing the water demands and so groundwater extraction (Peters, 2003; Famiglietti, 2014). This results in growing attention to groundwater droughts (Alley et al., 2005; Peters et al., 2005; Famiglietti, 2014; Schreiner-McGraw and Ajami, 2021). The impact and definition of groundwater drought are different for each stakeholder over space and time, which makes it hard to interpret.

Time scales for groundwater droughts can vary from months to years, which is enhanced by the low flow velocities of groundwater (Mishra and Singh, 2010; Van Lanen and Peters, 2000). Monitoring and modelling groundwater is crucial in groundwater management (Famiglietti, 2014). Drought indices are developed to capture the intensity, duration and spatial extent of droughts (Bloomfield and Marchant, 2013; Mishra and Singh, 2010). Indices provide quantitative information to decision-makers about drought characteristics (Jain et al., 2015; Kumar et al., 2016). In Section 0, the definition of a groundwater drought will be described in more detail.

3 Model description

3.1 Introduction

The data-driven modelling technique transfer function noise (TFN) modelling is used in this study. TFN modelling is a technique that is based on mathematical equations but the calibration of parameters is determined from the analysis of time-series data (Solomatine et al., 2008). A TFN time-series model is a method that translates one or more input series (e.g. precipitation or evapotranspiration) to an output series, based on impulse response functions (IRF). It is a popular subdiscipline of time-series analysis (Fabbri et al., 2011; Manzione et al., 2010; Mohanasundaram et al., 2017; Pezij et al., 2020; Remesan and Mathew, 2015; Rorink, 2019; Tankersley et al., 1993; Uwihirwe et al., 2021; van Geer and Zuur, 1997; Von Asmuth et al., 2002) and will be further explained in Section 3.2. Pezij et al. (2020) addressed some strengths of applying a TFN model: (1) TFN modelling is a fast and easy-to-construct data-driven alternative for complex process-based models. (2) IRFs are only based on observational data, resulting in no assumptions on the characteristics of the system. (3) IRF provide information on responses of the water system (groundwater levels) to various stresses (e.g. precipitation), resulting in more knowledge of hydrological characteristics and processes. (4) TFN models can explain system dynamics that are not well explained by physics, as a result of the stochastic nature of the noise model.

Various implementations of TFN modelling are available. Pastas will be used in this study, which is an open-source Python package (Collenteur et al., 2019). The technique is designed and widely used to perform time-series analysis (Brakkee et al., 2021; Pezij et al., 2020; Vinueza et al., 2020). Collenteur et al. (2019) concluded that the technique was performed accurately for the estimation of the effect of interventions on groundwater levels. The package was intended to create a framework for new modelling concepts and offer ready-to-use software for users (Collenteur et al., 2019). The application of Pastas works very well for systems with shallow groundwater tables (up to a few meters below the surface) and the reproducibility for other interventions due to the implementation in Python comes in handy for this research. This Section elaborated on the basics of TFN modelling and its implementation in Pastas.

3.2 Concept of TFN modelling

A TFN time-series model is a data-driven method that translates one or more input series (e.g. precipitation or evapotranspiration) to an output series, based on impulse response functions (IRF). An impulse response function is the function of the response of a system variable (groundwater levels) to impulses from a system shock, e.g., precipitation (Ronayne, 2011). An example is provided in Figure 4. In this study, the IRFs are estimated based on the Predefined Impulse Response Function In Continuous Time (PIRFICT) method (Von Asmuth et al., 2002). This method requires knowledge of the response to a system shock, as a specific type of IRF needs to be determined before implementation in Pastas (Pezij et al., 2020). The basic form of a TFN model is based on Equation 1 (Collenteur et al., 2019):

$$h(t) = \sum_{m=1}^{n} h_m(t) + d + r(t) \qquad (1)$$

With *h(t)* [m] the observed groundwater levels at time *t*, $h_m(t)$ [m] the contribution of a certain stress *m* to the head at time *t*, *d* [m] for the base elevation, and *r(t)* [m] for the residuals at time *t*. The various stresses that contribute to the head can be for example precipitation, evapotranspiration, groundwater abstraction, and surface water levels and are computed with Equation 2 (Collenteur et al., 2019):

$$h_m(t) = \int_{-\infty}^{t} S_m(\tau)\theta_m(t-\tau)d\tau \tag{2}$$

With S_m [m] the time-series of stress m, ϑ_m the impulse response function for stress m. The equation contains a convolution integral and is used to apply the IRF on a time-series of stress m, resulting in the contribution of stress m over time to the groundwater levels (Von Asmuth et al., 2002). If multiple stresses are present, Equation 1 adds these individual stresses linearly to obtain the total predicted groundwater level time-series.

3.3 Impulse response functions

Multiple IRFs are available and can be applied, depending on the characteristics of the system, variables, and impulses. Every IRF has a specific formula for implementation and a recommended application. The number of parameters in the formula varies between IRFs, with an increasing number of more complex responses. Von Asmuth et al. (2002) pointed out that this recommended application could also result in a reduced fit if this is not the best IRF. Therefore, it is recommended to apply an iterative process to find the optimal IRF.

Furthermore, all the IRFs can be divided into three responses, the impulse, step, and one-day block responses (R.A. Collenteur et al., 2019). First, the impulse response represents the response to an instantaneous stress event at time zero. Second, the step response represents the response to uniform stresses, like abstraction with constant discharge. Third, the one-day block response represents the response to uniform stresses, but for only 1 day. The responses are implemented as impulse responses (Equations 3 and 4) in Equation 2. Step and one-day block responses can be obtained by integrating the impulse response over time. Examples of the step and one-day block responses for the Gamma and Hantush IRFs are shown in Figure 4.

An example of a one-day block response could be the response to a precipitation stress event of 1 mm for one day. The gamma block IRF shows that the groundwater level quickly increases by 2.75 mm and then slowly decreases to reach the base groundwater level after 100 days. However, if this precipitation event lasts for an (unrealistically) infinite time, the groundwater level will increase till it reaches an equilibrium after 100 days at an increase of 100 mm, as seen in the step response plot in Figure 4. Next, two IRFs are elaborated on in a bit more detail. The IRFs Hantush and exponential are used as an example.

3.3.1 Hantush

The Hantush impulse function is recommended for the response of groundwater to groundwater abstraction and is provided in Equation 3 (Collenteur et al., 2019; Hantush and Jacob, 1955):

$$\theta(t) = -A\frac{t^{-1}}{2\mathrm{K}_0\left(2\sqrt{b/a}\right)}\mathrm{e}^{-t/a-b/t} \quad t \geq 0 \tag{3}$$

With A [m] the scaling factor, a [day] and b [day] the shape parameters and K_0 [-] for the modified Bessel function of the second kind and order zero. The Hantush impulse function is negative as groundwater abstraction negatively influences groundwater levels.

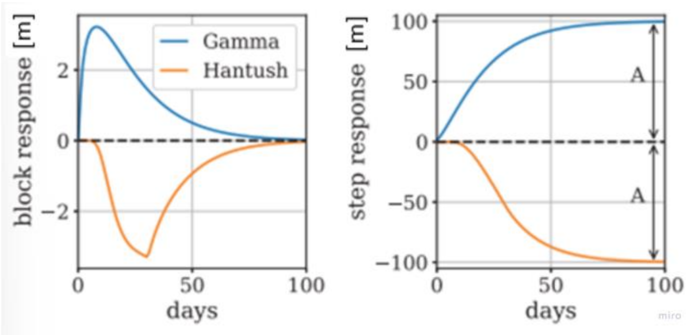

Figure 4: The one-day block and step response for the scaled Gamma and Hantush response function (Collenteur et al., 2019)

3.3.2 Exponential

The exponential response function is recommended if a stress has an instant effect on the groundwater table. The exponential response function formula is provided in Equation 4:

$$\theta(t) = \frac{A}{a} e^{-t/a} \tag{4}$$

With A [m] for the scaling factor and a [day] for the shape parameter. Examples of an exponential block response and a step response (integrating the impulse response over time) are provided in Figure 5 and Figure 6 respectively. These examples are obtained from the Pastas model used for this master thesis.

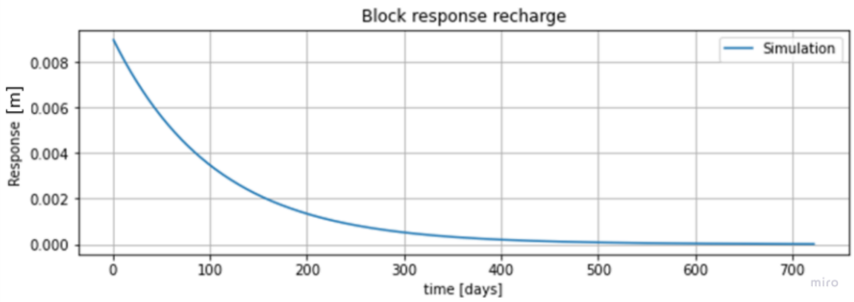

Figure 5: Exponential block response

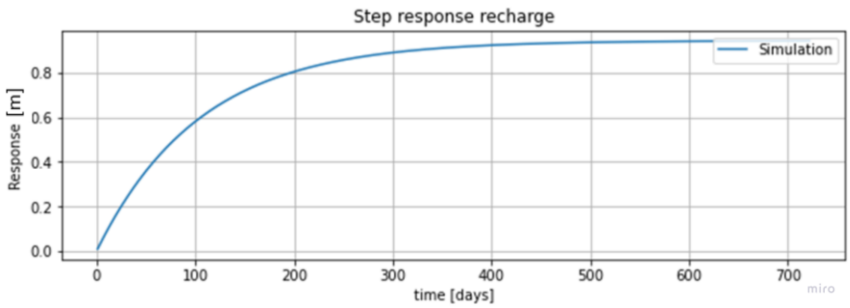

Figure 6: Exponential step response

3.4 Recharge model

Pastas provides the opportunity to combine precipitation and evapotranspiration into the recharge flux. Various recharge models are available and can result in more accurate outcomes. A recharge model can be implemented using the recharge flux R as contribution stress in Equations 1 and 2, instead of the precipitation and evapotranspiration as separate stress models. In this study, three models (Linear, Peterson, FlexModel) are considered which are elaborated on in the next sections.

3.4.1 Linear

The linear model uses a simple linear function of evapotranspiration *E* [LT^{-1}] and precipitation *P* [LT^{-1}] to approximate the recharge flux R [LT^{-1}] as shown in Equation 5 (Berendrecht et al., 2003; Von Asmuth et al., 2008). Parameter f [-] is a calibrated parameter and is referred to as the evaporation factor (Christophe Obergfell et al., 2019).

$$R = P - fE \tag{5}$$

3.4.2 Peterson

Peterson and Western (2014) described that the recharge process does not behave linearly and that linear recharge models were not able to simulate large recharge events. They proposed a non-linear model that would capture the recharge process more accurately, referred to as the Peterson recharge model. Even though more complex model structures may be more realistic and can result in more accurate results, modelling can become exceedingly slow and inefficient. The optimal model variables should be chosen carefully, including a tradeoff between computational time and performance, as acknowledged by (Yihdego and Webb, 2011). A more detailed description of the Peterson recharge model can be found in (Peterson and Western, 2014).

3.4.3 FlexModel

Collenteur et al. (2021) also proposed a nonlinear recharge model, referred to as the FlexModel. The model is based on two reservoirs, the interception and root zone reservoirs, as shown in Figure 7.

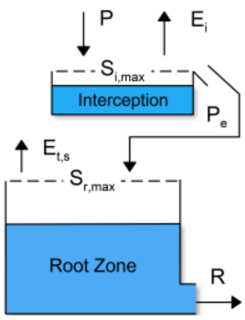

Figure 7: Two reservoirs of the FlexModel (Collenteur et al., 2021)

The interception reservoir intercepts the precipitation (P) until the maximum storage capacity $S_{i,max}$ is reached. The water in this reservoir can evaporate (E_i) or flow through as effective precipitation (P_e) till the second reservoir if the maximum capacity is reached in the first reservoir. In the root zone, reservoir water can evaporate through soil or vegetation transpiration ($E_{t,s}$) and drain deeper as the recharge flux (R). A more detailed description of the FlexModel recharge model can be found in Collenteur et al. (2021).

3.5 Noise model

The noise is defined as the differences between the optimal simulated value and the observed value. The noise describes randomness in the observed time-series and indicates the part that is not predictable (Bjarnadottir et al., 2019). The residuals of a model are the differences between the simulated value and the observed value and are often the result of errors in observed values, model concepts, simplifications or model parameters (Von Asmuth et al., 2002). Strong autocorrelation in residual or noise time-series may indicate model errors or missing input variables. It could be that not all contributions to the groundwater level fluctuations are considered or model assumptions are incorrect.

Modelling the residuals enhances accuracy in predictions at unobserved time steps. Therefore, a noise model could be applied to satisfy a white noise requirement for the residuals. (Pezij et al., 2020; Von Asmuth and Bierkens, 2005). To test this requirement, a diagnostic test could be performed, which ensures that the model adequately describes the observed time-series and if inferences can be made with the model (Hipel and McLeod, 1994). A model inference is a process by which the model is compared to the data, based on the principles of probability. The default noise model in Pastas is the autoregressive model of order one (AR1), with exponential decay of the residuals, and given by Equation 6 (Von Asmuth and Bierkens, 2005). An autoregressive model of order one predicts future points based on the previous points in a time-series and a stochastic term of order one:

$$r(t_i) = v(t_i) + r(t_{i-1})\mathrm{e}^{-\Delta t_i/\alpha} \tag{6}$$

With $r(t_i)$ [m] as the residual value on data point *i* where *j* is the day number. $v(t_i)$ [m] as the noise on time step t_i, $r(t_{i-1})$ [m] as the residual value on the previous time step and Δt_i [day] as the length between the time steps and α as the AR parameter of the model [day].

3.6 Parameter estimation

The estimation of parameters is executed by minimizing an objective function (Obergfell, 2019; Von Asmuth et al., 2002). Collenteur et al. (2019) provided various methods to estimate the parameters of the model. The default method of Pastas is the nonlinear least-squares algorithm. This method minimizes the objective function S in Equation 7 and provides the optimal parameters of the IRF (Pezij et al., 2020; Von Asmuth and Bierkens, 2005).

$$S = \sum_{i=1}^{N} r(t_i)^2 \tag{7}$$

With $r(t_i)$ [m] as the residual value on data point *i* for a total of *N* data points. This requires an initial set of parameters, which is based on the available data. It is also possible to improve these initial parameters by first running the model without noise model. Additionally, parameter bounds are specified for the parameters, to include physical interpretation. For example, parameter A from Equation 4 can be limited to only positive values if groundwater levels go up for positive recharge values. It is also possible to fix a parameter while solving the Pastas model. This is recommended if changes in a parameter do not significantly influence the outcome. Furthermore, a threshold method can be applied if it is expected that groundwater reacts differently for various groundwater levels. At last, decreasing the time step size could increase stability in the model. A more detailed description of this optimization can be found in Von Asmuth and Bierkens (2005).

4 Methodology

4.1 Research steps

The methodology to reach the research objective is provided and visualized in Figure 8. Research question 1 (Section 4.2) focuses on the modelling of the groundwater levels with and without the presence of an intervention, respectively abbreviated as SGWL and SGWL-i. These two series will be compared to assess the impact of the intervention on groundwater levels (RQ2) in Section 4.3, contributions to groundwater fluctuations (RQ3) in 4.4 and groundwater droughts (RQ4) in Section 4.5. The described steps are performed for three case studies, which are elaborated on in Section 4.6. Finally, the model setup is described in Section 4.7.

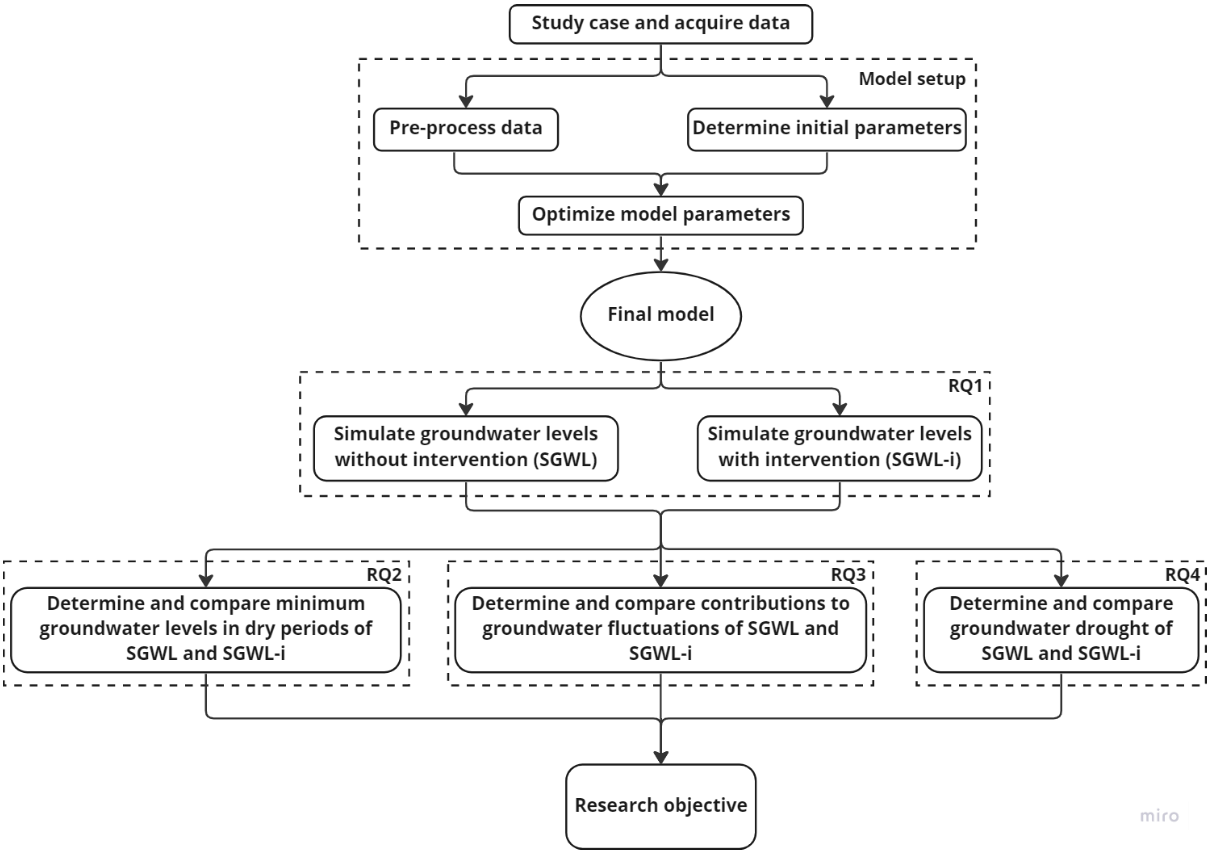

Figure 8: Flow diagram research steps

4.2 RQ1 - Autonomous groundwater behaviour

The objective of research question 1 is to create an understanding of groundwater dynamics with and without the presence of an intervention. Therefore, two series are required per monitoring well, which are shown in Figure 9:

- A groundwater series that is influenced by the intervention (SGWL);
- A groundwater series as if the intervention did not occur (SGWL-i).

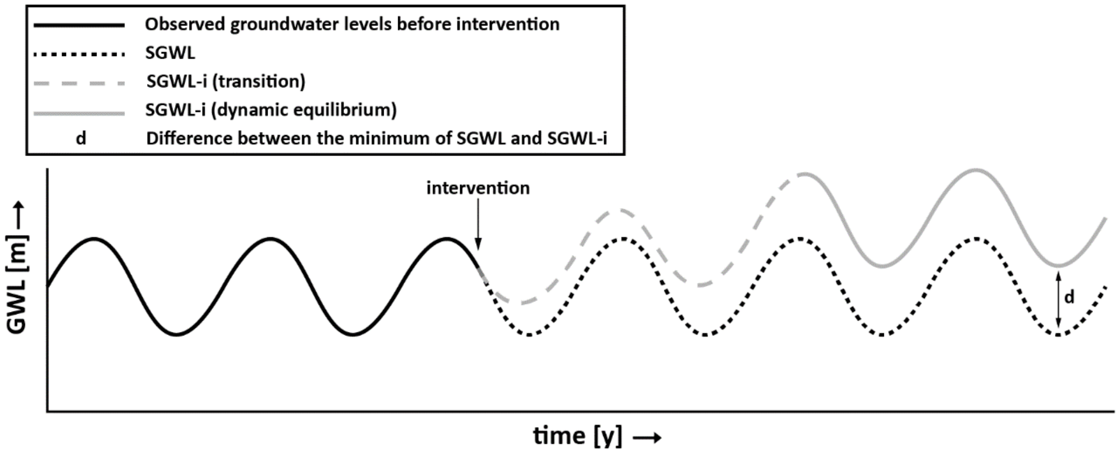

Figure 9: Simulations (Simulated groundwater levels without intervention (SGWL) and simulated groundwater levels with intervention (SGWL-i)

The following steps are executed to model the SGWL and SGWL-i and reach the objective:

1. The observed groundwater series are analysed to identify droughts and trends.
2. The observed groundwater series are compared with the input series to identify correlations and confounding variables. A confounding variable is an input variable that directly and indirectly influences the output variable in a way that produces inaccurate contributions to fluctuations in the output variable. Research question 3 is not answered if a confounding variable is present.
3. The Pastas model is trained to simulate the groundwater levels for the period **before** the intervention was constructed, using the observed groundwater levels and other input series such as precipitation, potential evapotranspiration, groundwater abstraction and surface water.
4. The trained Pastas model is used to simulate the **SGWL** for the period after the intervention was constructed, as shown in Figure 9.
5. The Pastas model is trained to simulate the groundwater levels for the period **after** the intervention was constructed using the observed groundwater level (after the intervention was construction) and other input series such as precipitation, potential evapotranspiration, groundwater abstraction and surface water.
6. The trained Pastas model is used to model the **SGWL-i** for the period after the intervention was constructed, as shown in Figure 9.
7. It could take time for a water system to adapt to an intervention. If this transition period is visible in the series, the **SGWL-i in transition** will be modelled separately from the **SGWL-i in dynamic equilibrium**, as responses from the groundwater table to the input series could differ. Putting the SGWL-i in transition and the SGWL-i in dynamic equilibrium together forms the **SGWL-i**, as shown in Figure 9. The length of the transition period is determined visually, as is also shown in Figure 9.
8. Droughts and trends are qualitatively described in the SGWL and SGWL-i to create an understanding of groundwater dynamics.

4.3 RQ2 - Impact intervention on groundwater levels

The objective of research question 2 is to analyse the impact of an intervention in dry periods. The years 2018 and 2019 are considered extreme dry periods. Therefore, this research question focusses on these extremely dry periods. The SGWL and SGWL-i are compared for all monitoring wells per intervention to reach the objective.

First, the minimum groundwater levels in the years 2018 and 2019 are focused on. To indicate the impact of an intervention on the minimum groundwater levels in 2018 and 2019, the **difference between the minimum of SGWL and SGWL-i** is calculated in 2018 and 2019, as shown as *d* in figure Figure 9. A confidence interval is added to assess if the changes are significant, (if the diagnostic check approves). This indicates the 95% confidence interval for the true best-fit line for the forecasted series. If the confidence interval of the SGWL-i does not overlap with the interval of the SGWL, there is enough evidence to tell that the groundwater level statistically significantly increased/decreased with the intervention. If the intervals overlap, there is not enough evidence to tell that the groundwater level statistically significantly increased/decreased with intervention. Second, the difference between the minimum of SGWL and SGWL-i in 2018 and 2019 are compared over space to identify the spatial effects of the intervention on groundwater levels. At last, the impact of the intervention on the timing of the minimum groundwater levels in 2018 and 2019 and the rate of variations in groundwater levels is qualitatively analysed.

4.4 RQ3 - Impact intervention on contributions to groundwater fluctuations

The objective of research question 3 is to analyse the impact of an intervention on the contributions of the auxiliary stresses (precipitation, potential evapotranspiration, surface water levels or groundwater abstraction) to the groundwater level fluctuations, as this can help explain variations in groundwater levels and droughts.

Pastas will be used to calculate these contributions for a fixed period for the SGWL and SGWL-i. The fixed period is used for all wells per case study to enhance comparability. The shortest SGWL-i in dynamic equilibrium between the series for a certain intervention is used as the fixed period. The difference between the **contributions of the auxiliary stresses to groundwater fluctuations** in the SGWL and SGWL-i is calculated to analyse the impact of the intervention.

4.5 RQ4 - Impact intervention on groundwater drought

The objective of research question 4 is to analyse the impact of an intervention on groundwater drought. First, the definition of groundwater drought is tightened. Second, it is determined how the impact of an intervention on groundwater drought is defined and analysed.

4.5.1 Definition groundwater drought

In Section 2.2, the general definition of groundwater drought is given as a decrease from normal conditions in groundwater level, groundwater storage, groundwater recharge, or groundwater discharge. The next key step is tightening this definition, by including threshold values. Peters (2003) derived The Partial Duration Series (PDS) method based on Rice (1945) and Yevjevich (1969) and this technique will be used for the definition. The PDS method indicates groundwater drought if groundwater levels are below a certain threshold. This method includes duration and multi-year droughts, which is essential for this research as shown in Figure 10.

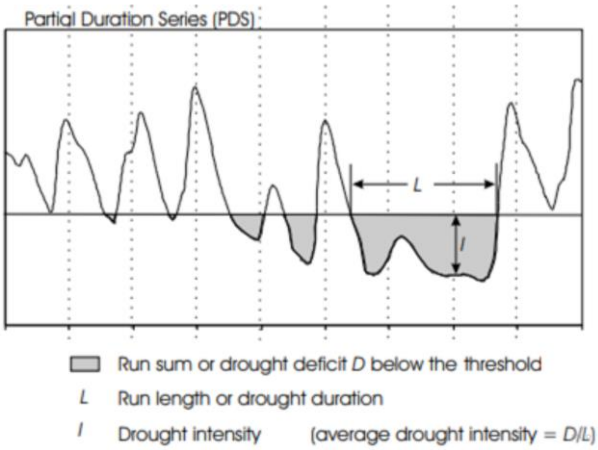

Figure 10: Two different methods for defining groundwater drought: a) AMS and b) PDS (Peters, 2003)

With *I* as drought intensity [m], *L* as drought duration [days] and *D* as drought deficit [mdays]. A limitation of PDS is the sensitivity of the chosen threshold value; a slightly different value could already result in a significantly different outcome in groundwater drought (Beguería, 2005). However, since this research focusses on the differences between groundwater droughts between the series with and without intervention, this only impacts the outcome minimally. Commonly used threshold values are based on the exceedance probabilities, but for series, with skewed distributions this method results in over- or underestimation of the threshold. Peters (2003) proposed a method that counters this limitation: the threshold value can be chosen as either constant or variable in time. For this research, a constant threshold is chosen as this is more usable operationally. The newly proposed method is based on the ratio between a deficit below the average and a threshold as shown in Figure 11. A more detailed description of this method can be found in (Peters, 2003)

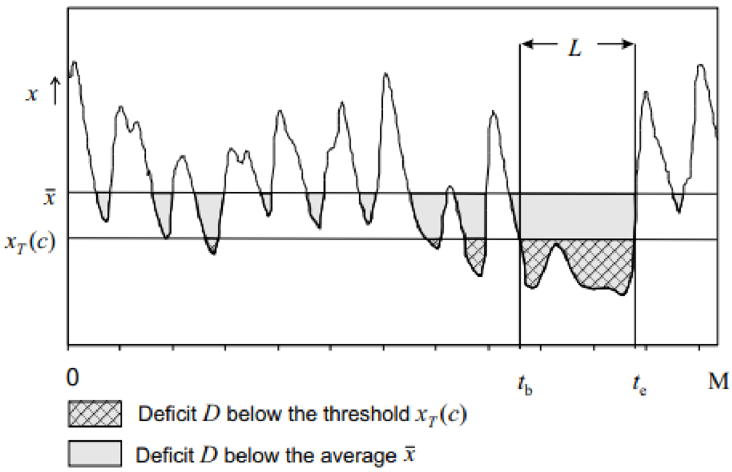

Figure 11: Illustration of the new threshold level approach

With *x* as the groundwater level series [m], $x_T(c)$ as the threshold [m] based drought criterion c [-], $\bar{x}$ as the average groundwater levels [m], t_b as the start of the drought [days] and t_e as the end of the drought [days]. Thus, the groundwater drought is defined in the remainder of this report as:

The period in which an averaged groundwater series is below a certain threshold, indicated by a duration and an intensity.

Where the groundwater series is averaged over two different time scales, three months and two years, as it is assumed that these scales capture the short (seasonal) and long (over the years) term impacts of groundwater droughts.

4.5.2 Impact of an intervention

The SGWL and SGWL-i are scaled to the minimum and maximum values of the SGWL to investigate the effect of the intervention on groundwater drought. The threshold technique proposed by Peters (2003) is used to calculate the threshold value based on the original groundwater series per monitoring well. This value is also scaled and applied for all time scales of this well. The drought criterion *c* is the ratio of the deficit below the threshold to the deficit below the average (Figure 11). This value will be set to 0.3 (Peters, 2003). More information on this threshold technique and its implementation can be found in Peters (2003). Threshold values are rounded to one decimal place to enhance comparability between wells. The scaled SGWL and SGWL-i and computed threshold value result in the groundwater drought series for SGWL and SGWL-i, which consists of values of zero for the periods where no groundwater drought is present. The impact of the intervention on groundwater drought is defined as:

The difference between groundwater droughts of the SGWL and SGWL-i.

The difference is computed by subtracting the groundwater drought series for SGWL from the groundwater drought series for SGWL-i for the short- and long-term. The impact of an intervention on groundwater droughts for different time scales is analysed qualitatively over time and space.

4.6 Case studies

The effects of nature-based human interventions are assessed in three study areas in the Netherlands. These interventions are chosen as enough data is available and the designs vary. This creates an understanding of the impact of various intervention types:

- Korenburgerveen
- De Doorbraak
- Scheller and Oldeneler Buitenwaarden

Figure 12: Locations of study areas and data stations

4.6.1 Korenburgerveen

Study area

The Korenburgerveen is located on the east side of the province of Gelderland, close to the border with Germany. The area is a bog remnant and is situated on the edge of a historical meltwater channel flowing from the northeast to the southwest (Verberk et al., 2001). Hullenaar (2000) divided the nature reserve into peatland and fringe zones which can be seen in Figure 13. The peatland area can be divided again into Vragenderveen, Corlese Veen, Maddose Veen and Korenburgerveen senu stricto (s.s.). The fringe zone is divided into four areas: Southeast, Northeast, Northwest, and Southwest fringe zones. Large parts of the area are bounded as a Natura-2000 area. Natura-2000 is defined as a European network of protected nature reserves with the objective to maintain the habitats of certain animals and plants. South of the Korenburgerveen, drinking water company Vitens abstracts groundwater at location Corle and the company Coberco also abstracts groundwater at the east of the area.

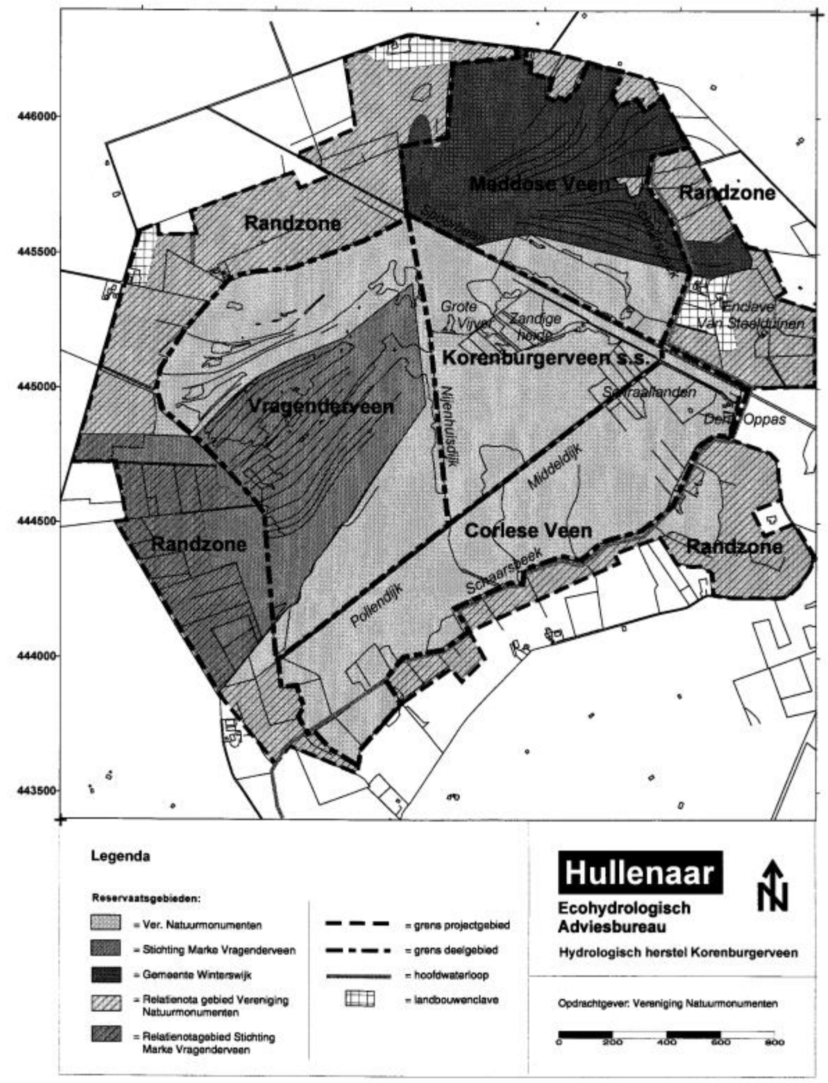

Figure 13: Sub areas Korenburgerveen (Hullenaar, 2000)

According to Hullenaar and Bell (2013), the Korenburgerveen is a result of a covered sand ridge in the valley of the Schaarsbeek, a channel in the Korenburgerveen. This ridge created a lake that turned into land after some time. Peaty clay was deposited on the bottom of the lake, referred to as gyttja, which is a poorly permeable soil type. This resulted in various types of peat, as shown in the peat distribution plot in Figure 52 in Appendix B – Korenburgerveen. In the Vragenderveen and Meddose Veen high moor peat (bog) is present, which is a nutrient-poor environment that receives only water from precipitation. In the lower areas of the Korenburgerveen low moor peat (fen) is present, which is peatland that is fed by nutrient-rich ground or surface water. On the edges of the high moor peat areas, a transitional peatland is present, which is peatland that is fed by ground or surface water and precipitation and has medium mineral content. At the southeast side of the peat, seepage-dependent wet barren land is present, which is grassland with slow-growing plants. An elevation map plus flow patterns of surface water and a cross-section of the current situation are provided in Figure 53 and Figure 54 in Appendix B – Korenburgerveen. Human activities like peat extraction resulted in the disappearance of acrotelm, a peat layer with a large storage capacity. This led to increased drainage in the wet periods and lower water levels in the dry periods. The low water levels resulted in the accession of oxygen which in turn led to the maturation and degradation of the peat. This positive feedback resulted in more losses of storage capacity and so on.

Intervention

Hullenaar (2000) elaborated on the project design and provided the objective of the nature restoration intervention. The objective of the project was the recovery of high-moor peat and low-moor peat based on a hydrological development plan. By optimizing the water storage capacity of the area, water level fluctuations were expected to dampen, and so desiccation of the areas could be countered. Various measures were taken to achieve this objective as can be seen in Figure 55 in Appendix B – Korenburgerveen.

The main measure of the hydrological recovery plan was the construction of a wooden barrier wall around areas of high peat, to decrease surface outflow and dam up the water. Because of the different thicknesses of the peat layer, various lengths were used for the sheet pile walls. A cascade construction of these barrier walls and spillways resulted in various compartments and the capability to regulate water levels. The emphasis of this intervention was on the regeneration of high peat moor in the sub-areas Vragenderveen and the higher part of Meddose Veen. For the sub-areas Korenburgerveen s.s., Corlese Veen and the lower part of Meddose Veen, the focus was on the conservation and recovery of the low peat moor. Next, for the sub-areas Korenburgerveen s.s. and the northeast part of Corlese Veen, the weir levels were sufficient, but water losses to lower situated areas and the Schaarsbeek needed to be addressed. To counter this, surface water levels in the Schaarsbeek were raised by installing weirs and sheet piles, and a barrier wall was constructed in the Pollendijk. Furthermore, the Schaarsbeek in the southwest part of Corlese Veen was also equipped with a weir to counter the draining effect of the stream. Additionally, at the south of the Schaarsbeek, a new waterway (Parallelsloot) was constructed for the drainage of the agricultural water. Besides, filling up secondary channels in infiltration areas and the Korenburgerveensloot stimulated groundwater supply towards the low peat moor and created a reserve for dry periods. In the lower part of the Meddose Veen a ground dam was constructed to counter surface water runoff towards the Enclave Van Staalduinen. A more detailed description of the main or additional measures can be found in Simmelink et al. (2021).

Data

Various groundwater time-series are obtained from monitoring wells in and surrounding the Korenburgerveen that are presented in Table 1 and Figure 14. Precipitation data are received specifically for every monitoring well via Meteobase (Meteobase, 2016). In this research, groundwater levels are identified by the last three numbers of the name of the monitoring well with i for inside and o for outside the Korenburgerveen, as can be seen in Figure 14. Groundwater abstraction data from Coberco is not obtained. No useable monitoring wells with a filter in the high peat moor are obtained, so the analysis does focus on groundwater heads of the aquifer below.

Table 1: Data sources for Korenburgerveen

Name product	Temporal resolution	Time period	Reference
Groundwater			
B41E0461 (i461)	Irregular	1985 – 2020	https://www.dinoloket.nl/ondergrondgegevens
B41E0457 (i457)	“”	1985 – 2020	“”
B41E0440 (o440)	Irregular (daily after 2004)	1988 – 2019	“”
B41E0243 (o243)	“”	1981 – 2019	“”
B41E0246 (o246)	“”	1981 – 2019	“”
B41E0438 (o438)	“”	1988 – 2019	“”
B41E0429 (o429)	“”	1981 – 2019	“”
B41E0206 (o206)	“”	1980 – 2019	“”
Precipitation			
All monitoring wells	Hourly	1990 – 2022	https://meteobase.nl/index.php?tb=rasterdata&dp=rasterdata&dp_sub=introductie
Potential evapotranspiration			
Weather station Twenthe	Daily	1987 – 2020	https://www.knmi.nl/nederland-nu/klimatologie/daggegevens
Surface water levels			
P41E0016	Irregular	1994 – 2020	Waterboard Rijn and IJssel
P41E0040	Irregular	2003 – 2021	
Groundwater abstraction			
Corle	Yearly	1940 – 2020	Vitens
Spatial characteristics			
Land use	Irregular	1984 – 2022	LGN

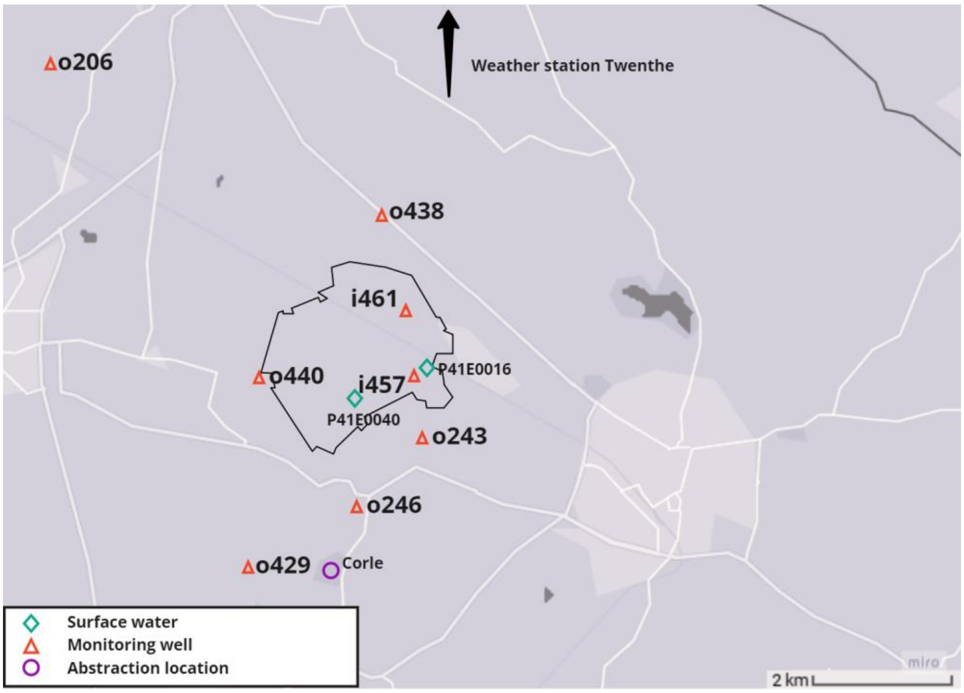

Figure 14: Map with locations of data sources for Korenburgerveen

4.6.2 De Doorbraak

Study area

De Doorbraak is an anthropogenic stream that is located south of Almelo. A map that shows the location of De Doorbraak is provided in Figure 16. The geology of the area is visualized in Figure 15. The top layer consists of cover sand which is located on two aquifers. In between these two aquifers, a separation layer is obtained for some locations. A sloping ground level is obtained for reducing levels towards the west as can be seen in Figure 15. In the landscape, a moraine is present, which is crossed by De Doorbraak indicated in yellow in Figure 16. This moraine acts like an elevated infiltration area with a bulging groundwater profile. Additionally, the groundwater abstraction location in Wierden is located near the new waterway. In 2013 a new abstraction point (III) was added to the groundwater abstraction location Wierden, located closer to De Doorbraak.

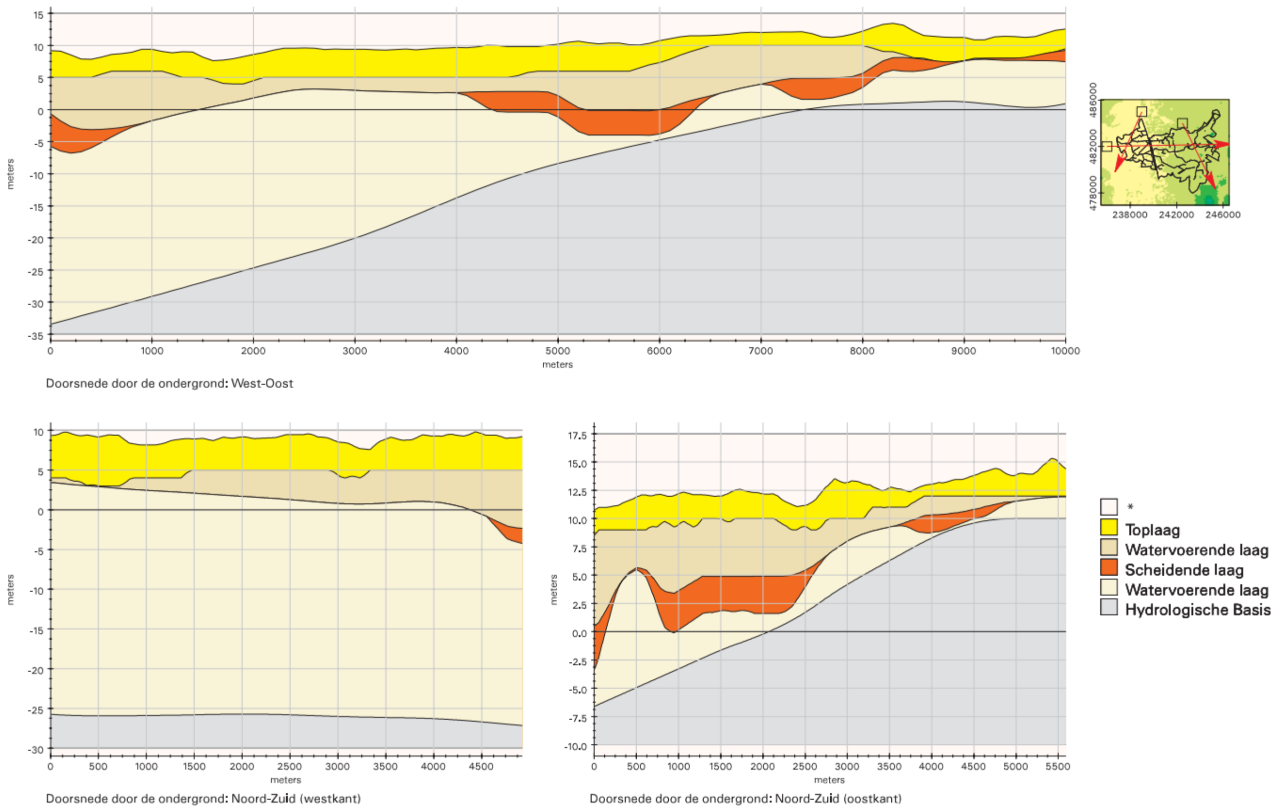

Figure 15: Geology De Doorbraak (Snepvangers, 2003)

Intervention

The idea of the intervention originated after the flooding of October 1998, when water safety became a hot topic (Leenaers, 2017).

The intervention was constructed between 2004 and 2016. Vechtstromen (2018) described the objective of the project, which initially was divided into three sub-goals:

- Increasing safety; creating more water storage capacity;
- Strengthening nature; creating ecological corridor;
- Improve the water system; strengthening the adjacent water streams dynamically and ecologically.

The following two goals were added during the implementation of the project:

- Increase recreational opportunities;

- No deterioration of agriculture.

Vechtstromen (2018) describes the four phases of the construction of the intervention: Mokkelengoor, Bornerbroek, Tusveld and Het Fleer as shown in Figure 10 in Appendix C – De Doorbraak. The first activities started at Mokkelengoor, in 2004. In 2006, the construction of the second phase (Bornerbroek) started. In this phase, the width of De Doorbraak was increased by 75 meters to create a buffer zone between the new channel and the XL Business Park. The activities of the third phase (Tusveld) started in 2009. This section connects De Doorbraak to the Loolee, a nearby waterway. Difficulties during this phase were related to the desiccation of the nature area the Krikkenhaar. Construction of the last phase, De Kleine Doorbraak, started in 2010. This section serves as a connection between De Doorbraak and the waterway De Azelerbeek. Additionally, since this research only focuses on the groundwater levels, independent activities like water quality analysis, are out of scope.

Data
Various groundwater time-series are obtained from monitoring wells surrounding De Doorbraak, as shown in Table 2 and Figure 16. The filters of the monitoring wells are located in the first aquifer, except for well 80, which is located in the second aquifer.

Table 2: Data sources for De Doorbraak

Name product	Temporal resolution	Time period	Reference
Groundwater			
B28D0371 (371)	Irregular (daily after 2005)	1987 – 2020	https://www.dinoloket.nl/ondergrondgegevens
B28G0407 (407)	“”	1984 – 2020	“”
B28G0344 (344)	“”	1975 – 2020	“”
B28D0329 (329)	“”	1984 – 2020	“”
B28D0350 (350)	“”	1979 – 2020	“”
B28D0331 (331)	“”	1984 – 2020	“”
B28D0080 (80)	“”	1962 – 2019	“”
B28H0675 (675)	“”	1988 – 2020	“”
Precipitation			
All monitoring wells	Hourly	1990 – 2022	https://meteobase.nl/index.php?tb=rasterdata&dp=rasterdata&dp_sub=introductie
Potential evapotranspiration			
Weather station Twenthe	Daily	1951 – 2020	https://www.knmi.nl/nederland-nu/klimatologie/daggegevens
Spatial characteristics			
Land use	Irregular	1984 – 2022	LGN

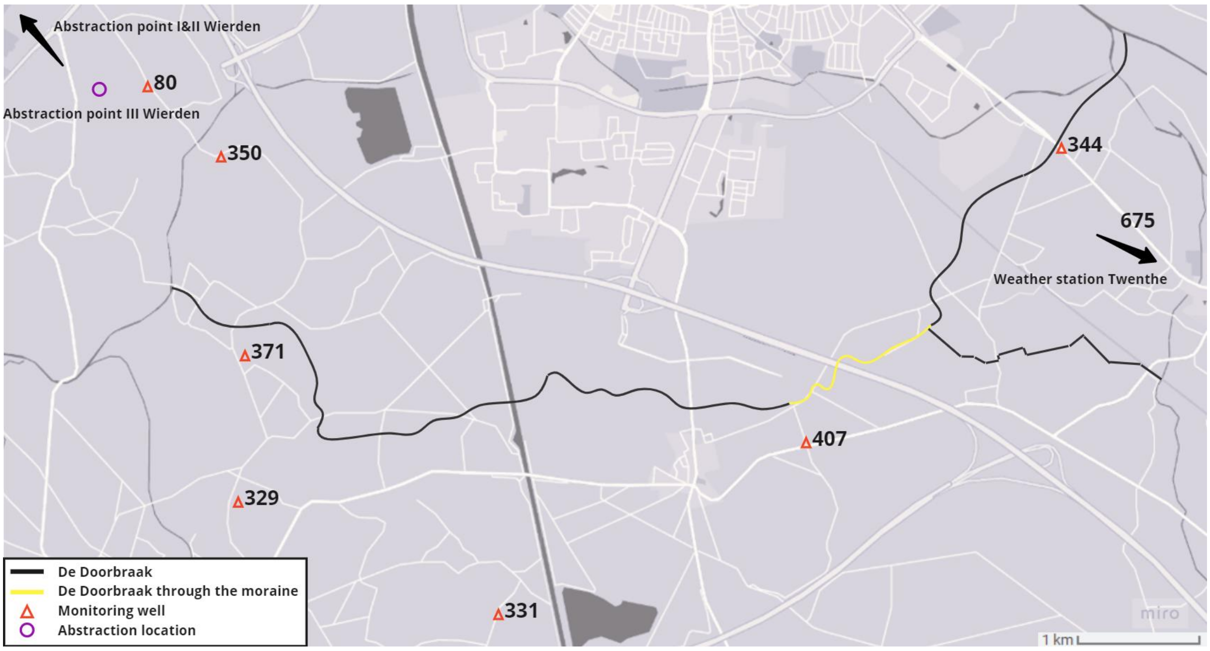

Figure 16: Map with locations of data sources for De Doorbraak

4.6.3 Scheller and Oldeneler buitenwaarden

Study area

The intervention is located in Zwolle as shown in Figure 12. Originally the area consisted of Het Engelse Werk which is a nature reserve on the northside, and a grassland section on the southside as shown in Figure 94 in Appendix E – Scheller and Oldeneler buitenwaarden. In the study area, groundwater abstraction location Het Engelse Werk is located. Since early '40, Vitens uses this location to provide drinking water for the region.

Furthermore, Royal Haskoning (2010) estimated that the soil structure at the location of the intervention is a moderately permeable loamy/clayish cover layer (2 to 6 m thick), with an aquifer below it. The soil on the landside of the winter dike exists of a sandy type of soil, which is classified between clay and sand.

Intervention

The Scheller and Oldeneler buitenwaarden is part of the Room for the River programme, which emerged since high water levels occurred in the main rivers in 1993 and 1995. The intervention consisted of a side channel and lowered flood plains and the construction of the intervention started in 2015 and was finished in 2017. The objective of the Scheller and Oldeneler buitenwaarden was to increase water storage to provide more safety for areas around the river, by decreasing the surface water level in the IJssel by 8 cm. The design also generated the opportunity for recreational and nature-related areas.

Data

Three monitoring wells in the vicinity of the intervention are analysed as shown in Table 3 and Figure 17. The filters of these wells are located in the first aquifer.

Table 3: Data sources for Scheller and Oldeneler buitenwaarden

Name product	Temporal resolution	Time period	Reference
Groundwater			
B27E0211 (211)	Irregular (daily after 2005)	1982 – 2020	https://www.dinoloket.nl/ondergrondgegevens
B21G0492 (492)	“”	1987 – 2020	“”
B27E0260 (260)	“”	1991 – 2020	“”
Precipitation			
All monitoring wells	Hourly	1990 – 2022	https://meteobase.nl/index.php?tb=rasterdata&dp=rasterdata&dp_sub=introductie
Potential evapotranspiration			
Weather station Heino	Daily	1991 – 2020	https://www.knmi.nl/nederland-nu/klimatologie/daggegevens
Groundwater abstraction			
Het Engelse Werk	Irregular	1990 – 2022	Vitens
Surface water levels			
Measurement station Wijhe	Regular	1990 – 2022	https://waterinfo.rws.nl/#!/thema/Waterbeheer/
Spatial characteristics			
Land use	Irregular	1984 – 2022	LGN

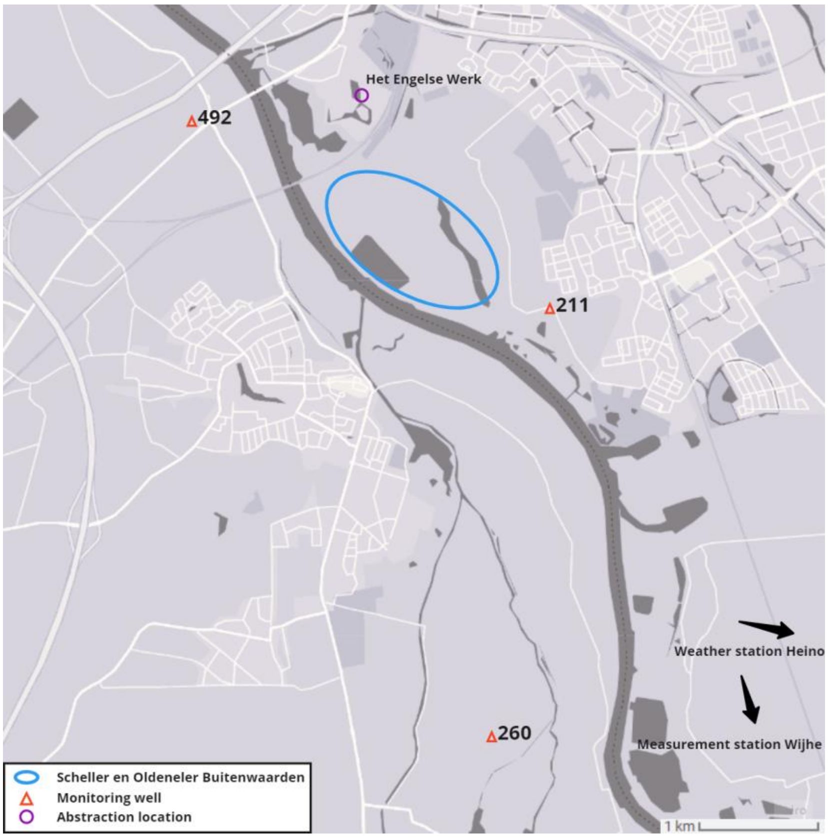

Figure 17: Map with locations of data sources for Scheller and Oldeneler buitenwaarden

4.7 Model setup

4.7.1 Data pre-processing

The quality of the time-series (groundwater levels and auxiliary data) is assessed for all case studies and the obtained time-series are checked on completeness and outliers. The first step is a visual inspection, where data quality is judged and non-qualified data points are removed, based on the expertise of the author. Next, the data rescue approach by Retike et al. (2022) is used to identify errors and correct groundwater series. This method proposes multiple error types: distinct errors, errors in measurements and data recording/preprocessing; technical problems at the observation site; local anthropogenic impact and other unclassified problems.

Distinct errors are obtained by analysing sudden peaks in the series. The following is applied for the sudden peaks of one day: If the peak is a deviation of one day and more than 0.40 m the peak is assumed to be unrealistic and excluded from the series (Burt, 2017). For sudden peaks longer than one day, the peaks are compared with other series and from this, it is concluded whether they are unrealistic and can be excluded from the series. If the series shows an unrealistic noisy series, probably enhanced by data processing errors, the moving average will be used to replace the relevant values. Furthermore, replacements or remeasurements of the monitoring wells could result in deviations in the groundwater series. These types of errors require transformations of the series.

In a Pastas model, the dependent data (groundwater levels) are allowed to be irregular and include missing data. However, regular time steps without missing data in independent data (auxiliary data) are mandatory, as these are used to simulate contributions to the groundwater levels. Filling in the missing data and creating regular time steps for the auxiliary data is done by interpolation. A Pastas function (ps.utils.get_equidistant_series()) is used to obtain these equidistant time-series. This function uses the nearest sampling with filling logic which holds that an original measurement is only used once in the new time-series.

The model for Korenburgerveen uses groundwater abstraction and surface water as auxiliary data, requiring specific data pre-processing steps. Groundwater abstraction data for abstraction point Corle has a yearly frequency till 2015 and after that, it becomes monthly. The precipitation and potential evapotranspiration data are daily. The Pastas model requires regular data and the same frequency as the input series. Therefore, groundwater abstraction is scaled to a daily frequency. To do so, the average distribution of groundwater abstraction data over a year will be fitted based on the monthly data after 2015. This yearly distribution in combination with the total yearly values will result in monthly abstraction rates before 2015. Next, linear interpolation is used to scale up to daily time steps. Eventually, the added value of adding the abstraction can be determined while modelling. Additionally, transformations are required to obtain useable surface water series. The first reason is that no surface water series inside the Korenburgerveen has a range from the year 1990 till 2021. Second, if a surface water series is used for determining the forecasted autonomous groundwater behaviour, a surface water series that is (fictionally) not affected by the intervention is required. Multiple surface water series are available inside the Korenburgerveen and if these series show significant visual correlations and clear step trends are visible before and after the intervention, values can be used for extrapolation or transformation. Then a transformed surface water series that is not influenced by the intervention can be determined and used as input stress for the Pastas model.

Correlations between input parameters and groundwater fluctuations are visualized to get insights into the relations between them, which could help in understanding the model results. Also, the correlation between recharge and surface water is important to determine. If there is a correlation, recharge becomes a confounding variable when surface water is added as stress in the model. Consequently, the contributions of surface water, precipitation and potential evapotranspiration to groundwater fluctuations become uncertain and only the groundwater levels and droughts are analysed for the relevant monitoring wells.

4.7.2 Initial parameters

Various parameters can be altered in the model, resulting in different outcomes. The initial set of parameters is based on recommendations and area characteristics. A distinction is made between monitoring wells in and outside the Korenburgerveen as it is expected that recharge inside the area reacts nonlinear (Simmelink et al., 2021). The initial set of parameters per case study is provided in Table 4.

Table 4: Initial parameter values

Parameter	Korenburgerveen (inside)	Korenburgerveen (outside)	De Doorbraak	Scheller and Oldeneler buitenwaarden
Input series	Prec, PE, GA and SW*	Prec, PE and GA	Prec, PE	Prec, PE and SW
Recharge model	FlexModel	Linear	Linear	Linear
IRF recharge model	Gamma	Gamma	Gamma	Gamma
Trend	Not added	Not added	Not added	Not added
Warmup period	Added	Added	Added	Added
Noise model	Added	Added	Added	Added
Improving parameters	Added	Added	Added	Added
Solver method	Leastsquares	Leastsquares	Leastsquares	Leastsquares
Frequency groundwater input series	Daily	Daily	Daily	Daily
Frequency simulation	Daily	Daily	Daily	Daily
Set parameters	Non	Non	Non	Non
Threshold method	Added	Added	Added	Added

* Prec = Precipitation, PE = Potential evapotranspiration, GA = Groundwater abstraction, SW = Surface water

4.7.3 Optimizing model parameters

Validation and calibration

The next step is finding the optimal parameters per monitoring well, which is based on three validations, as shown in Figure 18. Two validations before the intervention (validation and cross-validation) and validation of the dry years 2018 and 2019. The last mentioned is calibrated with the groundwater series with intervention and is executed to test whether the model can simulate extreme dry periods. For the calibration period, the SGWL-i in dynamic equilibrium is taken, as responses can differ before this equilibrium. The optimal parameters per monitoring well are computed using a trial-and-error method. Various parameter sets are tried for the three validations per monitoring well. Eventually, one optimal parameter set is chosen per monitoring well and implemented as a parameter set in the final model.

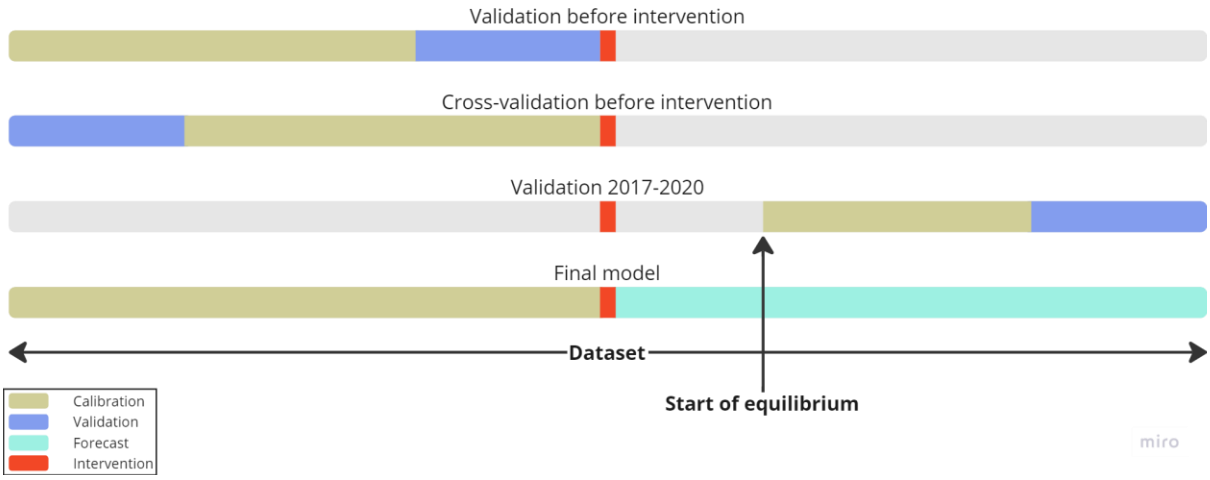

Figure 18: Calibrations and validations

Model performance

The performances of the models are quantified with three variables, the Explained Variance Percentage (EVP), the root-mean-square deviation (RMSE) and the difference between the simulated and observed minimum groundwater levels with intervention in the dry years 2018 and 2019 (RMSE_min). These variables are used as a goodness-of-fit metric. The EVP indicates the percentage of variance in the dependent variable (groundwater levels) that is explained by the independent variables (auxiliary data):

$$EVP = \frac{\sigma_h^2 - \sigma_r^2}{\sigma_h^2} \quad (8)$$

With σ_h^2 [m^2] the variance of the observations and σ_r^2 [m^2] the variance of residuals. An EVP < 70% indicates an inaccurate simulation of fluctuations of the groundwater levels. This EVP threshold is based on a rule of thumb proposed by van Engelenburg et al. (2020) and Collenteur (2021). The RMSE is used to quantify the differences between simulated and observed groundwater levels:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} r(t_i)^2}{N}} \quad (9)$$

With $r(t_i)^2$ [m] the residuals on data point *i* with a total of *N* data points. A threshold of 0.22m for RMSE for inaccurate simulations is established based on a suggested RMSE threshold by Izady et al. (2013). The third variable, RMSE_min, is considered to check whether drought periods are simulated accurately. The variables are calculated for the calibrations and validations of the three validations and the final model. The worst score per variable per monitoring well is used to decide whether the well will be used for further analysis. The possible performances of the model and its consequences for further analysis are elaborated on in Table 5.

Table 5: Possible model performances

Performance	RMSE_min [m]	RMSE [m]	EVP [%]	Consequence
Inaccurate	≥ 0.22	-	-	No further analysis
Inaccurate	-	≥ 0.22	< 70	No further analysis
Decent(1)	< 0.22	≥ 0.22	≥ 70	Only contributions analysis
Decent(2)	< 0.22	< 0.22	< 70	All but contributions analysis
Good	< 0.22	< 0.22	≥ 70	All analysis

Additionally, residuals and noise of the simulation are provided to ensure that the model adequately describes the observed time-series (Hipel and McLeod, 1994). A diagnostic test is performed to check if noise behaves as white noise and inferences can be made with the model, by applying a confidence interval on the forecasted groundwater levels. This diagnostic test included a visual normality and Ljung box test. The visual normality test plots the noise values in a histogram and determines visually if the values are normally distributed. The Ljung box test plots the autocorrelation of the noise series and checks if there is too much autocorrelation present.

At last, a sensitivity analysis on the calibration length is executed as the calibration length could have a significant influence on the model results (Li et al., 2010). This analysis is another method to show the confidence of the final model. If the results for different calibration lengths show little variation, the confidence that the computed value is close to the real value increases. Six additional runs are performed for the models that simulate the SGWL and SGWL-i with decreasing calibration length (three runs for the model for SGWL and three for the model for SGWL-i). For every run, the start of the calibration of the models decreases by one year. Except for the SGWL-i for the Scheller and Oldeneler Buitenwaarden, for which it decreases by half a year. Otherwise, the calibration length decreases to zero for the last run. The results of the sensitivity analysis are included as error bars in the results for research questions 2 and 3 and qualitatively described for research question 4.

5 Korenburgerveen

5.1 Autonomous groundwater behaviour

In this Section, the results of research question 1 are presented for Korenburgerveen. The data pre-processing steps for the groundwater, surface water, groundwater abstraction series are provided in Appendix A – Korenburgerveen data pre-processing. The distinct errors are shown in Figure 58 in Appendix B – Korenburgerveen.

5.1.1 Observed groundwater series

The pre-processed observed groundwater series are shown in Figure 19.

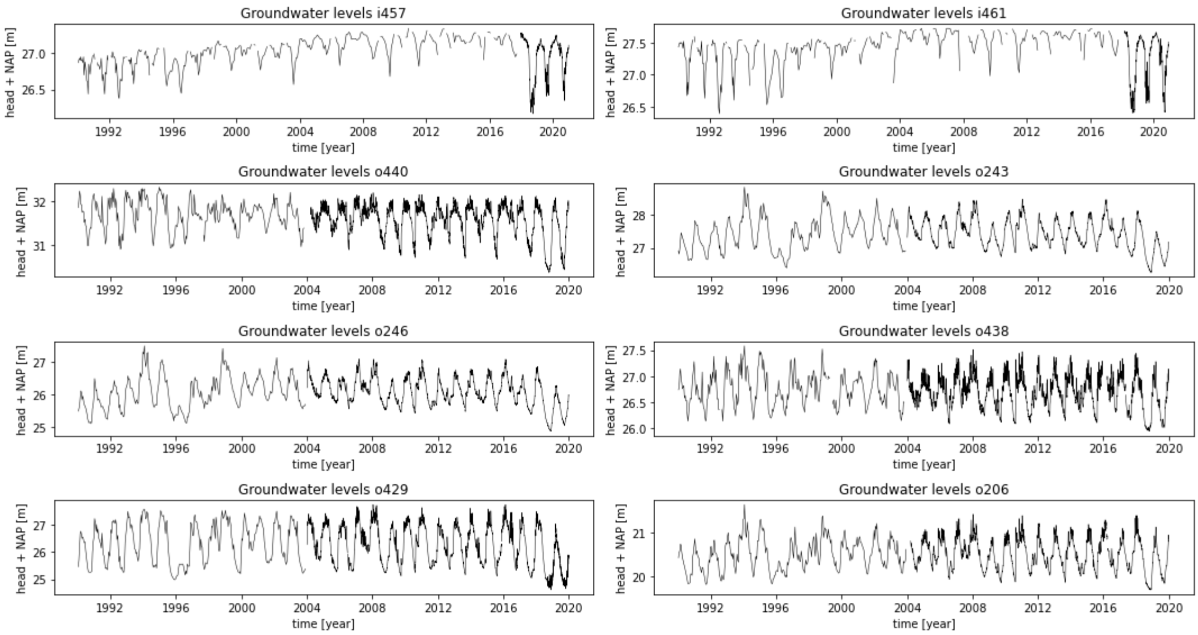

Figure 19: Pre-processed observed groundwater series Korenburgerveen

Low groundwater levels in the years 2018, 2019 and 2020 are visible in all groundwater series. Also, low groundwater levels are observed in 1996 in all groundwater series and in the years 1988-1992 in most of the series. Furthermore, in the time-series inside the Korenburgerveen, an upwards trend is observed after 1997. It is expected that this trend is induced by the intervention.

5.1.2 Correlation input series

A visual correlation is found between the groundwater series and the surface water series and between the groundwater series and the abstraction series. This indicates the influence of these input series on groundwater fluctuations. Additionally, the input series surface water is a confounding variable, as is elaborated on in Appendix B – Korenburgerveen. Therefore, models including surface water cannot be used for analysing the contributions.

5.1.3 SGWL Simulation

Next, the SGWL are simulated per well. Even though groundwater abstraction influences groundwater fluctuations, it is excluded as input series because it increased parameter uncertainty significantly. In Table 6, the EVP and RMSE values of the calibration of the final models including the performance are provided. Other monitoring wells performed badly and are not further considered. The performances of all the calibrations and validations are presented in Table 12 in Appendix B – Korenburgerveen. In Table 7 the final set of parameters is shown.

Table 6: Performance SGWL models Korenburgerveen

	i461	i457	o440	o243	o246	o438	o429	o206
RMSE	0.10	0.05	0.18	0.13	0.16	0.14	0.21	0.13
EVP	0.87	0.89	0.73	0.94	0.90	0.82	0.92	0.89
Performance	Decent2	Decent2	Good	Good	Good	Decent2	Decent1	Good

Table 7: Parameters of models for various monitoring wells Korenburgerveen

Parameter	i461	i457	o440	o243	o246	o438	o429	o206
Precipitation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
*PE**	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
*GA**	No	No	No	No	No	No	No	No
Surface water	No	Yes	No	No	No	No	No	No
Recharge model	FlexModel	FlexModel	FlexModel	FlexModel	Linear	Linear	Peterson	FlexModel
IRF recharge model	Exp.	Exp.	Exp.	Exp.	Gamma	Gamma	Exp.	Exp.
Trend	No	No	No	No	No	No	No	No
Warmup period	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Noise model	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Improve parameters	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Solver method	LS*	LS	LS	LS	LS	LS	LS	LS
*Frequency GW**	Original	Original	14D	8D	18D	10D	20D	18D
Frequency simulation	D	D	D	D	D	D	D	D
Set parameters	Rch_ks	Rch_ks	Rch_ks	Rch_ks	No	No	No	Rch_ks
Threshold method	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes

* PE = Potential evapotranspiration, GA = Groundwater abstraction, Exp = Exponential , LS = Leastsquares and GW = Groundwater

5.1.4 SGWL series

In all SGWL series, relatively low minimum groundwater levels are obtained in 2007, 2018 and 2019. In 1996, relatively low groundwater levels in the wet period are obtained in all autonomous series. Additionally, no trends are obtained in the mean groundwater levels.

5.2 Impact intervention on groundwater levels

In this Section, the results of research question 2 are elaborated for Korenburgerveen. The Section focuses on the differences between the SGWL and SGWL-i and especially the differences during the dry years 2018 and 2019.

In Figure 20 the differences between the drought periods in 2018 and 2019 are shown. Monitoring well o429 is excluded because of the decent(1) performance. Additionally, the differences are spatially visualized in Figure 21. Furthermore, by analysing the confidence intervals, the model for wells i457 and i461 showed a significant increase in minimum groundwater levels in 2018. The significant increase in 2019 was also significant for well i461.

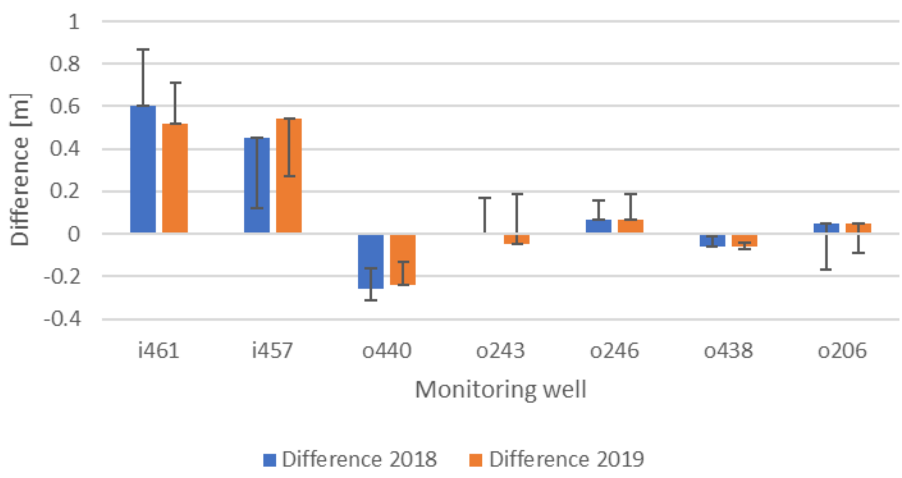

Figure 20: Impact intervention on minimum groundwater levels in 2018 and 2019 at Korenburgerveen

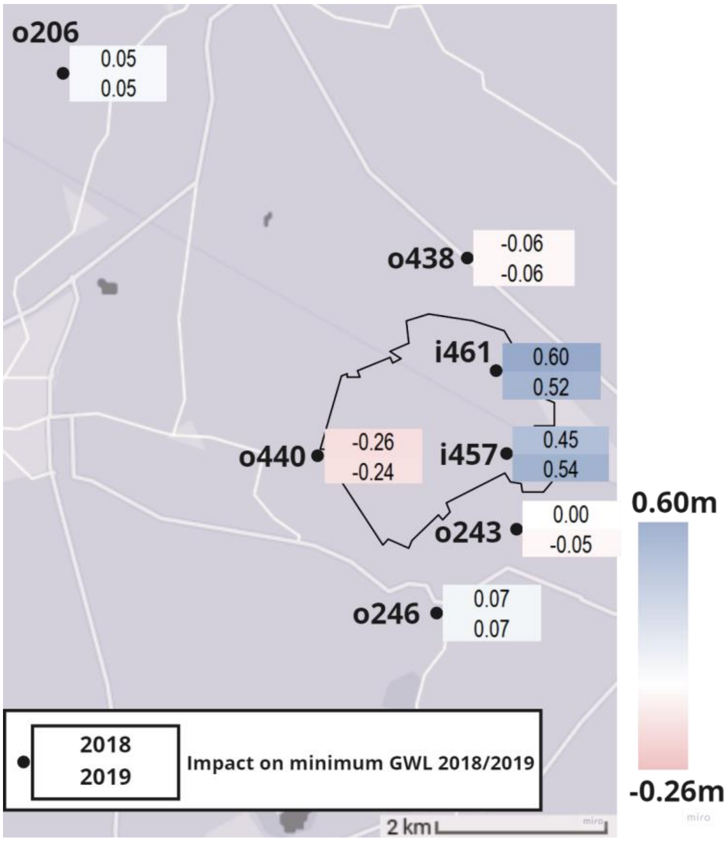

Figure 21: Spatial impact on minimum groundwater level in 2018 and 2019 at Korenburgerveen

5.2.1 Sensitivity analysis

The results of the sensitivity analysis are shown in Figure 20 as error bars. The results show various sensitivities for the calibration length. First, the simulations for well o438 show almost no sensitivity to varying calibration length, while the simulations for well o440 and o246 show some variation between 0-0.12m. Next, the simulations for wells i461, i457, o243 and o206 show more variation and for well i457 the model became unstable for the run with the shortest calibration lengths, caused by the lack of data points for this series. It is assumed that the longest calibration lengths are the most accurate for the models for wells i457 and i461.

5.2.2 Results

The minimal groundwater levels in the years 2018 and 2019 in the simulations for wells i461 and i457 (only 2019) did statistically significantly increase for the SGWL-i series. Next, the results for well o246 show a slight increase in minimum groundwater levels in 2018 and 2019 with intervention, enhanced by the sensitivity analysis. Besides, the results for well o440 show a slight decrease in minimum groundwater levels in 2018 and 2019 with intervention. Additionally, the simulations for wells o243 and o206 showed sensitivity for variation in the calibration length, indicating no evidence for an increase or decrease in minimum groundwater levels in 2018 and 2019. Furthermore, the timing of the minimum groundwater levels in 2018 and 2019 only varied very little with and without intervention. At last, the rate of groundwater decrease and increase in 2018 and 2019 did decrease in the results for wells i457 and i461. This rate did slightly increase in the results for well o440. Also, it is remarkable that the minimum groundwater levels in the results for well o246 stayed low for a shorter period in the SGWL-i. The total recovery rate (between the minimum and maximum) remained the same. For the other monitoring wells, the differences in this rate were minimal.

5.3 Impact intervention on contributions

In this Section, the results of research question 3 are presented for Korenburgerveen. Wells i461 and o438 are excluded because of the decent(2) performances. Furthermore, well i457 is excluded because of the confounding variable recharge. The contributions without and with intervention are shown in Figure 22 and Figure 23, respectively. The impact of the intervention on these contributions is presented in Figure 24.

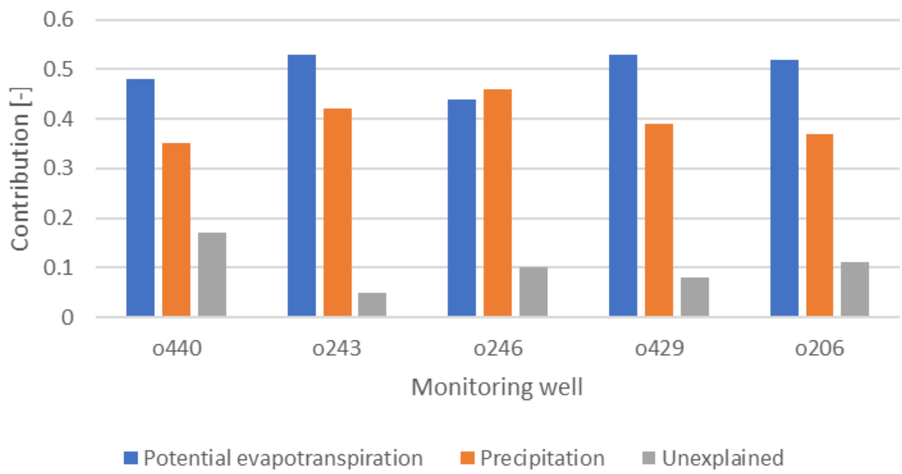

Figure 22: Contributions to groundwater fluctuations without intervention at Korenburgerveen

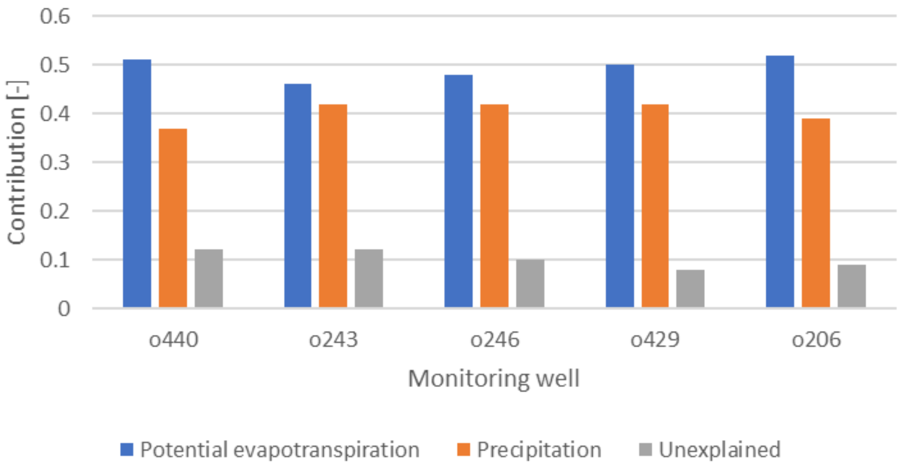

Figure 23: Contributions to groundwater fluctuations with intervention at Korenburgerveen

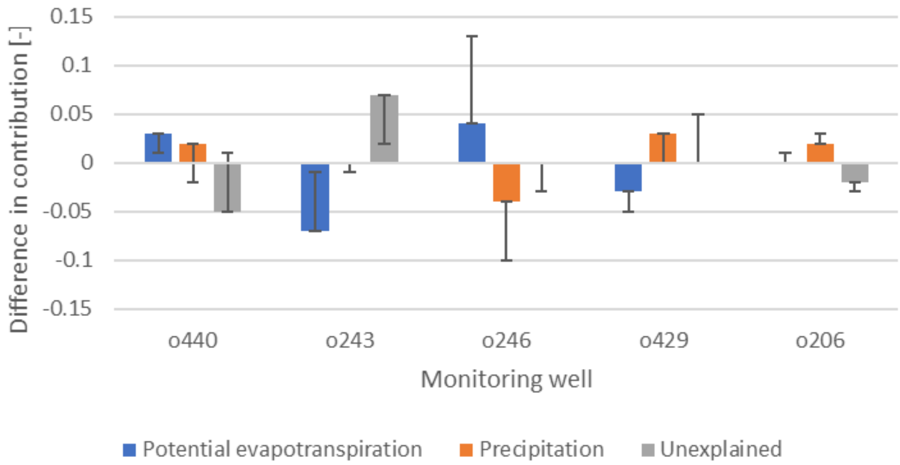

Figure 24: Impact intervention at Korenburgerveen on contributions to groundwater fluctuations

5.3.1 Sensitivity analysis

The results of the sensitivity analysis are shown in Figure 24 as error bars. The sensitivity analysis shows low sensitivity of the contribution difference for various calibration lengths in the simulations for well o206 (0-0.02). The simulations for other wells show more sensitivity, with some increasing differences (o246) and some decreases in the differences (o440 and o243). These ranges introduce uncertainty that needs to be considered in further analysis.

5.3.2 Results

The results for wells o440, o243 and o206 show almost no impact due to the intervention, also considering the sensitivity analysis. Next, the results for well o246 show a slight increase in the contribution of potential evapotranspiration and a slight decrease in the contribution of precipitation, enhanced by the sensitivity analysis. At last, the results for well o429 show a slight decrease in the contribution of potential evapotranspiration.

5.4 Impact intervention on groundwater drought

In this Section, the result of research question 4 is elaborated on for Korenburgerveen.

5.4.1 Results

The impact of the intervention on short and long-term groundwater droughts for all wells are visualised in the upper plots of Figure 25 and Figure 26, respectively. These plots show the difference between groundwater droughts of the SGWL and SGWL-i. The bottom plots of both figures show the groundwater droughts for the SGWL, indicating the observed groundwater drought without intervention. For a reminder, groundwater drought is defined as the period in which a scaled averaged groundwater series is below a certain threshold. These thresholds are determined per well and based on the distributions of the groundwater series. Values of the scaled averaged groundwater series above the corresponding threshold are excluded in the bottom plots to only present the groundwater droughts. The impact of the intervention on short- and long-term groundwater droughts is shown in Appendix B – Korenburgerveen in more detail per well. Furthermore, the results of the sensitivity analysis did show confidence in the simulated impact of the intervention.

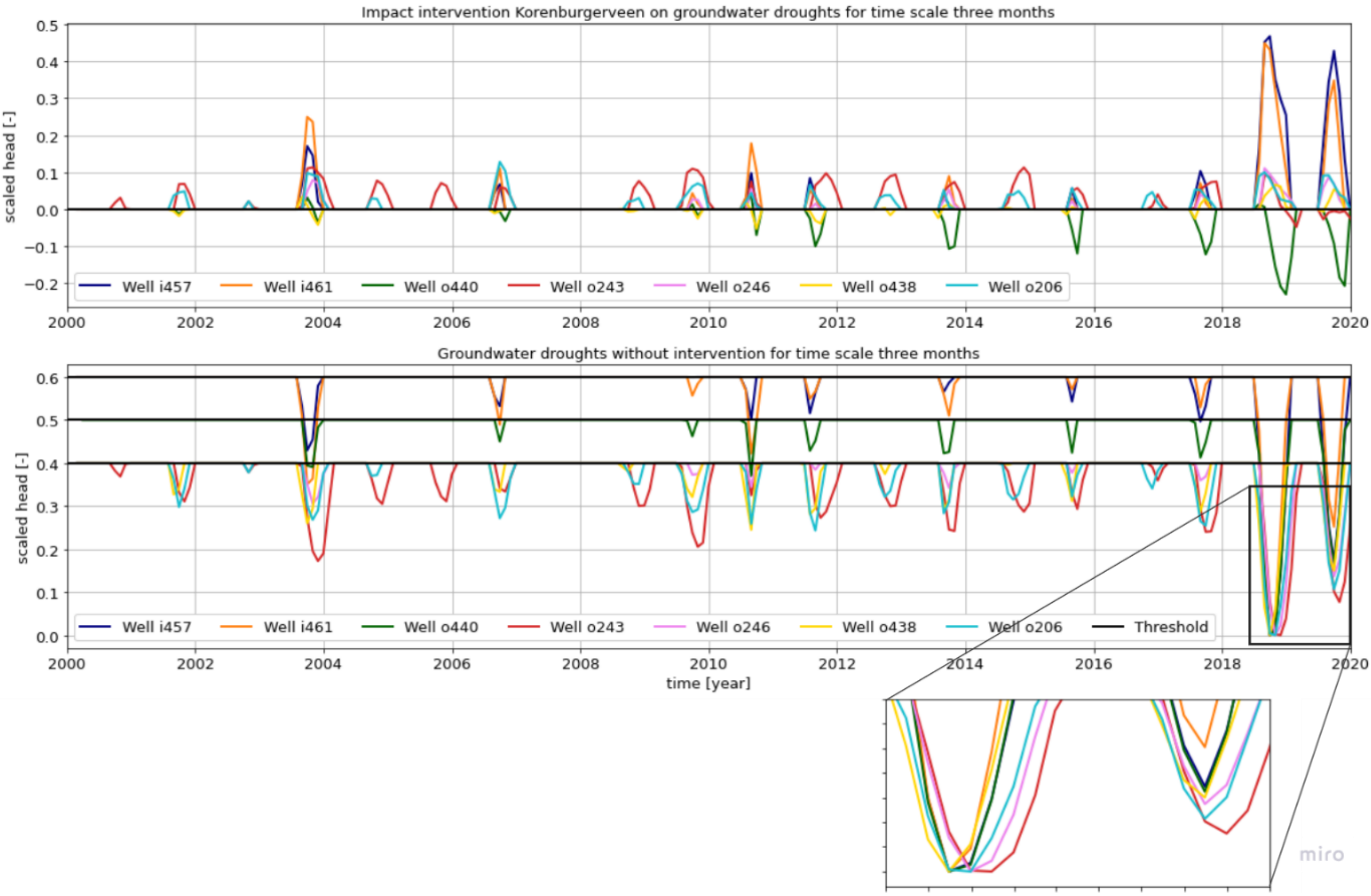

Figure 25: Impact intervention Korenburgerveen on groundwater droughts for time scale three months

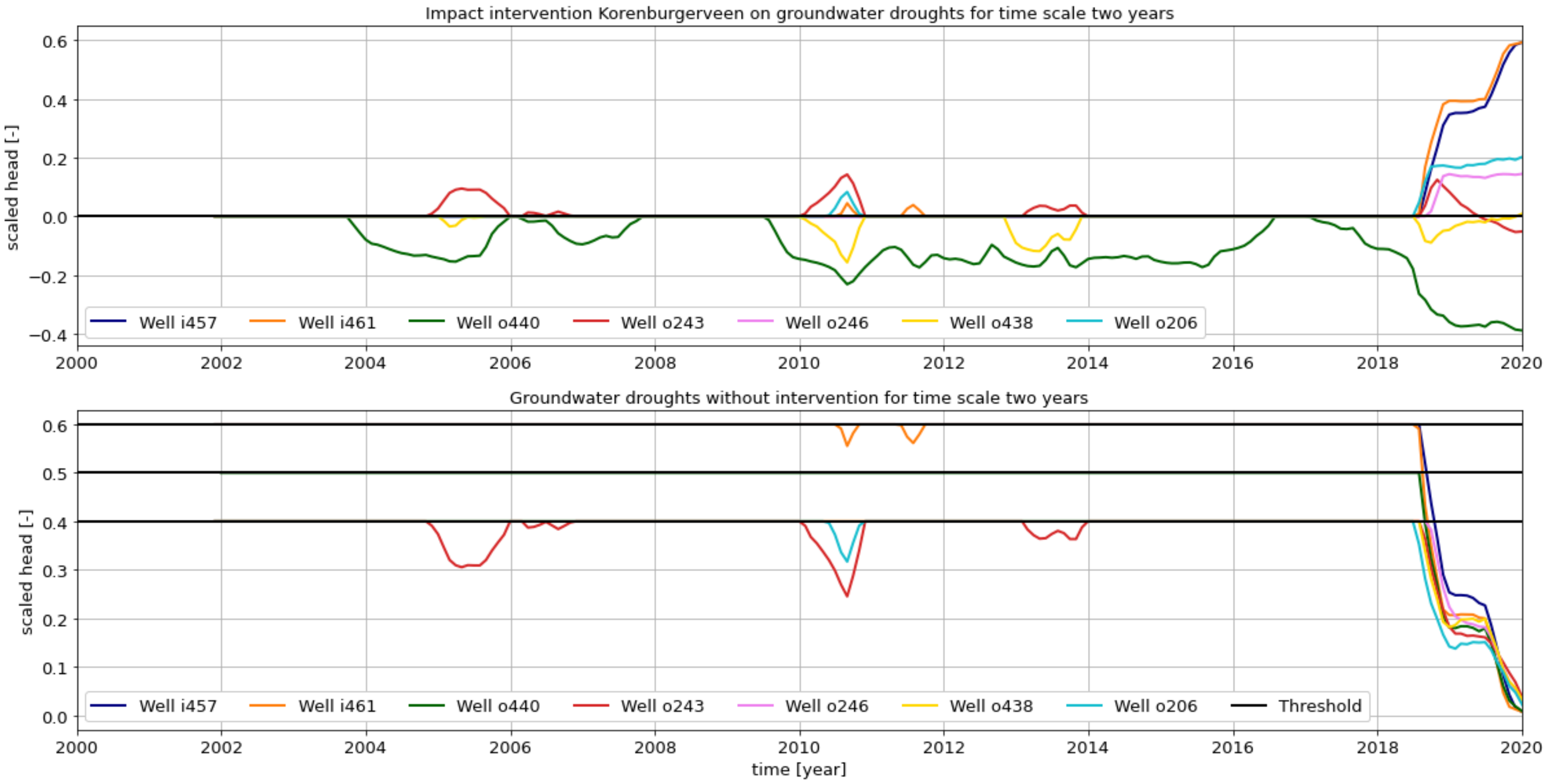

Figure 26: Impact intervention Korenburgerveen on groundwater droughts for time scale two years

The results show a strong decrease in the number, duration and intensity of short and long-term groundwater droughts with intervention for wells i457 and i461 in the years 2018 and 2019. This result is also obtained for wells o246 and o206 but with a smaller magnitude. Additionally, despite the sensitivity in the minimum groundwater levels in 2018 and 2019 shown in Section 5.2.1 in the simulations for well o206, the visual control did show a constant impact on groundwater drought for varying calibration lengths. Next, the results for well o243 show a decrease in groundwater drought, except for the dry years 2018 and 2019 where almost no impact is indicated for the short term and a lagged groundwater drought is observed with intervention for the long term. Furthermore, an increase in duration and intensity of short- and long-term groundwater drought is obtained for well o440. At last, the results for the well o438 show no impact of the intervention on short-term groundwater droughts and an increase in the number, duration and intensity of long-term groundwater droughts.

6 De Doorbraak

6.1 Autonomous groundwater behaviour

In this Section, the results of research question 1 are presented for De Doorbraak. The distinct errors obtained by the data pre-processing steps are shown in Figure 75 in Appendix C – De Doorbraak.

6.1.1 Observed groundwater series

The pre-processed observed groundwater series are shown in Figure 27.

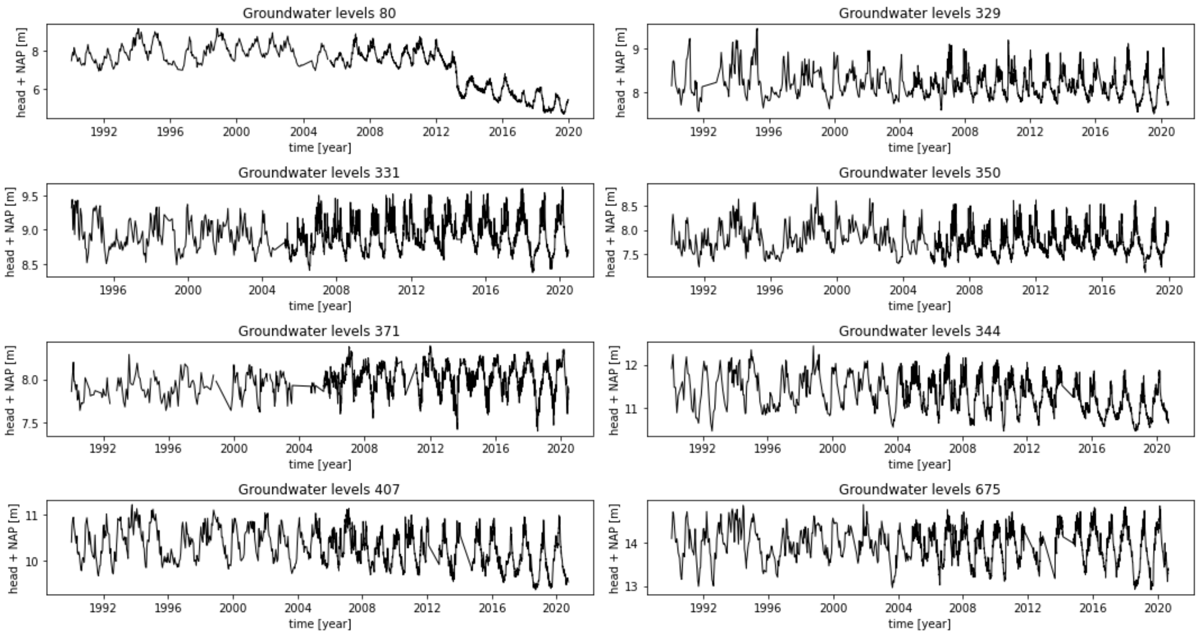

Figure 27: Pre-processed observed groundwater series De Doorbraak

Low groundwater levels in the years 2018 and 2019 are visible in all groundwater series except for monitoring well 336. Also, low groundwater levels are observed in 1996 in all groundwater series. Furthermore, in the series of well 80, a downward trend is obtained after 2012. No further visual remarkable observations are obtained from the series.

6.1.2 Correlation input series

No correlations are analysed since no surface water series and no abstraction data are available. No confounding variable is found.

6.1.3 SGWL simulation

Next, the SGWL are simulated per well. In Table 8, the EVP and RMSE values of the calibration of the final models including the performance are provided. Other monitoring wells simulated inaccurate results and are not further considered. The performances of all the calibrations and validations are presented in Table 13 in Appendix C – De Doorbraak. In Table 9 the final set of parameters is shown.

Table 8: Performance SGWL models De Doorbraak

	371	**407**	**344**	**329**	**350**	**331**	**80**	**675**
RMSE	0.09	0.14	0.18	0.17	0.15	0.10	0.17	0.18
EVP	0.55	0.85	0.80	0.76	0.78	0.76	0.89	0.78
Performance	Decent2	Good	Decent2	Good	Decent2	Good	Good	Good

Table 9: Parameters of models for various monitoring wells De Doorbraak

Parameter	371	407	344	329	350	331	80	675
Precipitation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
*PE**	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
*GA**	No	No	No	No	No	No	No	No
Surface water	No	No	No	No	No	No	No	No
Recharge model	Linear	FlexModel	Linear	Linear	Linear	Linear	Linear	Linear
IRF recharge model	Gamma	FourP.	Gamma	FourP.	Exp.	Exp.	Gamma	FourP.
Trend	No	No	No	No	No	No	No	No
Warmup period	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Noise model	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Improve parameters	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Solver method	LS*	LS	LS	LS	LS	LS	LS	LS
*Frequency input GW**	Original	Original	Original	Original	Original	Original	Original	Original
Frequency simulation	14D	D	14D	8D	D	D	D	7D
Set parameters	No	No	No	No	No	No	No	No
Threshold method	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

* PE = Potential evapotranspiration, GA = Groundwater abstraction, Exp = Exponential , LS = Leastsquares and GW = Groundwater

6.1.4 SGWL series

In all SGWL series, relatively low minimum groundwater levels are obtained in 2018 and 2019. Also, in most of the SGWL series, the groundwater levels are relatively low for the whole year 2003. Furthermore, in 1996, relatively low groundwater levels in the wet period are obtained in all autonomous series. At last, no trends are obtained in the mean groundwater levels.

6.2 Impact intervention on groundwater levels

In this Section, the results of research question 2 are elaborated on for De Doorbraak. The Section focuses on the differences between the SGWL and SGWL-i and especially the differences during the dry years 2018 and 2020.

In Figure 28 the differences between the drought periods in 2018 and 2019 are shown. All monitoring wells are analysed since no model had inaccurate results or a decent(1) performance. By analysing the confidence intervals, the model for monitoring well 80 showed a significant decrease in minimum groundwater levels in 2018 and 2019 with intervention. Additionally, the differences are spatially visualized in Figure 29.

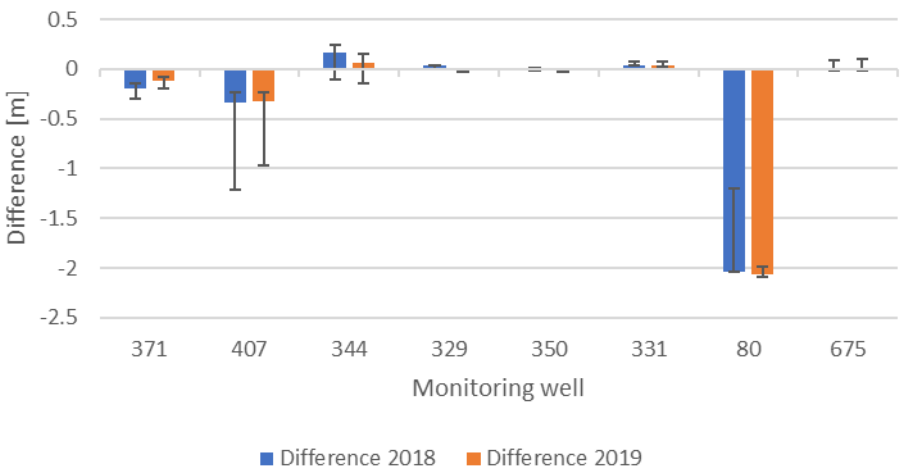

Figure 28: Impact De Doorbraak on minimum groundwater levels in 2018 and 2019

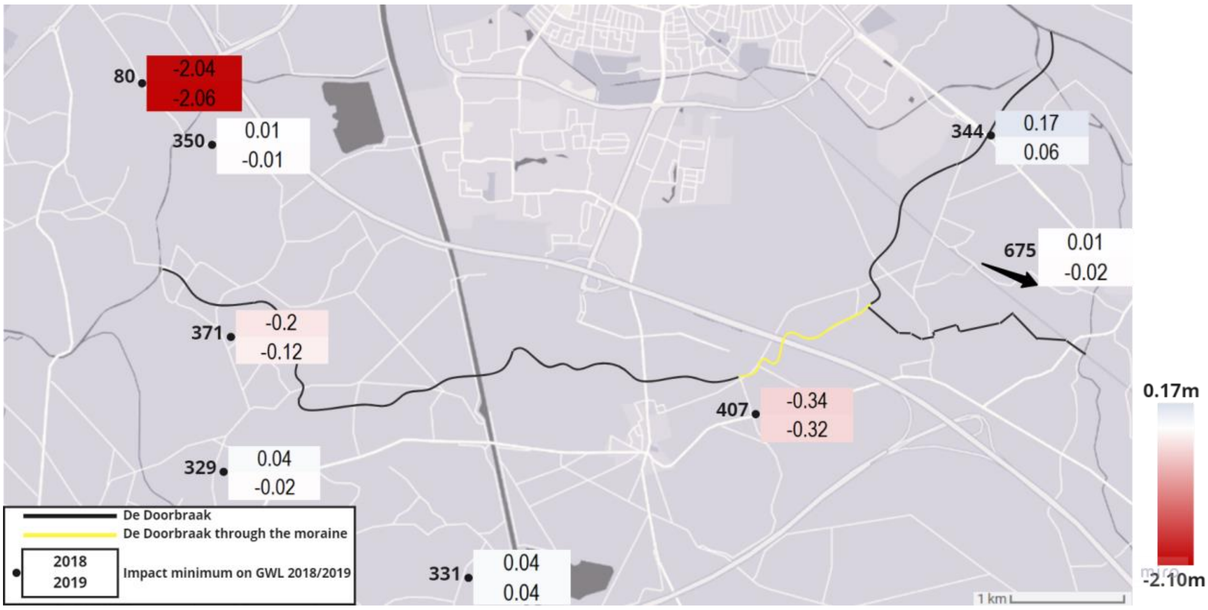

Figure 29: Spatial impact of De Doorbraak on minimum groundwater levels in 2018 and 2019

6.2.1 Sensitivity analysis

The results of the sensitivity analysis are shown in Figure 28 as error bars. For the simulation of the groundwater series with intervention for well 80 the calibration length was only decreased twice, due to data shortage. The results show various sensitivities for the calibration length. First, the simulations for wells 329, 350 and 331 almost show no sensitivity to various calibration lengths. Next, the simulations for wells 371 and 675 show some variation for varying calibration lengths (0-16m), but no clear increase or decrease. Furthermore, the simulation for wells 407, 344 and 80 shows more variation.

6.2.2 Results

First, the results for well 80 showed a significant decrease with intervention and the sensitivity analysis did not change this result. Next, for the results for wells 329, 350, 331 and 675, the differences in minimum groundwater levels in 2018 and 2019 are very little and the sensitivity analysis did also not change the outcome. Furthermore, the results for wells 371 and 407 show a slight decrease with intervention, which is not changed by the sensitivity analysis for well 371. Additionally, the results for well 344 initially showed an increase in minimum groundwater levels in 2018 and 2019. However, the sensitivity analysis indicated some uncertainty in this variation. Next, the sensitivity analysis for the simulation for well 407 showed a large variation in the results. This indicates that the difference in minimum groundwater levels in 2018 and 2019 with intervention could be significant. Besides, the timing of the minimum groundwater levels in 2018 and 2019 only varied very little with and without intervention in the results for most wells. In the results for well 80, the timing of the minimum groundwater level did slightly delay with intervention. At last, the rate of decrease and increase of groundwater levels changed in the results for most wells. For the results for wells 371 and 675, the rate of decrease and increase of groundwater levels did increase with intervention. This rate decreased in the results for wells 344 and 350. The same goes for the results for wells 329 and 331, but the sensitivity analysis indicated no variations. For the results for well 407, it is remarkable that the groundwater levels remained low for a shorter time with intervention.

6.3 Impact intervention on contributions

In this Section, the results of research question 3 are presented for the De Doorbraak. Wells 371, 344 and 350 are excluded because of the decent(2) performances. Additionally, well 80 is excluded because the calibration of the series with intervention (in equilibrium) starts after 2014. This would result in a period of contribution calculation that is too short. The contributions without and with intervention are shown in Figure 30 and Figure 31, respectively. The contributions values indicate how much certain stresses contributes to the total groundwater fluctuations. The impact of the intervention on these contributions is presented in Figure 32.

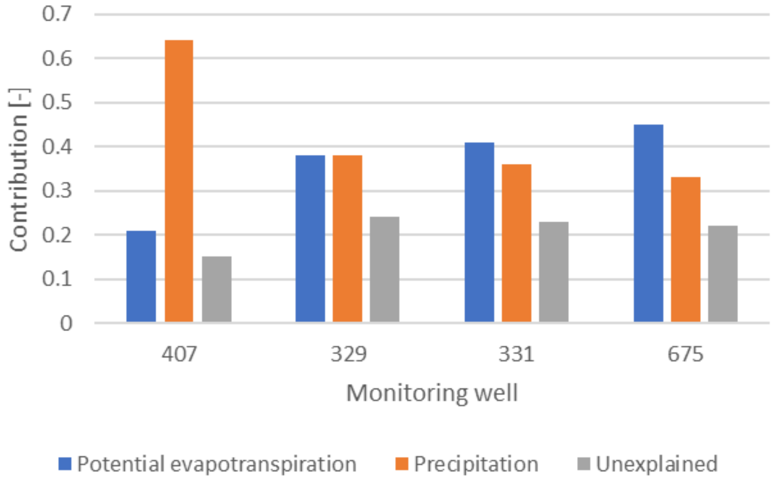

Figure 30: Contributions to groundwater fluctuations without De Doorbraak

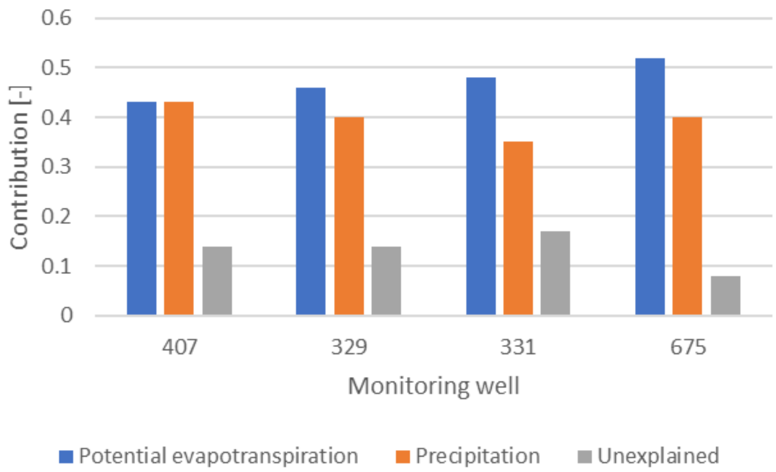

Figure 31: Contributions to groundwater fluctuations with De Doorbraak

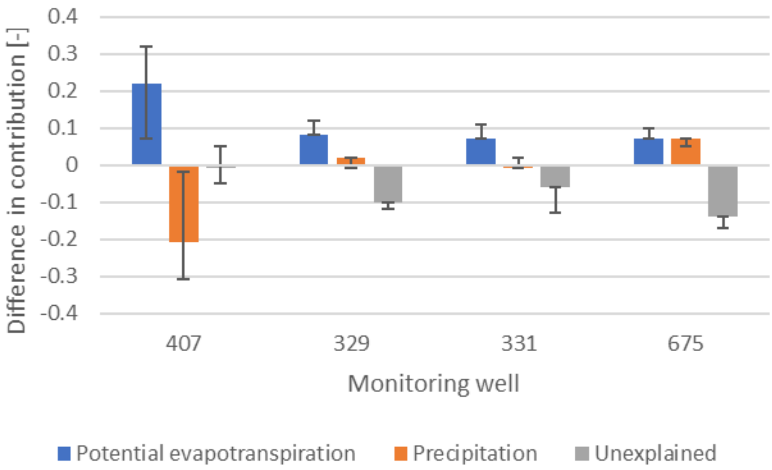

Figure 32: Impact De Doorbraak on contributions to groundwater fluctuations

6.3.1 Sensitivity analysis

The results of the sensitivity analysis are shown in Figure 32 as error bars. The simulations for wells 329, 331 and 675 show little changes in contributions induced by a varying calibration length (0-0.07). The simulations for well 407 show more variation (0-0.20).

6.3.2 Results

The results for wells 329, 331 and 675 all show a slight increase in the contribution of potential evapotranspiration and a decrease in unexplained. Additionally, the results for well 675 show a slight increase in the contribution of precipitation as well. The original run for well 407 shows significant variations with intervention. Even though the sensitivity analysis shows uncertainty in these differences, it is assumed that the original run is valid, and the intervention did enhance a significant increase in the contribution of potential evapotranspiration and a significant decrease in the contribution of precipitation.

6.4 Impact intervention on groundwater drought

In this Section, the result of research question 4 is elaborated on for De Doorbraak.

6.4.1 Results

The impact of the intervention on short and long-term groundwater droughts for all wells are visualised in Figure 33 and Figure 34, respectively. The impact of the intervention on short and long groundwater droughts in more detail is shown in Appendix C – De Doorbraak per monitoring well. The y-axis is limited in Figure 33 and Figure 34 to preserve a clear plot. The groundwater drought after 2013 for well 80 can be observed in Figure 91 in Appendix C – De Doorbraak.

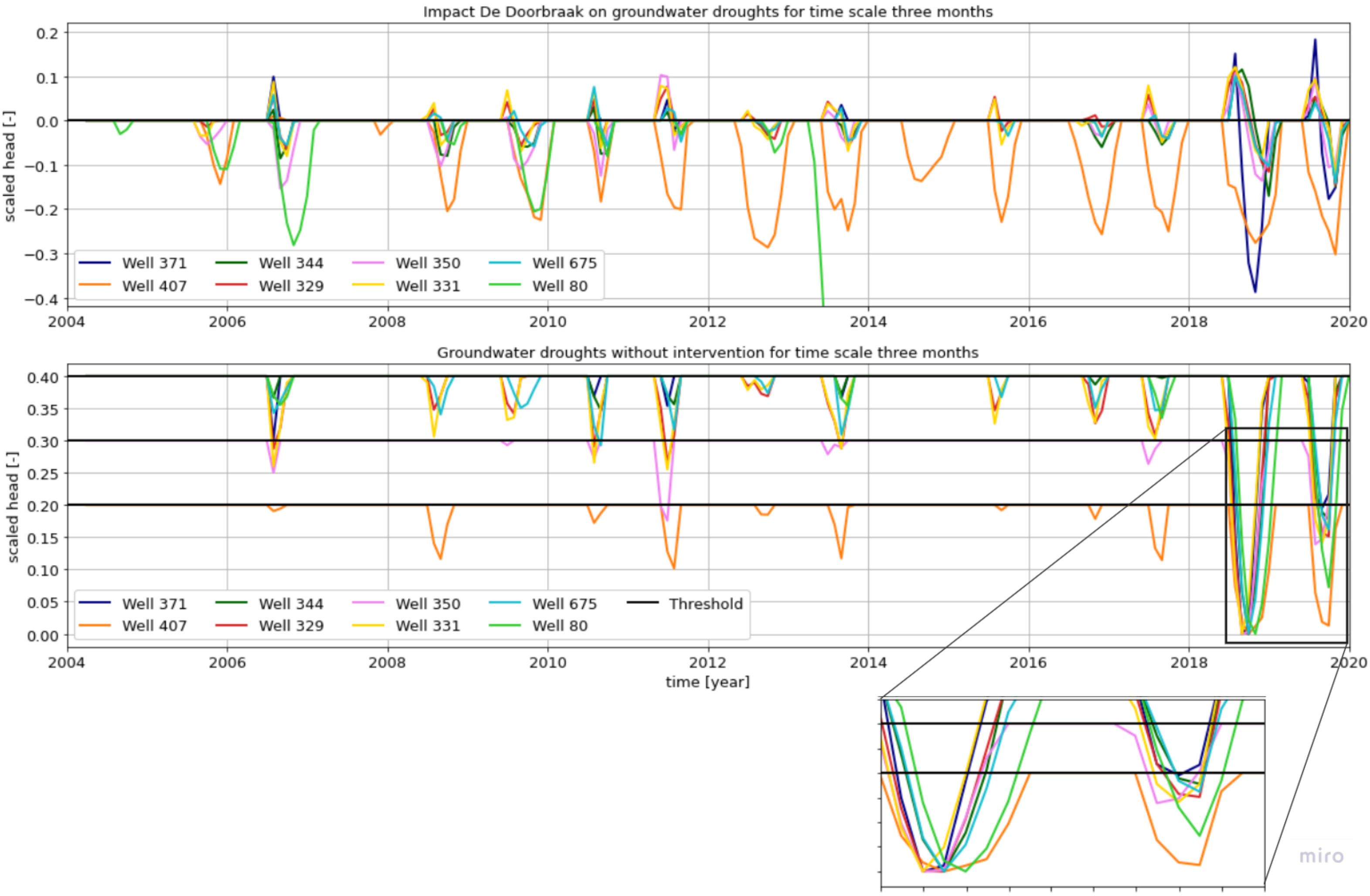

Figure 33: Impact De Doorbraak on groundwater droughts for time scale three months

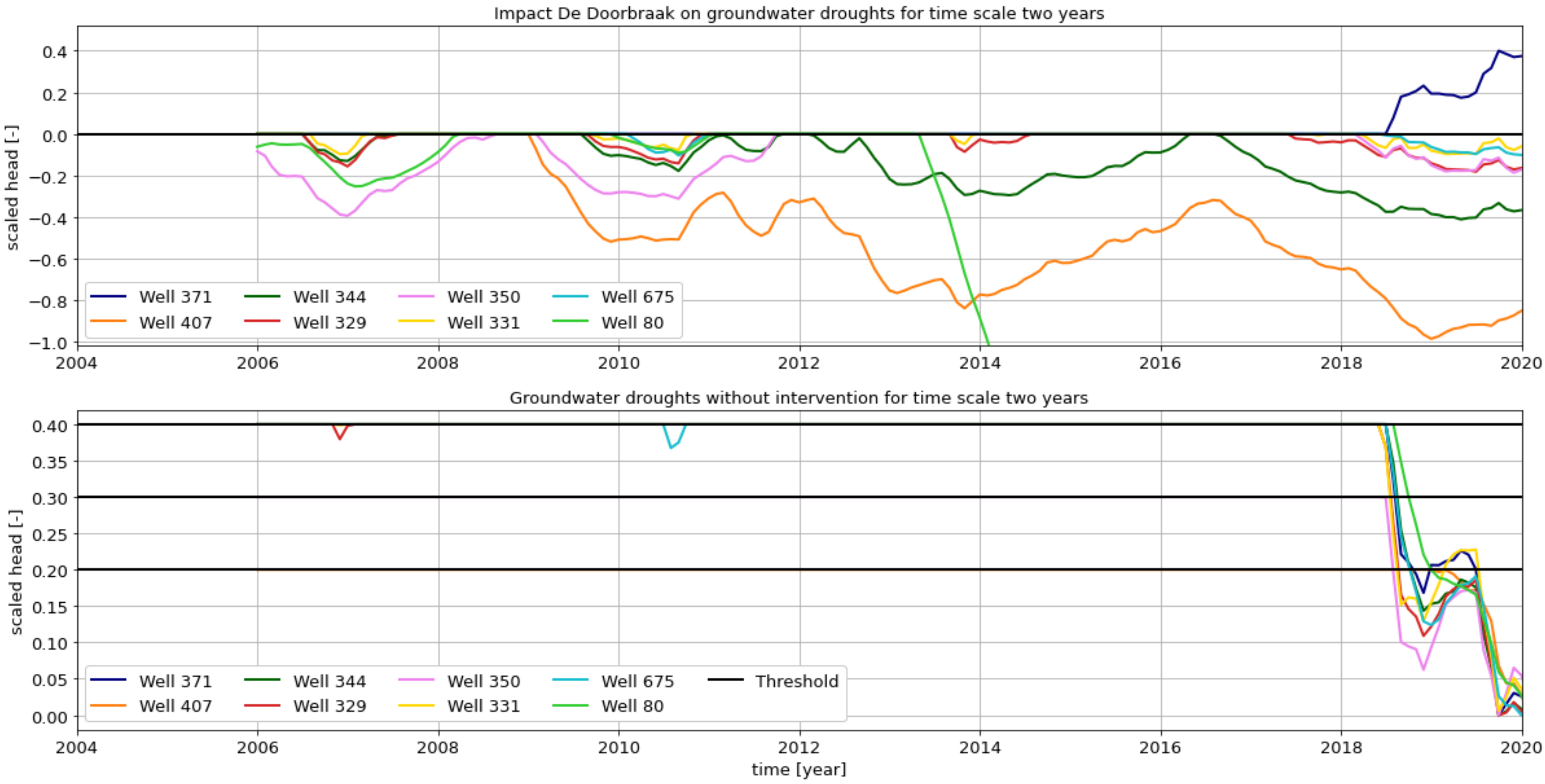

Figure 34: Impact De Doorbraak on groundwater drought for time scale two years

The results show various impacts on short-term groundwater drought. First, the results for wells 407 and 80 show a very strong increase in the number, duration and intensity of the short and long-term groundwater droughts with intervention, enhanced by the visual control. This increase was also obtained for well 344 but with less magnitude and for 2018 where it had a positive effect on the intensity of the short term and for 2019 where no impact was found. Next, the results for well 350 show an increase in the number, duration and intensity of the short- and long-term groundwater droughts with intervention. The figure shows that the intervention only decreased long-term groundwater drought for well 371. The impact on the short-term groundwater drought varies over time for well 371, as an increase in groundwater drought is observed in 2018 and 2019 and a decrease was obtained for the other years. For the other wells, the visual control showed that there was almost no impact of the intervention on groundwater drought, as different runs resulted in approximately zero impact or extremely small increases in groundwater drought.

7 Scheller and Oldeneler buitenwaarden

7.1 Autonomous groundwater behaviour

In this Section, the results of research question 1 are presented for the intervention at the Scheller and Oldeneler buitenwaarden. The distinct errors obtained by the data pre-processing steps are shown in Figure 96 in Appendix E – Scheller and Oldeneler buitenwaarden.

7.1.1 Observed groundwater series

The pre-processed observed groundwater series are shown in Figure 35.

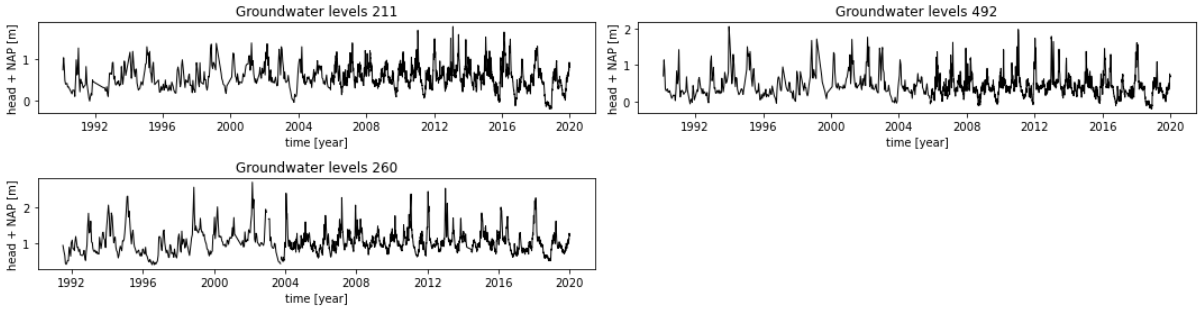

Figure 35: Pre-processed observed groundwater series at Scheller and Oldeneler buitenwaarden

Low groundwater levels are visible in 2018 and 2019, as well as the dry winters in 1996. Additionally, a dry period is indicated at the end of the year 2003. No further remarkable observations are observed.

7.1.2 Correlation input series

The correlation plot in Figure 92 in Appendix D – Scheller and Oldeneler buitenwaarden data pre-processing, indicated a strong correlation between surface and groundwater levels. Additionally, no confounding variable has been designated. Also, it is observed that the IJssel acts as a gaining and losing stream during the year.

7.1.3 SGWL simulation

Next, the SGWL are simulated per well. Groundwater abstraction did increase some simulations for monitoring well 211 but significantly increased parameter uncertainty. It is therefore not included as input series. Additionally, surface water data without intervention was not available and could also not be simulated based on other input series like discharge. Therefore, the surface water series with intervention is used for the model of SGWL. In Table 10, the RMSE and EVP values of the calibration of the final models including the performances are provided. The performances of all the calibrations and validations are presented in Table 14 in Appendix E – Scheller and Oldeneler buitenwaarden. In Table 11 the final set of parameters is shown.

Table 10: Performance SGWL models Scheller and Oldeneler buitenwaarden

	211	**492**	**260**
RMSE	0.10	0.09	0.12
EVP	0.85	0.92	0.87
Performance	Good	Good	Good

Table 11: Parameters of models for various monitoring wells Scheller and Oldeneler buitenwaarden

Parameter	211	492	260
Precipitation	Yes	Yes	Yes
*PE**	Yes	Yes	Yes
*GA**	No	No	No
Surface water	Yes	Yes	Yes
Recharge model	Linear	Linear	Peterson
IRF recharge model	Exp.	Exp.	Gamma
Trend	No	No	No
Warmup period	Yes	Yes	Yes
Noise model	Yes	Yes	Yes
Improve parameters	Yes	Yes	Yes
Solver method	LS*	LS	LS
*Frequency input GW**	Original	Original	Original
Frequency simulation	D	D	7D
Set parameters	No	No	No
Threshold method	Yes	Yes	No

* PE = Potential evapotranspiration, GA = Groundwater abstraction, Exp = Exponential , LS = Leastsquares and GW = Groundwater

7.1.4 SGWL series

In all simulated SGWL series, the groundwater droughts in 2018 and 2019 are obtained. No further remarkable information is obtained from the SGWL.

7.2 Impact intervention on groundwater levels

In this Section, the results of research question 2 are elaborated on for the Scheller and Oldeneler buitenwaarden. The Section focuses on the differences between the SGWL and SGWL-i and especially the differences during the dry years 2018 and 2019.

In Figure 36 the differences between the drought periods in 2018 and 2019 are shown. These differences are spatially visualised in Figure 37. No statistically significant impact on the minimum groundwater levels in 2018 and 2019 is observed by analysing the confidence intervals.

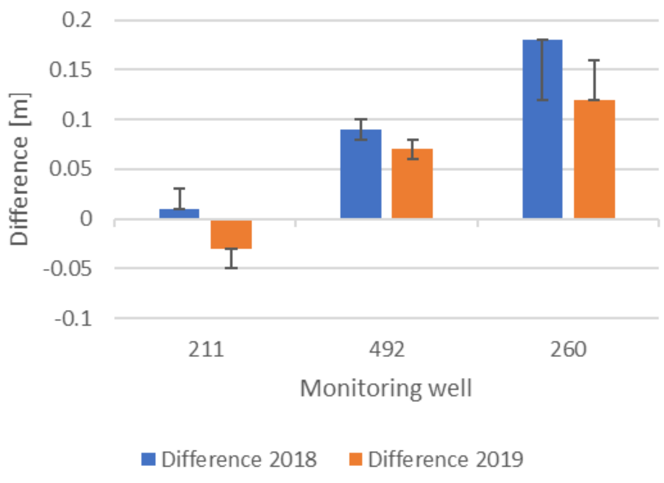

Figure 36: Impact intervention at Scheller and Oldeneler buitenwaarden on minimum groundwater levels in 2018 and 2019

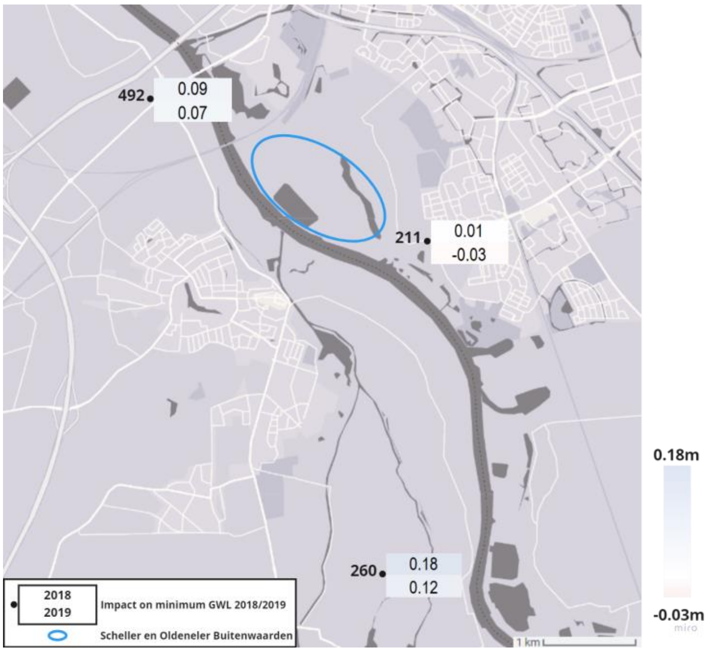

Figure 37: Spatial impact intervention at Scheller and Oldeneler buitenwaarden on minimum groundwater levels in 2018 and 2019

7.2.1 Sensitivity analysis

The results of the sensitivity analysis are shown in Figure 36 as error bars. It was remarkable that the parameter uncertainty became extremely high for the last run for well 492 and the last two runs for well 211, assumed to be caused by the short calibration length. Therefore, these runs are excluded from the analysis. No remarkable sensitivity is observed.

7.2.2 Results

The results for well 211 show minimal variation. However, the results for the other two wells did show an increase in minimum groundwater levels in 2018 and 2019 with intervention. Additionally, the intervention did not impact the timing of the minimum groundwater levels in 2018 and 2019 in the results for all wells. At last, the rate of groundwater variations did increase in the results for well 211. The sensitivity analysis did not change this result. This rate did decrease for wells 492 and 260.

7.3 Impact intervention on contributions

In this Section, the results of research question 3 are presented for the intervention at Scheller and Oldeneler buitenwaarden. The contributions without and with intervention are shown in Figure 38 and Figure 39, respectively. The contributions values indicate how much certain stresses contributes to the total groundwater fluctuations. The impact of the intervention on these contributions is presented in Figure 40.

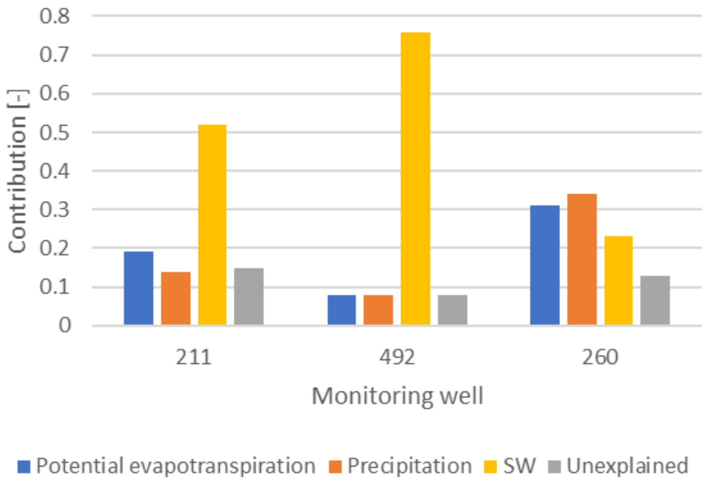

Figure 38: Contributions to groundwater fluctuations without intervention at Scheller and Oldeneler buitenwaarden

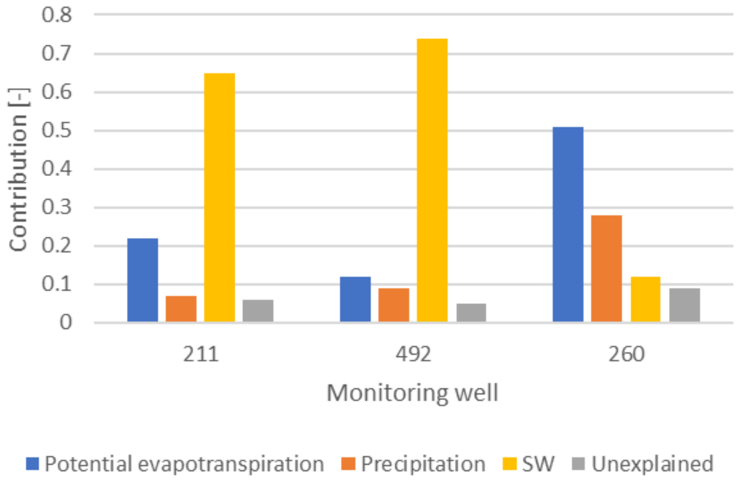

Figure 39: Contributions to groundwater fluctuations with intervention at Scheller and Oldeneler buitenwaarden

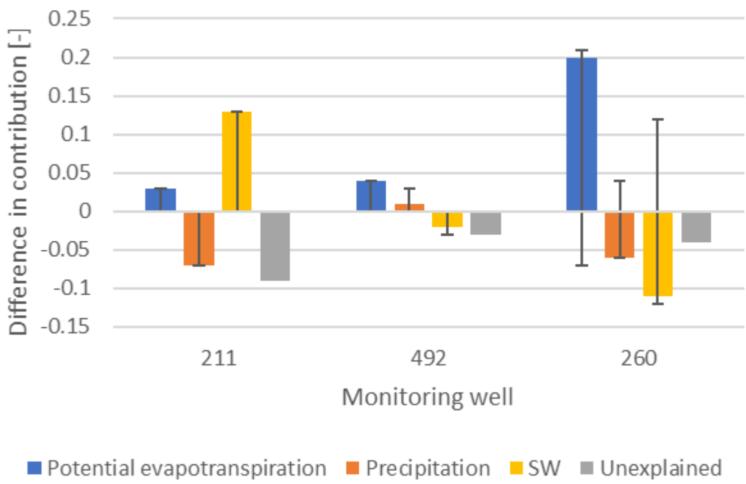

Figure 40: Impact intervention at Scheller and Oldeneler buitenwaarden on contributions groundwater fluctuations

7.3.1 Sensitivity analysis

The sensitivity analysis showed quite some variations for varying calibration lengths in the simulations for wells 211 and 260, indicating less impact than the original runs did show. Well 492 remained similar for the different runs.

7.3.2 Results

Considering the sensitivity analysis, it is difficult to indicate the impact of the intervention on the contributions for wells 211 and 260. For these locations, it is therefore assumed that the intervention did not have an impact. The result for well 492 clearly shows no impact.

7.4 Impact intervention on groundwater drought

In this Section, the results of research question 4 are elaborated on for Scheller and Oldeneler buitenwaarden.

7.4.1 Results

The impact of the intervention on short and long-term groundwater droughts for all wells are visualized in Figure 41 and Figure 42, respectively. The impact of the intervention on short and long-term groundwater droughts in more detail is shown in Appendix E – Scheller and Oldeneler buitenwaarden per monitoring well. Additionally, the visual control did show extremely high parameter uncertainty for the last run for well 492 and the last two runs for well 211, assumed to be caused by the short calibration length. Excluding these runs, the visual control did show confidence in the simulated impact of the intervention on groundwater drought.

The results show a decrease in duration and intensity in short- and long-term groundwater drought with intervention for all three wells, except for the short-term effect for well 211 and the long-term effect before 2018, where no impact is observed. Here, the simulation with intervention did show a lagged groundwater drought compared to the situation without intervention.

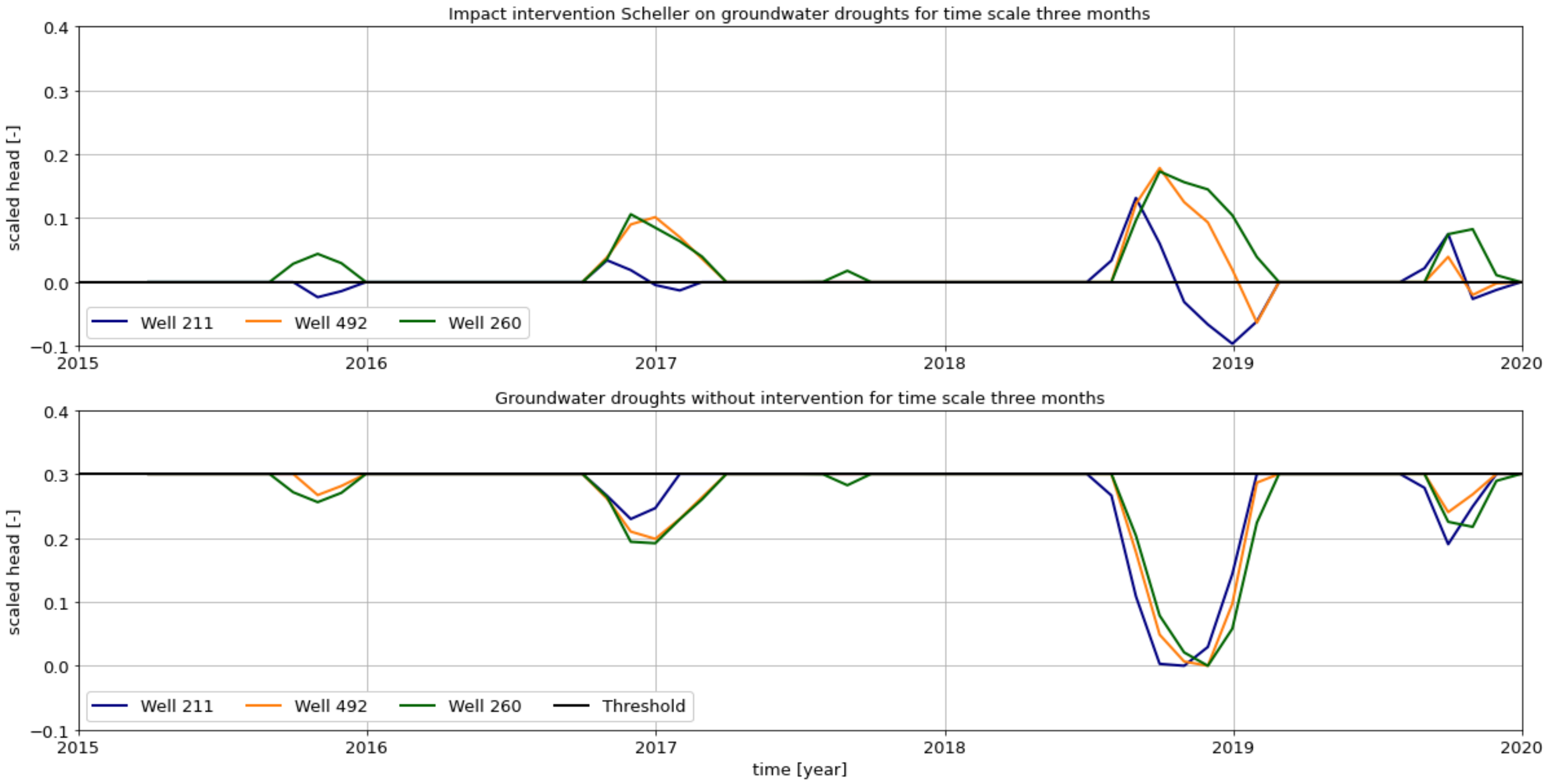

Figure 41: Impact Scheller and Oldeneler buitenwaarden on groundwater drought for time scale three months

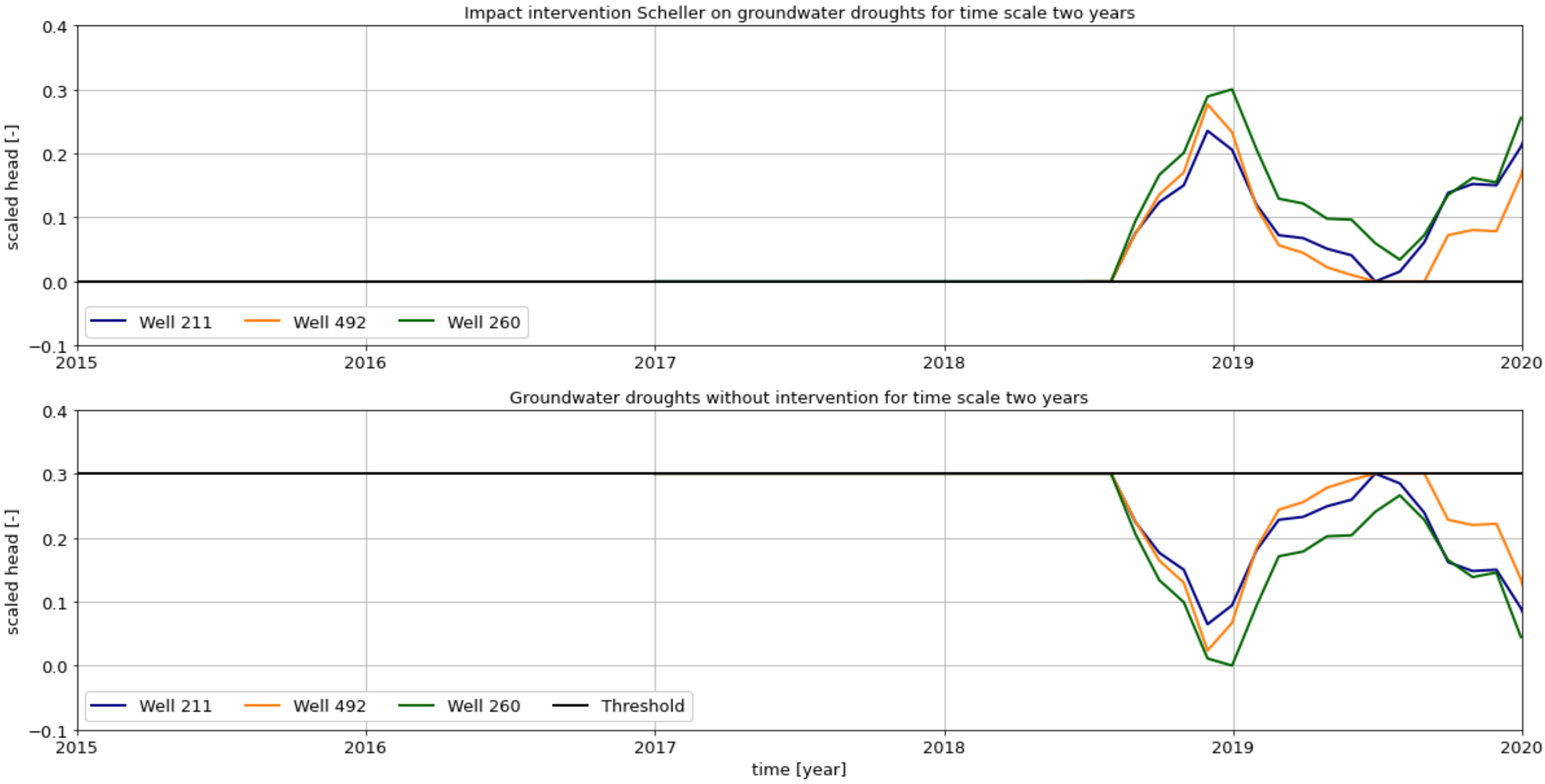

Figure 42: Impact Scheller and Oldeneler buitenwaarden on groundwater drought for time scale two years

8 Discussion

In this Section, the results are interpreted, explained and compared with existing literature. First, the results are discussed and interpreted per intervention. The goal is to determine the temporal and spatial impact of the intervention on groundwater drought. To do so, it is necessary to identify if deviations in the results are enhanced by the intervention or other influences. If it is concluded that a deviation is caused by another influence, it is excluded from the specific spatial impact figure per intervention (Figure 43, Figure 44 and Figure 45). These figures are presented to provide a clear spatial overview of the impact of the interventions on groundwater drought. A distinction is made between the years before and after 2018, as the results generally varied between these periods. Additionally, groundwater levels in the wet periods and contributions of input series to groundwater fluctuations are considered, as this can support the explanations for the impact of the intervention on groundwater drought. At last, the limitations and validity of the research, the model and its application are discussed.

8.1 Korenburgerveen

First, the Korenburgerveen is analysed for which the section is split between the wells inside and outside the area.

8.1.1 Inside the Korenburgerveen

In this analysis, the results of the wells inside the Korenburgerveen show an impact on groundwater droughts for wells i461 and well i457 after implementation of the intervention, especially in the dry years 2018 and 2019 where a significant increase in groundwater levels is observed. Only for the long-term groundwater drought before 2018, no impact is found inside the area. These results suggest a decrease in the duration and intensity of groundwater drought caused by the intervention for the wells inside Korenburgerveen. It is assumed that this impact is enhanced by the rising of the surface water levels of the Schaarsbeek and the installed ground dam at the Enclave Van Staalduinen, as an increase in water storage and a decrease in drainage and surface runoff creates a water buffer for drought periods (Snepvangers, 2003). Simultaneously, the increase in groundwater levels also reduced the duration of groundwater droughts. It takes more time for a groundwater drought to start and less time for recovery. Additionally, it was expected that the increase in groundwater levels resulted in the regeneration of low-moor peat, which in turn created more water storage capacity. The impact of these water conservation measures is in line with studies performed by Ketcheson and Price (2011), Jaenicke et al. (2011) and Stachowicz et al. (2022). Also, Simmelink et al. (2021) performed a time-series analysis to analyse the impact of the intervention on groundwater levels inside the area. These results support the findings of this research as an increase in groundwater levels was obtained for the same wells. Therefore, it can be stated that the observed decrease in groundwater droughts is caused by the intervention as shown in Figure 43.

8.1.2 Outside the Korenburgerveen

In the area outside the Korenburgerveen, five wells were analyzed, which showed varying impacts of groundwater droughts with intervention. Firstly, well o440 just outside the area at the west showed an increase in duration and intensity in short- and long-term groundwater drought, especially in the dry years 2018 and 2019. This result suggests that the intervention has negatively influenced the groundwater drought at this location. However, this result was unexpected as secondary waterways and the Korenburgerveensloot close to this well were filled up (bed level raised). Normally, this would result in less surface water outflow and therefore higher groundwater levels (Asl et al., 2020; Snepvangers, 2003). Additionally, the result contradicts the findings in the studies by Ketcheson and Price (2011), Jaenicke et al. (2011) and Stachowicz et al. (2022). So, as the intervention could not have resulted in this impact and no other influences are obtained, it is assumed that this deviation is a result of a data error. An unexplained step trend is observed in the original groundwater series after 2004. It is assumed that this step trend is caused by a measuring or data processing error. Therefore, this well is not included in Figure 43.

The results of well o243 showed a positive impact of the intervention on groundwater drought, except for the years 2018 and 2019. For those years, no deviation was found. The results suggest that the intervention caused a decrease in groundwater drought for this location. It is assumed that this impact was caused by the rising of the headwaters of the Schaarsbeek, like the explanations for wells i457 and i461. Initially, it was expected that the construction of a new stream (Parallelsloot) decreased groundwater levels and increased groundwater droughts, as the Parallelsloot could increase drainage (Simmelink et al., 2021). However, this newly constructed waterway is shallow, suppressing the drainage effect on groundwater levels in the surroundings. Therefore, it is concluded that the increased water levels of the headwater of the Schaarsbeek in dry periods decreased the groundwater flow towards the area, resulting in less intense groundwater droughts at the southeast of the Korenburgerveen, as shown in Figure 43.

The results for wells o246 and o206 showed a decrease in the number, duration and intensity of short- and long-term groundwater droughts. These results suggest less intense groundwater droughts caused by the intervention for these two locations. For well o246, a possible explanation is related to the water conservation measures. The increased water storage inside the area could have led to more water outflow out of the area in the dry periods, leading to increased surface water levels downstream. Besides, well o246 is located downstream of the Korenburgerveen, resulting in less drainage or more infiltration, depending on the type of stream (losing or gaining). This enhances the better conservation of water, which in turn positively impacts groundwater drought. However, no surface water data is available near this well, so this hypothesis could not be supported by this data. It is still stated that the intervention caused this impact and it is therefore included in Figure 43.

Next, well o206 is interpreted. It is concluded that land use could have enhanced the impact on groundwater drought, as land use has changed a few times over the years. Additionally, well o206 is located more than 4km away from the Korenburgerveen, which supports the explanation. However, no evidence is obtained about the impact of the intervention on groundwater drought for this location and it is therefore not included in Figure 43.

At last, the simulations for well o438 showed almost no impact on short-term groundwater droughts. The long-term droughts did increase slightly in number, duration and intensity. This indicates a small structural decrease in groundwater levels north of the area. However, no hydrological explanation is found that indicated that the intervention did enhance this increase in groundwater drought. Additionally, no land use changes are obtained in the surroundings of the well. Therefore, it is assumed that the deviations are caused by the exclusion of abstraction for irrigation or artificial drainage. Thus, it is not included in Figure 43.

All in all, the analysis at Korenburgerveen shows a decrease in groundwater drought caused by the intervention inside Korenburgerveen. Outside the area, the influence of the intervention was less significant, but still, a decrease in groundwater drought can be observed in the south of the area. The other investigated wells provided no evidence of an impact of the intervention on groundwater drought. For a more detailed impact of the intervention on groundwater drought, plots in Appendix B – Korenburgerveen can be consulted.

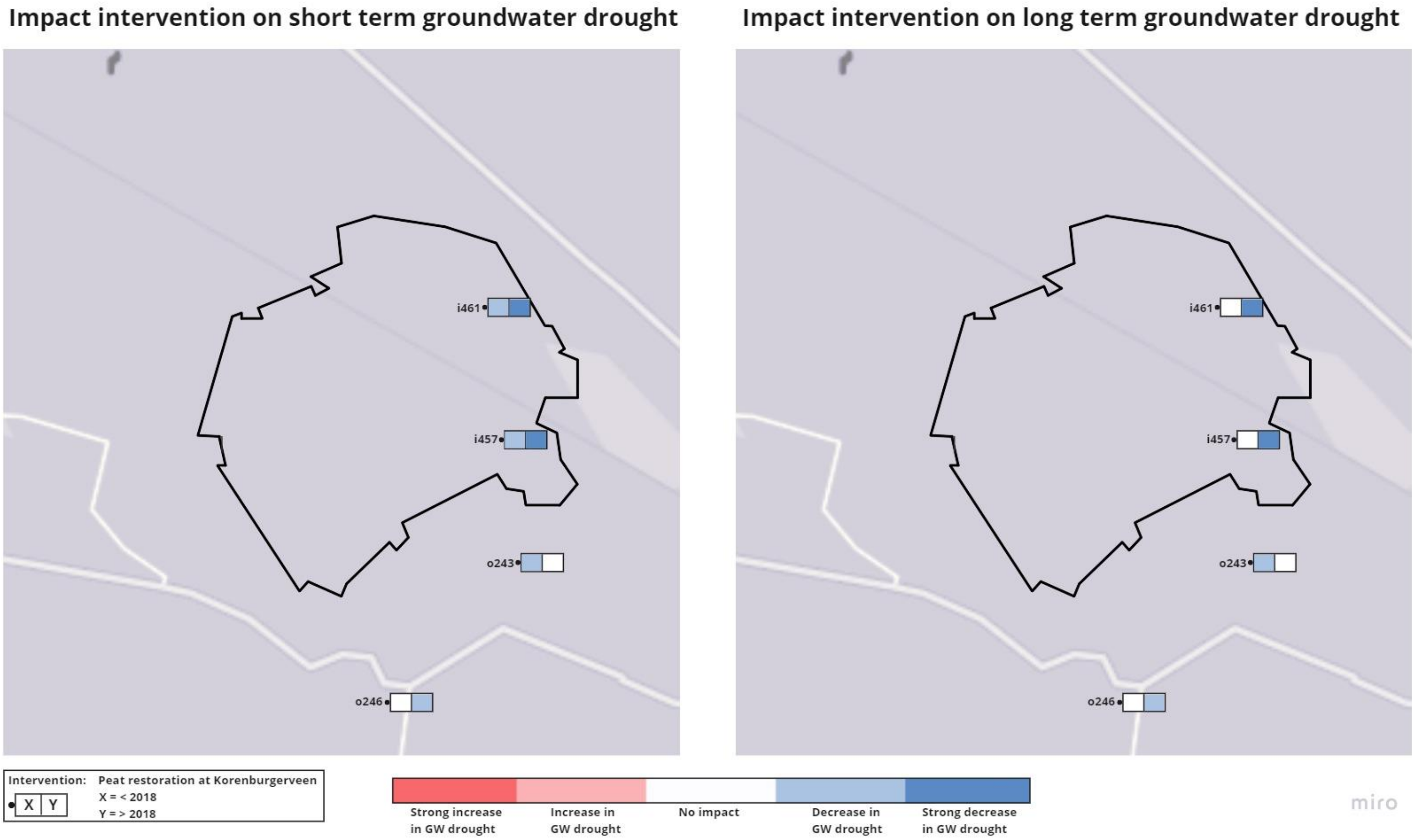

Figure 43: Spatial impact intervention at Korenburgerveen on short- and long-term groundwater drought

8.2 De Doorbraak

In general, the results suggest a varying effect of the construction of De Doorbraak on groundwater drought. This suggestion is elaborated on in this section, starting with well 80, located northwest of the new stream. The simulations for this well showed a significant increase in the number, duration and intensity of the short and long-term groundwater droughts with intervention. It is, however, concluded that the intervention did not cause this negative effect on groundwater drought because of the magnitude of the deviation. It is known that the groundwater abstraction station Wierden opened a new abstraction point in 2013, located quite close to this well. Because the deviations in the groundwater series started in 2013, it is assumed that the newly opened abstraction point enhanced the significant impact on groundwater drought. Van Loon et al. (2016) addressed the impact of abstraction on the groundwater table, supporting this explanation. Therefore, no evidence is obtained about the impact of the intervention on groundwater drought for this location and it is not included in Figure 44.

Similar to well 80, the results for well 407 showed quite an impact on short- and long-term groundwater droughts, compared with other results. This suggests a strong increase in the intensity and duration of groundwater droughts caused by De Doorbraak. It is concluded that this impact is caused by the construction of the new waterway through a moraine. The groundwater levels in this elevated infiltration area are expected to be higher than the designed surface water levels of De Doorbraak, due to the bulging groundwater table (De Meij et al., 2015). Therefore, hydraulic head differences create a draining effect on the groundwater and so a structural decrease in groundwater levels. The drainage effect is supported by the increase in the contribution of potential evapotranspiration to groundwater fluctuations as the intervention enhanced the exchange from groundwater towards surface water. This increased the evaporation term as the evaporation of surface water is higher than the evaporation of groundwater. Also, Snepvangers (2003) analysed the effects of De Doorbraak on the groundwater table before construction using a numerical groundwater model. His findings support this draining effect in the moraine caused by the intervention. The impact of the intervention is indicated in Figure 44.

The results of the model of well 371 showed an increase in the duration and intensity of short-term groundwater drought caused by the intervention in the years 2018 and 2019. Instead, the long-term effect was the opposite in these years. By looking at the SGWL and SGWL-i off this well, it is found that the intervention did increase groundwater levels in the wet periods and did not have an impact on the minimum groundwater levels in the dry periods. However, in 2018 and 2019 the intervention caused a decrease in minimum groundwater levels. It is concluded that the construction of De Doorbraak led to higher surface water levels compared to the situation without intervention due to the construction of weirs. Therefore, the surface water levels were higher in the wet periods and less groundwater would flow into the waterway, resulting in higher groundwater levels. This increase in groundwater levels in the wet seasons was also obtained by Snepvangers (2003). Besides, it was expected that the retention of water in the wet periods would result in higher groundwater levels in the dry periods. However, Snepvangers (2003) pointed out that surface water levels in the dry periods are maintained at a lower level than the original situation, resulting in more water outflow in the extreme dry periods. The same is found in this analysis and the impact of the intervention is shown in Figure 44.

The results of the wells mentioned above, well 344 showed an increased intensity and duration of short and long-term groundwater droughts with intervention, except for 2018 where a decrease in the intensity of the short-term was found. The overall increase in groundwater drought is probably enhanced by the draining effect of De Doorbraak, as the surface water levels are assumed to be generally lower than the groundwater table (Asl et al., 2020). These assumptions are supported by Snepvangers (2003), but his results contradict the decrease in groundwater drought in 2019. A possible explanation for the increase in minimum groundwater level in 2019 in this research, could be the weirs in De Doorbraak, which prevents surface water levels to sink further in dry periods and therefore maintain higher groundwater levels. This assumes that surface water levels in the old situation sank deeper. However, this hypothesis cannot be supported as no surface water data is available before the intervention. The various impacts of the intervention on this location are shown in Figure 44.

The results for wells 329, 331 and 675 show that the intervention did not impact the short- and long-term groundwater droughts which are also indicated in Figure 44.

At last, the results of well 350 indicate an increase in the number, duration and intensity of short- and long-term groundwater droughts with intervention. However, this result could not be linked to the intervention, as no hydrological explanation is found. Additionally, findings by Snepvangers (2003) did contradict the research of this study, as he did obtain no impact at that location. Also, no other influences are observed that could be a possible explanation, except for the exclusion of abstraction of groundwater or artificial drainage. So, the deviations are assumed to be caused by those explanations. Therefore, no evidence is found that indicates an impact of the intervention on groundwater drought for this location and it is excluded from Figure 44.

In summary, it is found that the impact of the intervention on groundwater drought was varying per location and between short- and long-term groundwater drought at the east and west side of the new stream. For the location in the moraine, a strong increase in the duration and intensity of groundwater drought caused by the intervention was found. A limited spatial impact was observed. The other investigated wells provided no evidence of an impact of the intervention on groundwater drought. For a more detailed impact of the intervention on groundwater drought, plots in Appendix C – De Doorbraak can be consulted.

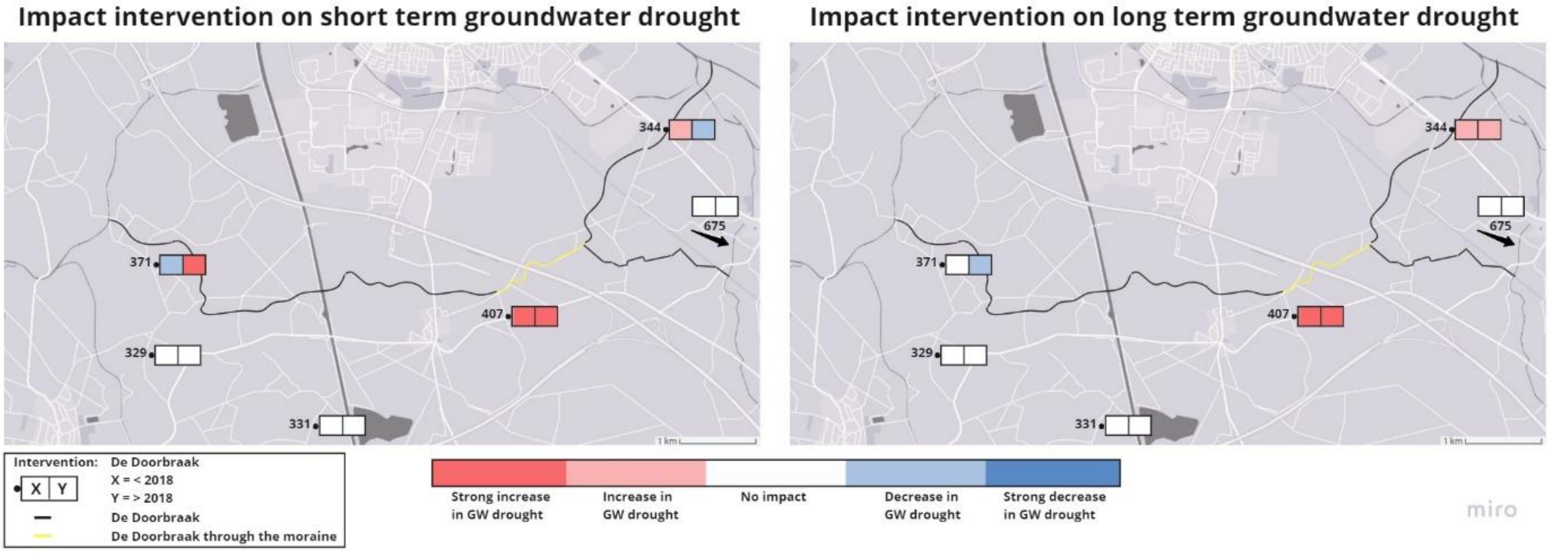

Figure 44: Spatial impact De Doorbraak on short- and long-term groundwater drought

8.3 Scheller and Oldeneler buitenwaarden

The results related to the intervention at Scheller and Oldeneler buitenwaarden all showed a decrease in the duration and intensity of short- and long-term groundwater drought with intervention. First, the results of well 492 are discussed. This well is located on the opposite side of the IJssel as the constructed side channel with floodplains. The results suggest that the intervention caused the deviations in short- and long-term groundwater droughts. However, before diving into the impact on groundwater drought, the results on maximum groundwater levels are discussed. A slight decrease in maximum groundwater levels is observed with intervention by looking at the SGWL and SGWL-i. It is concluded that this decrease in maximum groundwater levels is caused by the slight decrease in surface water levels for high discharges. On one hand, this indicates a strong correlation between surface water levels and groundwater levels, which is supported by the contributions of surface water level to groundwater fluctuations for well 492. Additionally, findings by Koeninger and Leibundgut (2001), Dochartaigh et al. (2019) and Haskoning Royal (2010) associated with this relationship between surface water and groundwater close to rivers are also in line with the results. On the other hand, the contributions for well 260 did not support this correlation between surface and groundwater. This well is in a polder where the water levels are regulated (M. Pezij, personal communication, 22 December 2022). Therefore, surface water has no significant contribution to groundwater fluctuations like in the model for well 492. Despite the lack of information on water regulations, the model performed well. As mentioned earlier, the results suggest that the intervention caused a decrease in short- and long-term groundwater droughts. A possible explanation could be that this effect is enhanced by increased filtration by the side channel and lowered flood plains. More water is stored in the aquifer, which reduced the groundwater drop in dry periods. This contribution of the side channel and lowered flood plains to groundwater recharge is also addressed by Jercich (1997) and Vázquez-Suñé et al. (2007). However, it was not expected that the increased infiltration would result in increased groundwater levels on the other side of the river and a few kilometres upstream. Furthermore, no studies are found indicating an impact on the opposite side of the river. So, even though it is concluded that the intervention caused the decrease in groundwater drought on the opposite side of the river, more research towards this subject is required to support this conclusion. These wells are included in Figure 45.

The results for well 211 suggest a decrease in duration and intensity of long-term groundwater drought caused by the intervention, but not for the short term where a lagged groundwater drought is observed. The maximum groundwater levels are discussed first. Here, these maximum groundwater levels did increase slightly during wet periods. It is concluded that the enlarged infiltration caused this increase, as more water recharges the groundwater and this well is located close to (500 m) and on the same side of the IJssel as the constructed side channel. For short-term groundwater drought in the dry years, it is assumed that the side channel and lowered flood plains enhanced drainage, as the surface water levels in the IJssel dropped more than the groundwater levels. Therefore, groundwater levels close to the channel, like well 211, dropped lower compared to locations further away. This explains the difference in the impact of the intervention in short-term groundwater drought between the well close to the intervention and the wells further away. The results for both sides of the river contradict the findings of TAUW (2013), who calculated the impact of multiple side channels and flood plains on groundwater levels. They concluded that the interventions did not have a significant impact on the groundwater levels in the wet and dry periods at the landside of the levee. Despite these findings, it is still concluded that the intervention at this location did cause a decrease in long-term groundwater drought for well 211. Therefore, it is included in Figure 45.

In summary, the intervention did decrease the groundwater drought on the same side of the river as the intervention in the long term, but not in the short-term due to the drainage effect of the side channel. The intervention decreased groundwater drought on the other side of the river, but more research is needed to support this conclusion. For a more detailed impact of the intervention on groundwater drought, plots in Appendix E – Scheller and Oldeneler buitenwaarden can be consulted.

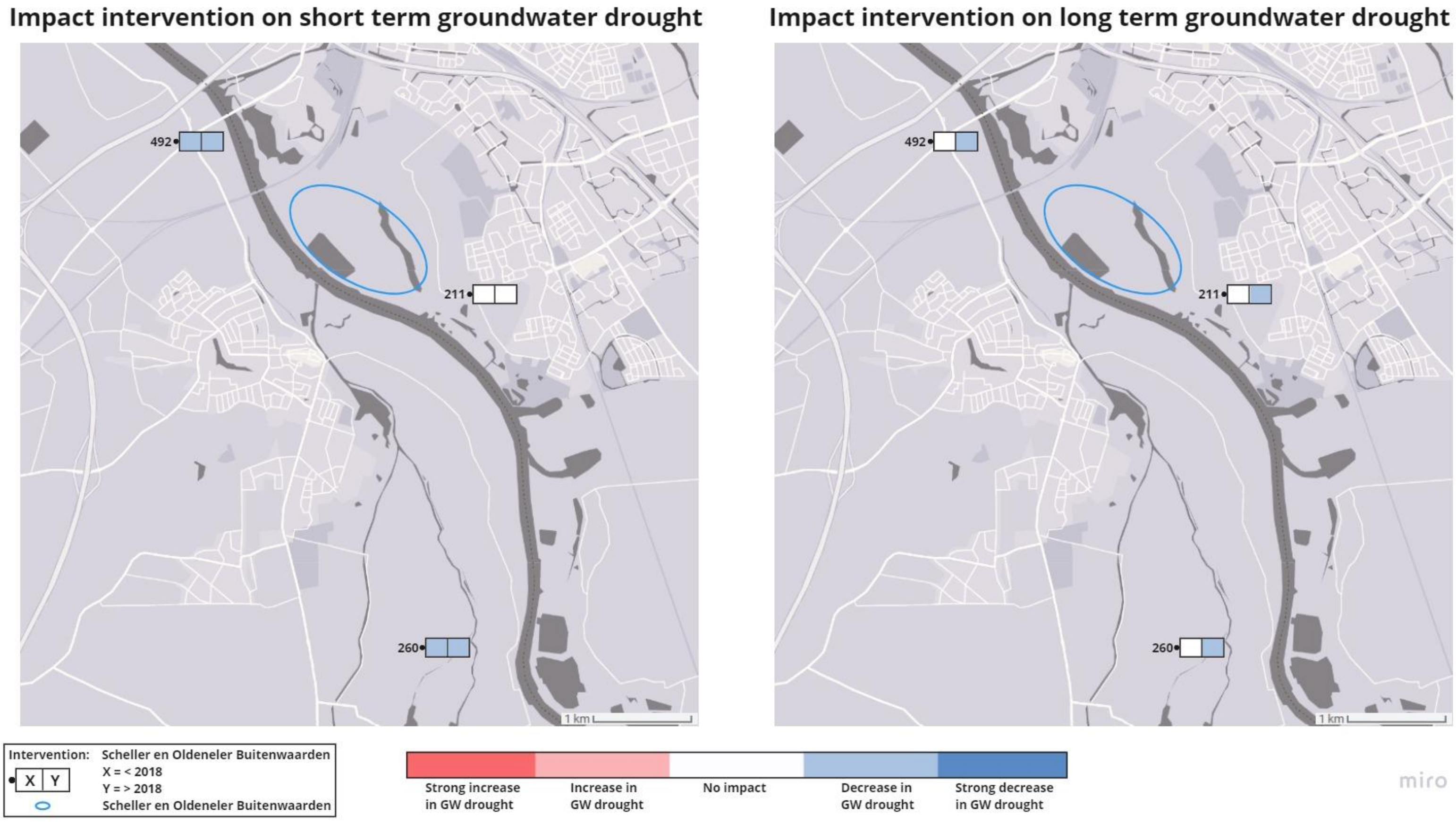

Figure 45: Spatial impact intervention at Scheller en Oldeneler Buitenwaarden on short- and long-term groundwater drought

8.4 Limitations and validity

In this analysis, model uncertainty is considered, which is an important measurement of the validity and accuracy of the model. However, not all model uncertainty is considered. For example, the validation of the dry years is based on the SGWL-i and should indicate whether the model can simulate extreme dry groundwater levels in the SGWL. Yet, the responses of the SGWL-i and SGWL could differ due to the intervention, possibly resulting in inaccurate simulation of the dry periods. However, these inaccuracies cannot be considered in the analysis, as validation is not possible. This introduces uncertainty in the dry period simulation (David et al., 2017).

Additionally, in this research, the potential evapotranspiration is used as an input series, which is the maximum evapotranspiration when the water supply in the soil is not a problem (Pezij et al., 2020). However, this deviates from the actual evapotranspiration and could result in an underestimation of the groundwater levels, as the model simulates evapotranspiration of water which might not be available.

Finally, it has been recognized that the TFN technique requires a significant amount of data to perform accurately. For example, the method requires groundwater series of a few years before the construction of the intervention to consider variability between seasons and years. Especially for older interventions, these long groundwater series are scarce, resulting in a limited application of the TFN model for such interventions (Brakkee et al., 2022). Additionally, abstraction for irrigation and drinking water and artificial drainage could have a significant impact on the groundwater table (Van Loon et al., 2016). Gemitzi and Stefanopoulos (2011) also addressed this influence on groundwater fluctuations. Including such data could increase simulation accuracy. However, the availability of sufficient-quality data for these human influences is usually limited as learned during this research.

9 Conclusion

The objective of this research was *to investigate the effect of nature-based human interventions on groundwater drought by analysing groundwater level time-series in the vicinity of the interventions*. First, the conclusions are drawn for the specific intervention and at the end, the main conclusion is given.

The bog remnant area, **Korenburgerveen**, had to cope with a decrease in groundwater levels and storage, caused by human activities like peat extraction. To counter this problem, various water conservation measures were constructed, referred to as the intervention, to restore the peat and increase water levels and storage. Inside the intervention, it can be concluded that the intervention did decrease the groundwater droughts in the short- and long-term. In fact, groundwater droughts did completely vanish due to the intervention, except for the extremely dry year 2018. This impact emphasizes damming and filling up of surface water streams as a successful water conservation measurement. Outside the area, the intervention did cause a smaller decrease in groundwater droughts. Still, this indicates that measures could influence groundwater levels a kilometer outside the area in all directions.

The anthropogenic stream, **De Doorbraak**, was constructed to increase flood safety by creating more surface water storage capacity. Overall, it can be concluded that the newly constructed stream did have various impacts on the groundwater drought close to the stream, depending on local characteristics and the design of the new waterway. Surface elevation, groundwater levels in the old situation and designed surface water levels before and after the construction were indicated as the most influential characteristics. Variations in the characteristics of this area resulted in no clear trend in the impact on groundwater drought. Additionally, further away (ca. >1km) from the stream, no impact was found of the intervention on groundwater drought.

The room for the river project, **Scheller and Oldeneler buitenwaarden**, was also executed to increase flood safety by increasing the water storage capacity. For the well located at the same side of the IJssel as the intervention, the constructed side channel and lowered flood plains did decrease groundwater drought in the long-term as the enlarged infiltration enhanced by the intervention created a water buffer for the dry periods. However, no impact of the intervention on the short-term groundwater drought was observed due to the drainage effect of the side channel. The intervention did decrease groundwater drought on the other side of the river. However, more research is required to support this conclusion.

The **main conclusion** is that nature-based human interventions can have varying impacts on groundwater droughts, depending on area characteristics and design choices. Even similar interventions could result in different impacts if the characteristics and design choices vary, as the impact of De Doorbraak varies over space. This indicates that detailed knowledge of these characteristics can significantly increase accuracy in the prediction of the effects of such interventions on groundwater droughts. Additionally, it can be concluded that De Doorbraak did only impact groundwater droughts close to the intervention and the effects reduced rapidly further away. This reduced impact over space is also observed for the Korenburgerveen, but no maximum range of the impact is obtained. For Scheller and Oldeneler buitenwaarden the impact of the intervention on groundwater drought increased with distance, as the draining effect of the intervention reduced further away. However, no maximum range of the impact could be determined.

10 Recommendations

In this study, the impact of three interventions on groundwater drought is investigated. Based on this research, several recommendations are made for practical use and further research.

10.1 Practical use

- **Importance of preliminary investigation**. This study highlights the importance of a preliminary investigation of area characteristics, as local spatial differences in characteristics could result in significantly varying impacts of interventions on the groundwater table. It is therefore recommended that decision-makers perform highly detailed preliminary investigations on hydrology, geology, and other area characteristics to create a great understanding of the area. This positively contributes to accuracy in forecasting the effects of interventions on groundwater drought.
- **Artificial influences**. The availability of sufficient-quality data on human influences like abstraction for irrigation and drinking water and artificial drainage is limited but could contribute to more accurate performances of the model. It is therefore recommended for drinking water companies, water authorities and provinces to monitor and archive these data with higher quality.

10.2 Further research

- **More detailed data error identification**. This research shows that removing data errors leads to significantly improved models. Similar findings were identified by Brakkee et al. (2021) and Van Loon et al. (2016). Additionally, the difficulty of deciding whether deviations are either due to errors or real external influences has been greatly acknowledged in this research. As noted by Van Loon et al. (2016), real deviations in the groundwater time-series should ideally not be excluded, to increase model certainty. Therefore, it is recommended to use a more detailed technique like Brakkee et al. (2022) for data error identification to possibly increase performances if this research method is used for other interventions.
- **Surface water input series**. For the model for the intervention Scheller and Oldeneler buitenwaarden, the surface water series without intervention could not be simulated or transformed into an accurate series. This results in uncertainty in this input series and could enhance model uncertainty if this method is used for other locations, as surface water contributes largely to fluctuations in groundwater levels. Therefore, it is recommended to research how surface water series without intervention could be simulated, transformed or maybe calculated, accurately.
- **Include the severity of the drought**. In the current definition of groundwater drought, the severity is not included. It is recommended to investigate how to consider this severity in further research, as this would enhance more valuable information for decision-makers and other related parties. This could lead to better management of droughts.
- **Use actual evapotranspiration**. In this research, the potential evapotranspiration is used as an input series. It is recommended to consider the actual evapotranspiration if this method is used for other locations.
- **Impact side channel and lowered flood plains on the other side of the river**. As mentioned in the discussion, no studies are found that investigate the impact of side channel and lowered flood plains on the other side of the river. Further research towards this subject is recommended as this research suggests an impact on the other side of the river.
- **More locations**. It has been shown that the method used in this study yielded useful results in understanding the effects of interventions on groundwater drought, while using a fast and

easy-to-construct model. Even though it is concluded that impacts depend on area characteristics, this study increased knowledge of the possible effects of three different types of interventions on groundwater drought. This indicates a reliable (and fast) alternative method for the analysis of the impact of interventions on groundwater droughts, compared to a numerical model. Therefore, it is recommended to execute the same research for more (or future) interventions, to map all the possible effects and create a better understanding in forecasting these effects. These could be interventions in other countries, as data acquisition for interventions in the Netherlands could be a problem.

- **Impact thresholds**. In this study, the decision of whether there is an impact, no impact or a strong impact is based on a comparison between all impact results and distributing them over a scale. This does not include strict thresholds based on literature. However, determining these thresholds based on other studies or methods could enhance better comparability and reproducibility.

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12 Appendix A – Korenburgerveen data pre-processing

In this Section, the results of data pre-processing for Korenburgerveen are provided.

12.1 Groundwater abstraction

The groundwater abstraction data is scaled up to daily time steps. To do so, the average distribution over a year is fitted based on the monthly data after 2015. These average monthly abstraction rates are shown in Figure 46.

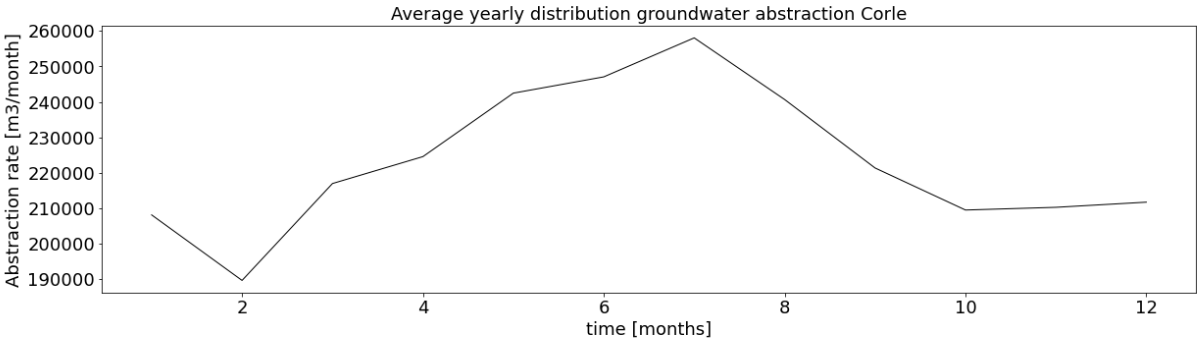

Figure 46: Average yearly distribution of groundwater abstraction Corle

This distribution is added to all the yearly values before 2015. To obtain the daily abstraction rates linear interpolation is executed between the monthly data points, resulting in abstraction series of Corle as shown in Figure 47.

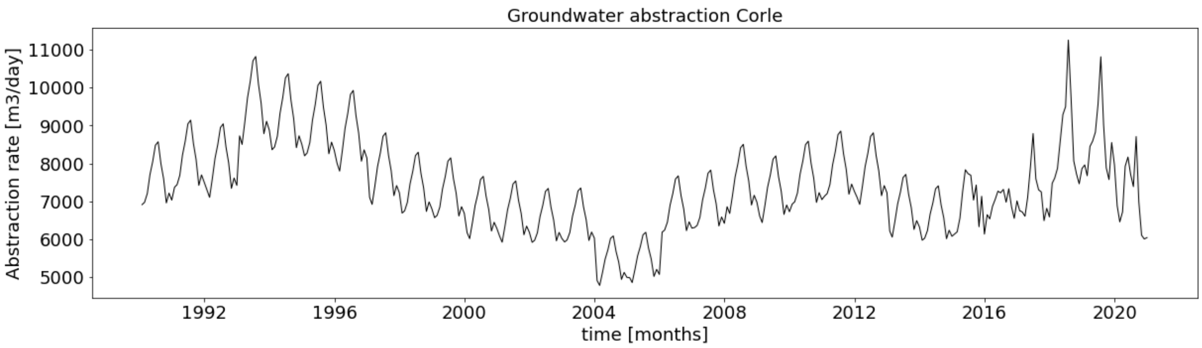

Figure 47: Resampled groundwater abstraction Corle

Even though the transformation leads to more realistic results, the same distribution for all the years till 2015 enhances uncertainty for the analysis of daily/monthly fluctuations in the groundwater level series. This uncertainty is qualitatively considered during further analysis.

12.2 Surface water

It is assumed that surface water could significantly contribute to forecasting groundwater fluctuations, as surface water receives water from the groundwater. Additionally, a visual correlation is observed between the groundwater series and the surface water series. A transformation based on various series is required to obtain usable surface water series. Figure 48 shows the surface water series that are considered for this transformation.

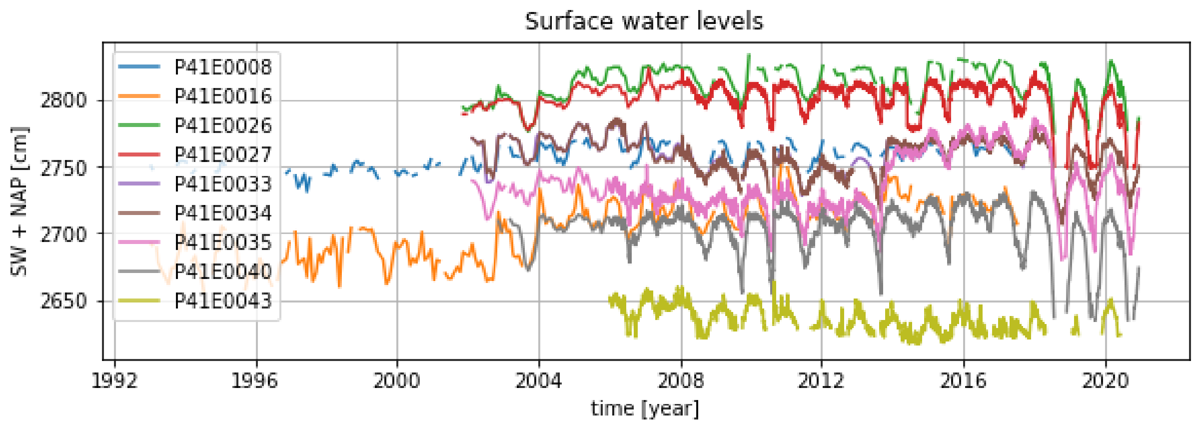

Figure 48: Observed surface water series at Korenburgerveen

P41E0016 is the only series consisting of useable data before and after the intervention. Two transformations are applied to the series. First, the series is extrapolated till 2021. The series of P41E0040 shows similar fluctuations as P41E0016 and is therefore used to extrapolate. Second, the series after the jump in 2003 is transformed to the average of the series before the jump, as shown in Figure 49. The transformed series is assumed to represent the surface water level if the intervention was not constructed. The Pastas model for the groundwater series inside the Korenburgerveen is run from the year 1993 till 2021 because of the length of the surface water series.

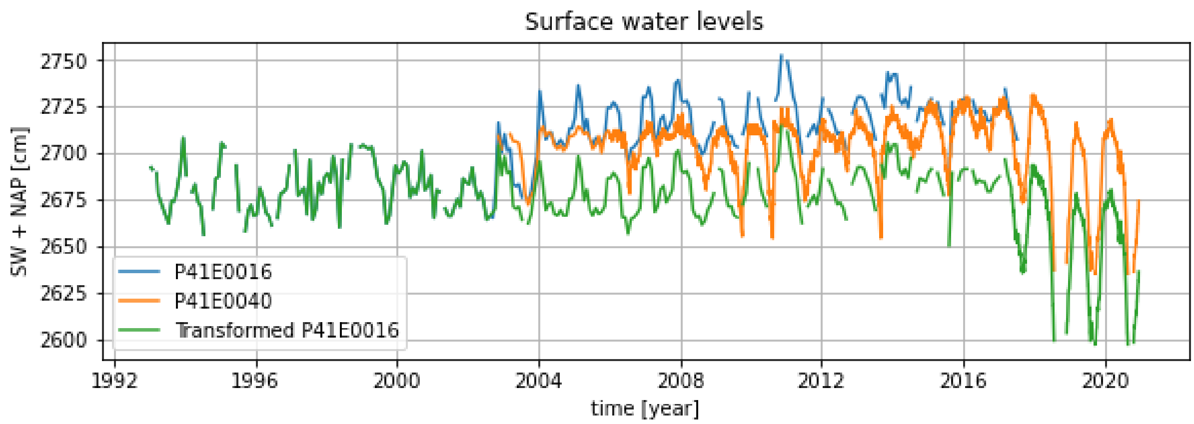

Figure 49: Transformed surface water series at Korenburgerveen

This transformation method is unable to quantify the uncertainty that is enhanced by the adjustment. The real values of the autonomous surface water behaviour vary within a certain range. Transformation of other series is assumed to enhance too much uncertainty, as these series do not contain enough data before and after the intervention. Extrapolation before the intervention would add another uncertainty factor and is therefore assumed to be unusable. Monitoring wells 456 and 457 are located close to this surface water measuring point and can use the transformed P41E0016 for further analysis.

12.3 Examples

The series outside the Korenburgerveen changed to daily frequency around 2004. In some series, a remarkable peak is observed at that time. By looking at the exact data it is obtained that we cannot conclude this peak is unrealistic as no data is available for weeks in advance and after this point.

However, while testing the model it was noticed that removing this peak enhances better performance. Therefore, the value is removed and filled with the average of the adjacent values.

In Figure 50 the groundwater levels between 2018 and 2020 of monitoring well 429 are shown. The sudden change in 2018-09 is assumed to be a data processing error (Retike et al., 2022), as this pattern is never to be found in the other series and no changes in the area are obtained. The error is removed using a moving average with an interval of 12 days.

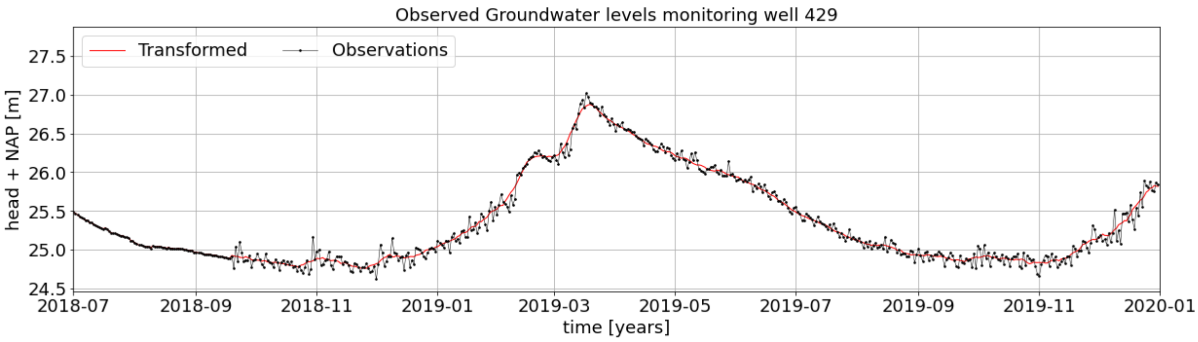

Figure 50: Transformed groundwater series monitoring well 429

Due to the low frequency (mostly two points per month or monthly) and missing values, it is difficult to identify errors in the groundwater series inside the Korenburgerveen. The groundwater series of monitoring well 440 shows an instant decrease around 2004 as shown in Figure 57 in Appendix B – Korenburgerveen. Via Natuurmonumenten it is obtained that the filter setting had been remeasurement on the 12th of November in 2004. The top and bottom of the filter decreased by 0.26m. It is assumed that the monitoring well remained untouched. This indicates that the data points before the 12th of November in 2004 have to be decreased by 0.26m.

Other corrected groundwater series are shown in Appendix B – Korenburgerveen and Appendix C – De Doorbraak.

12.4 Correlation input series

Analysing the correlation of the input parameters is preferred before the modelling. In Figure 51 the normalized series of the observed groundwater levels, transformed surface water and abstraction data are shown. It is obtained that the observed groundwater levels are correlated with the surface water levels. This seems reasonable as groundwater flows towards surface water (or the other way around). Additionally, the observed groundwater levels are inversely correlated with the abstraction data. This is also logical, as abstraction reduces groundwater levels.

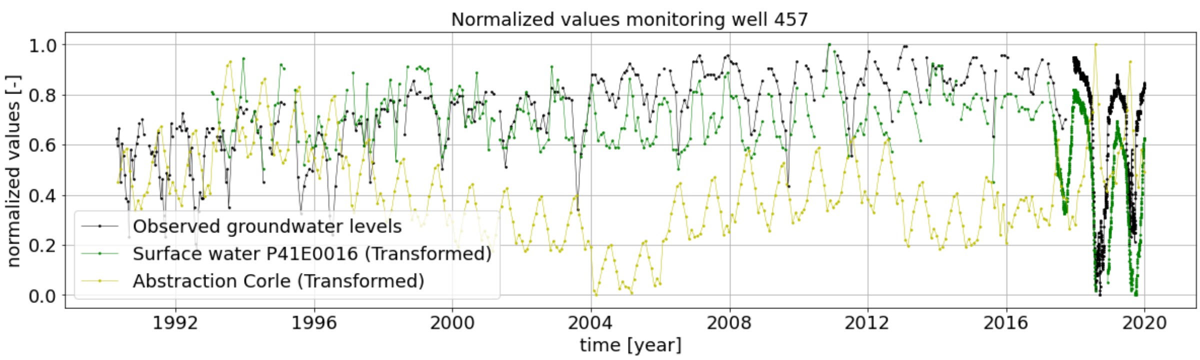

Figure 51: Correlation input series Korenburgerveen

To compute the correlation between recharge and surface water, the Pastas model is used to simulate the surface water levels (extrapolated series of P41E0016) with recharge as a stress model. The simulation shows an EVP value of 0.74 for the calibration. This indicates that surface water is a confounding variable and contributions cannot be analysed if it is added as a stress model.

13 Appendix B – Korenburgerveen

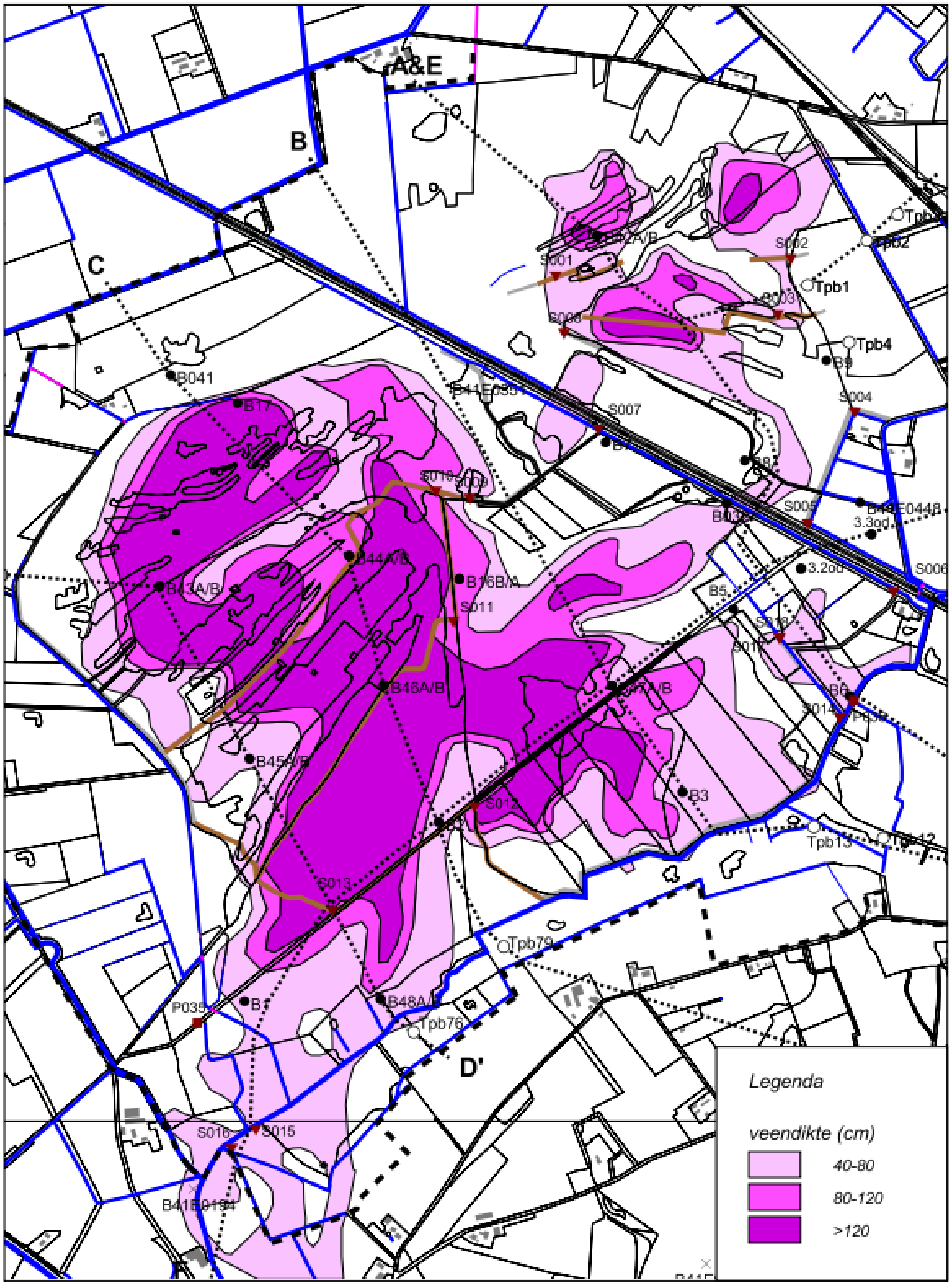

Figure 52: Peat areas (Hullenaar and Bell, 2013)

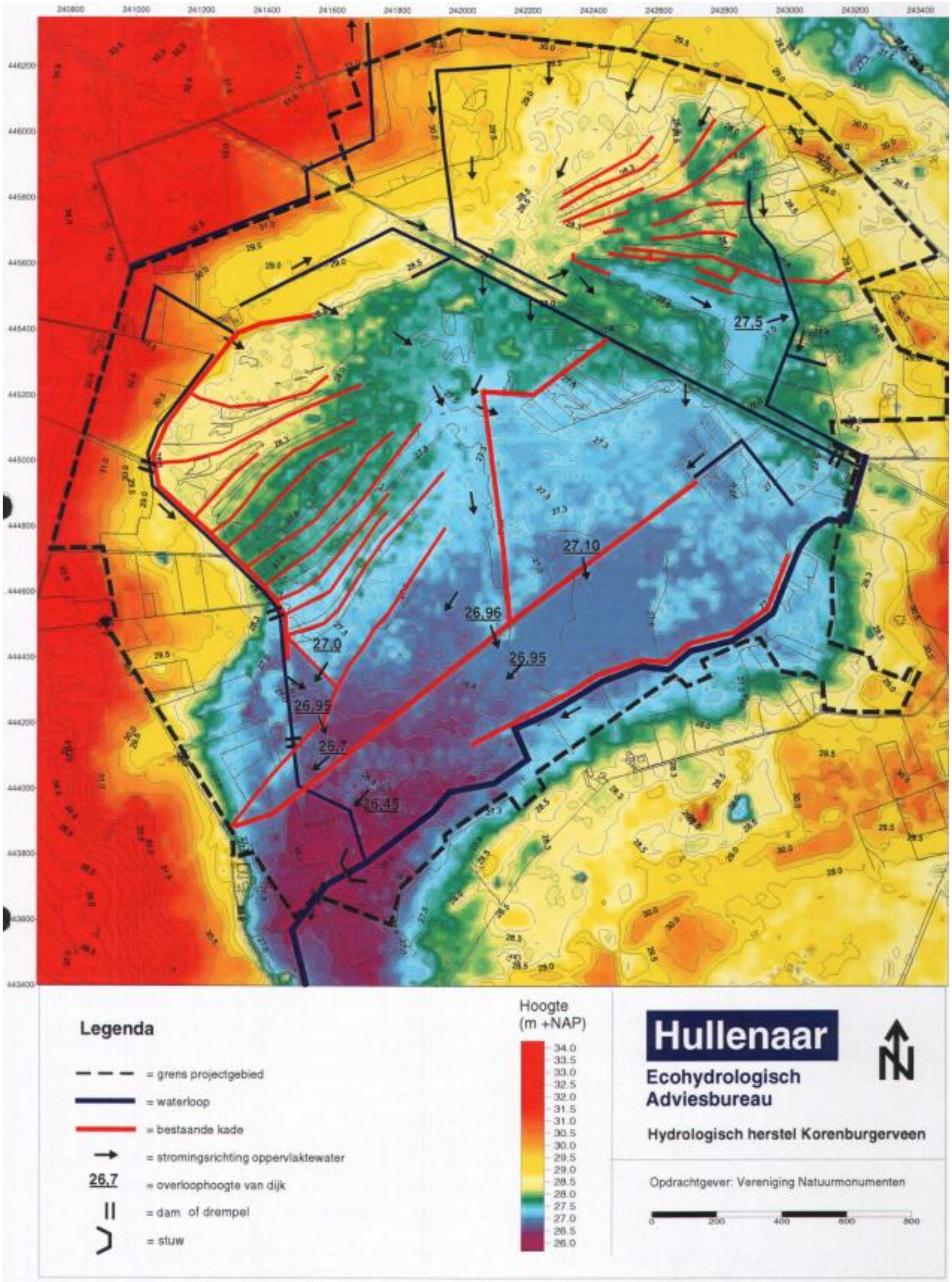

Figure 53: Elevation map with dikes and flow patterns of surface water from 1997 (Hullenaar, 2000)

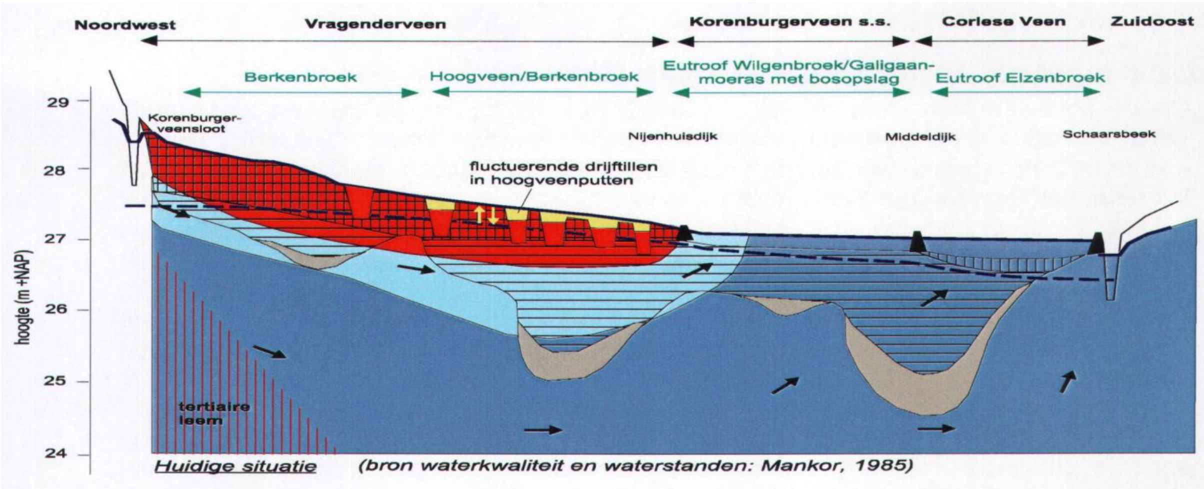

Figure 54: Cross section current situation (Hullenaar, 2000)

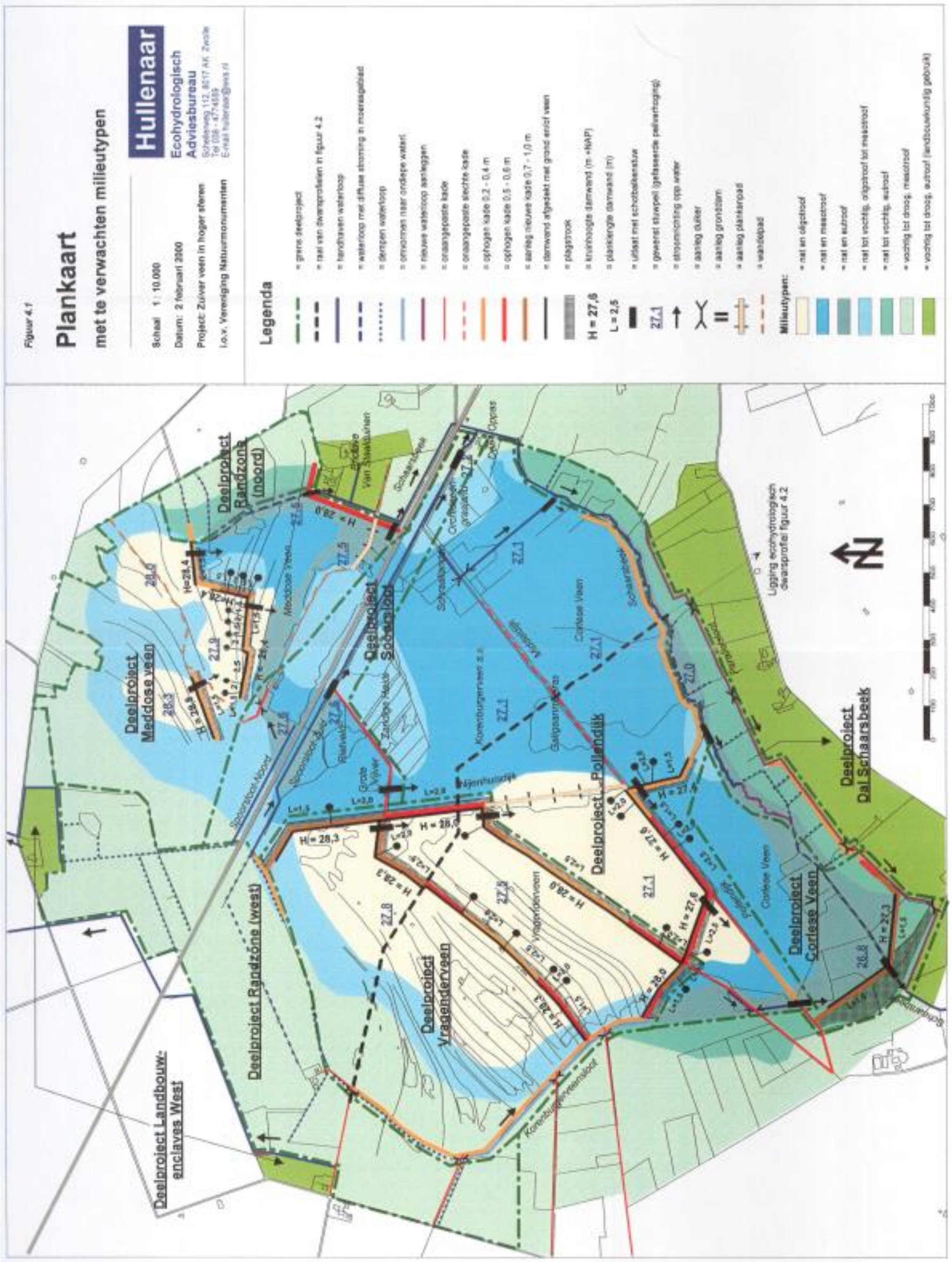

Figure 55: Plan map (Hullenaar, 2000)

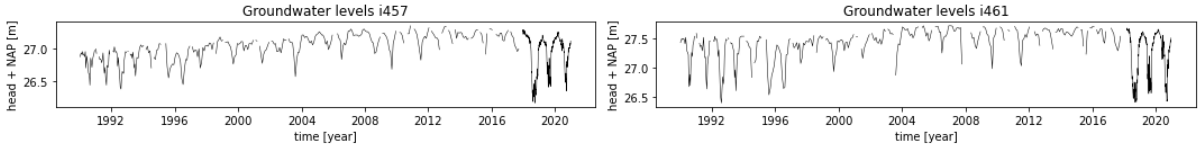

Figure 56: Groundwater levels inside Korenburgerveen

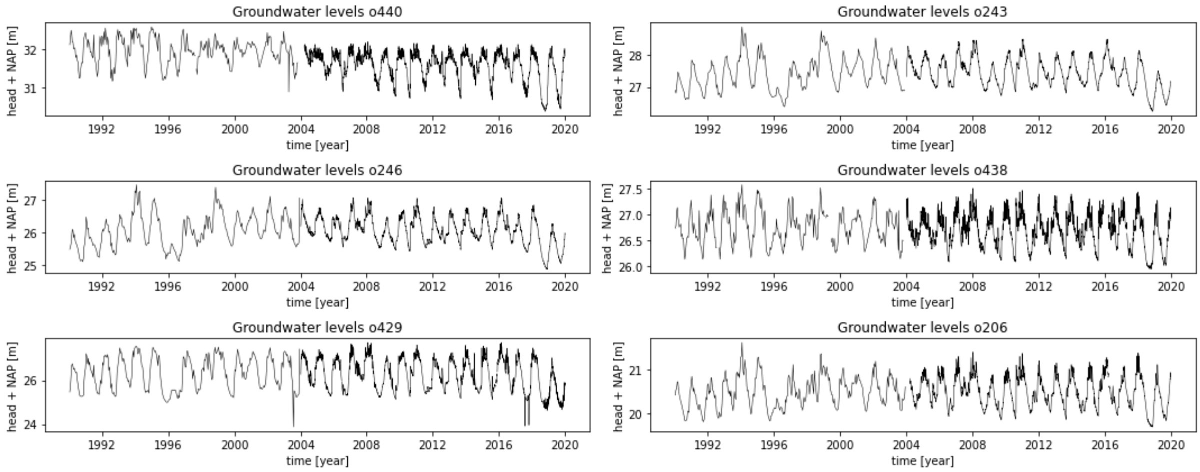

Figure 57: Groundwater levels outside Korenburgerveen

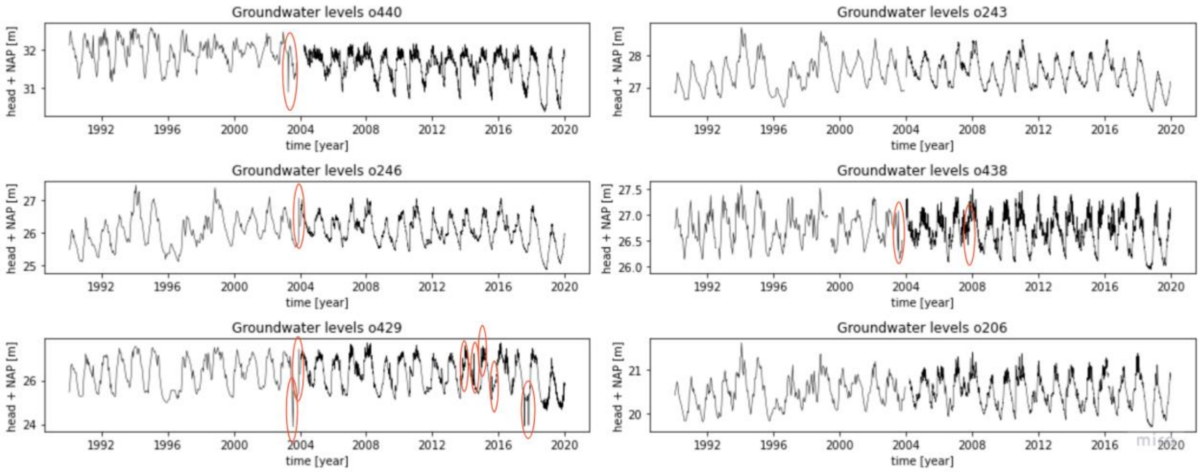

Figure 58: Distinct errors in groundwater levels outside Korenburgerveen

Table 12: Model performances Korenburgerveen

Monitoring well	Calibration		Validation	
i461	*RMSE*	*EVP*	*RMSE*	*EVP*
Validation	0.12	0.85	0.13	0.49
Cross-validation	0.09	0.87	0.12	0.86
Validation 2017-2020	0.04	0.93	0.15	0.89
Final model	0.10	0.87	-	-
i457				
Validation	0.05	0.90	0.07	0.84
Cross-validation	0.04	0.89	0.08	0.90
Validation 2017-2020	0.04	0.84	0.10	0.91
Final model	0.05	0.89	-	-
o440				
Validation	0.17	0.81	0.23	0.71
Cross-validation	0.18	0.71	0.21	0.70
Validation 2017-2020	0.10	0.88	0.21	0.85
Final model	0.18	0.73	-	-
o243				
Validation	0.11	0.96	0.18	0.89
Cross-validation	0.12	0.95	0.14	0.88
Validation 2017-2020	0.13	0.88	0.17	0.89
Final model	0.13	0.94	-	-
o246				
Validation	0.17	0.91	0.15	0.87
Cross-validation	0.16	0.92	0.17	0.82
Validation 2017-2020	0.11	0.90	0.24	0.81
Final model	0.16	0.90	-	-
o438				
Validation	0.14	0.84	0.14	0.72
Cross-validation	0.13	0.81	0.16	0.64
Validation 2017-2020	0.11	0.85	0.20	0.71
Final model	0.14	0.82	-	-
o429				
Validation	0.21	0.92	0.23	0.88
Cross-validation	0.19	0.94	0.30	0.87
Validation 2017-2020	0.18	0.92	0.45	0.72
Final model	0.21	0.92	-	-
o206				
Validation	0.12	0.91	0.14	0.83
Cross-validation	0.12	0.90	0.14	0.87
Validation 2017-2020	0.08	0.93	0.15	0.85
0.13	0.13	0.89	-	-

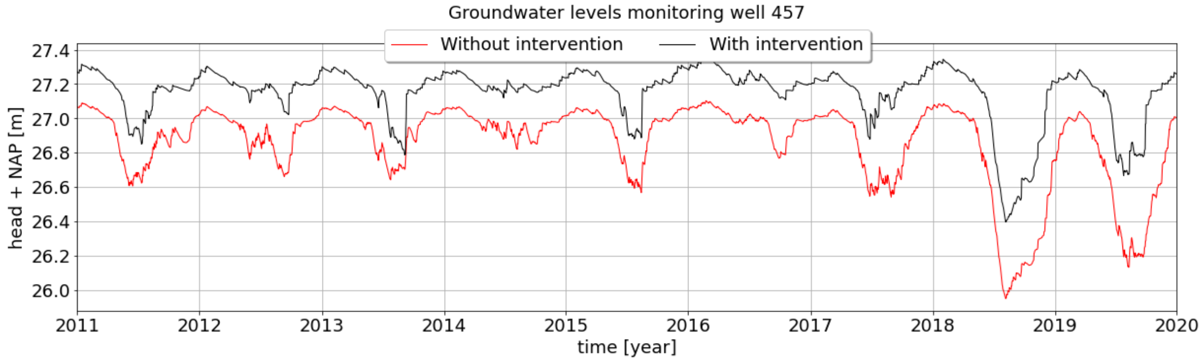

Figure 59: Forecasted groundwater levels with and without intervention monitoring well i457

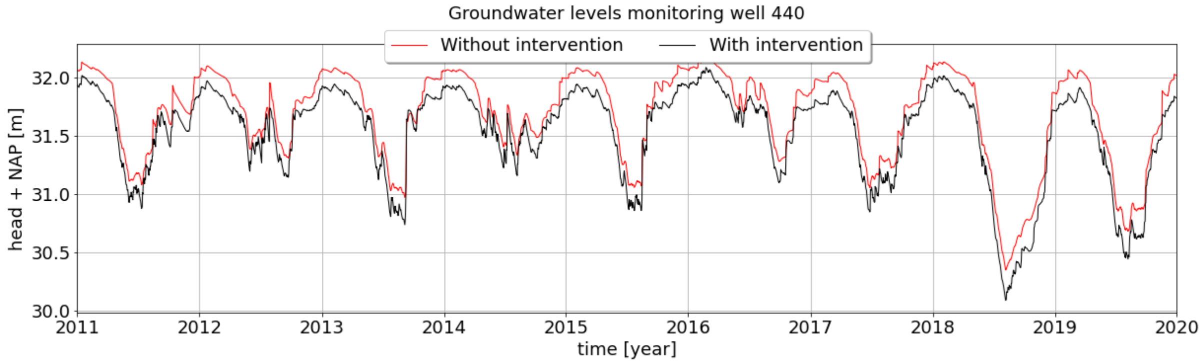

Figure 60: Forecasted groundwater levels with and without intervention monitoring well o440

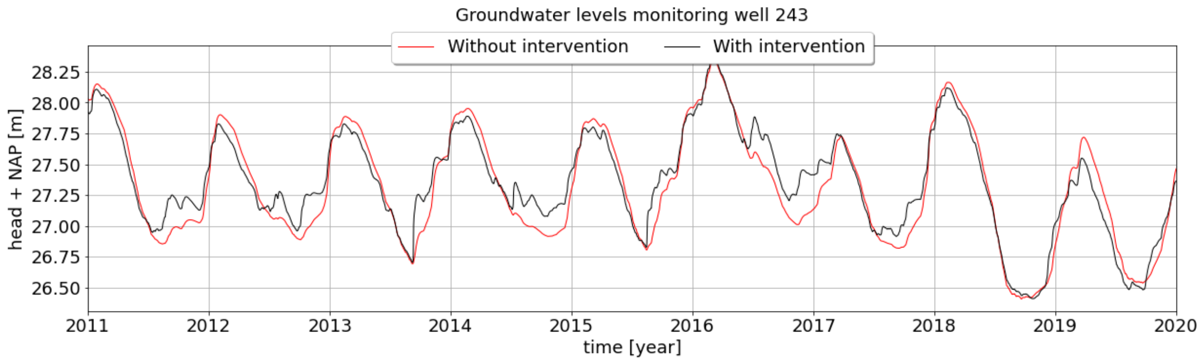

Figure 61: Forecasted groundwater levels with and without intervention monitoring well o243

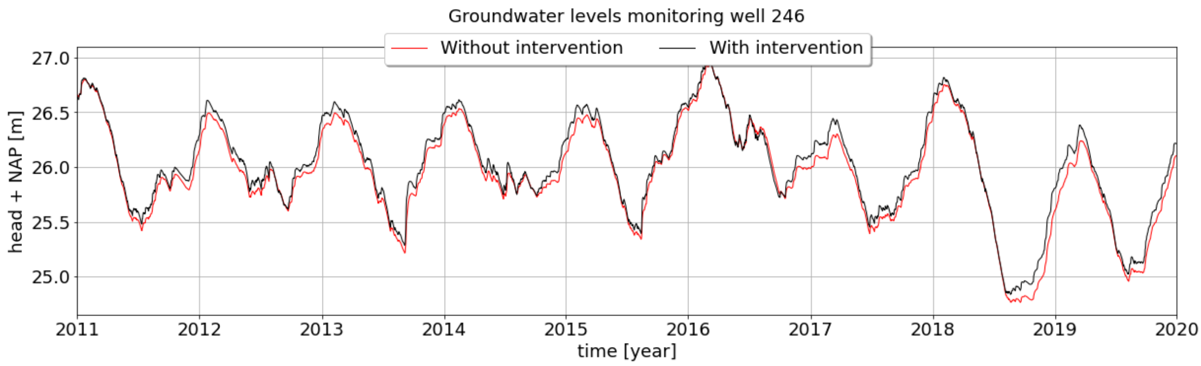

Figure 62: Forecasted groundwater levels with and without intervention monitoring well o246

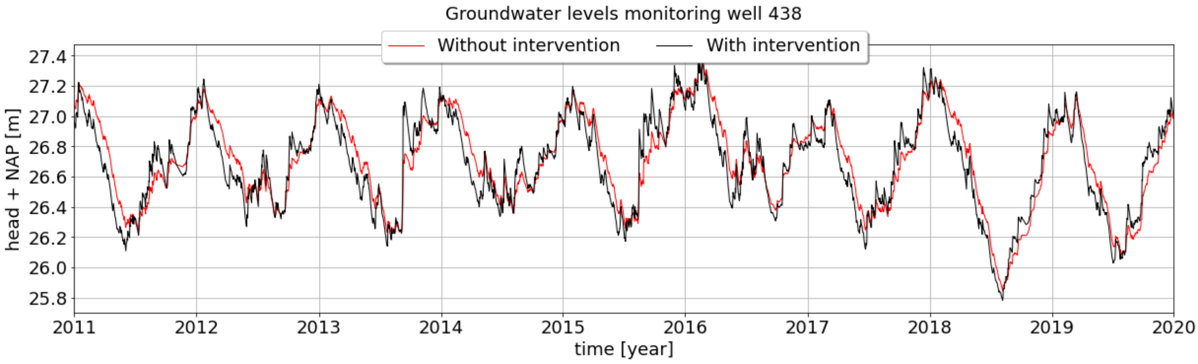

Figure 63: Forecasted groundwater levels with and without intervention monitoring well o438

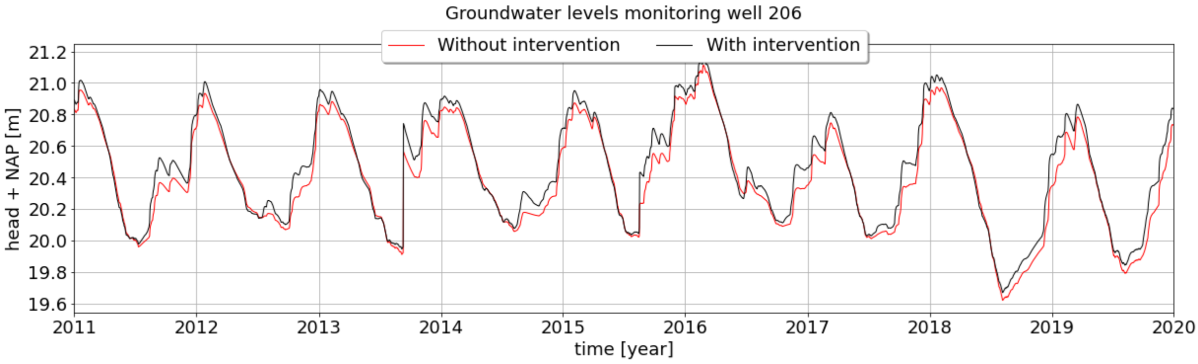

Figure 64: Forecasted groundwater levels with and without intervention monitoring well o206

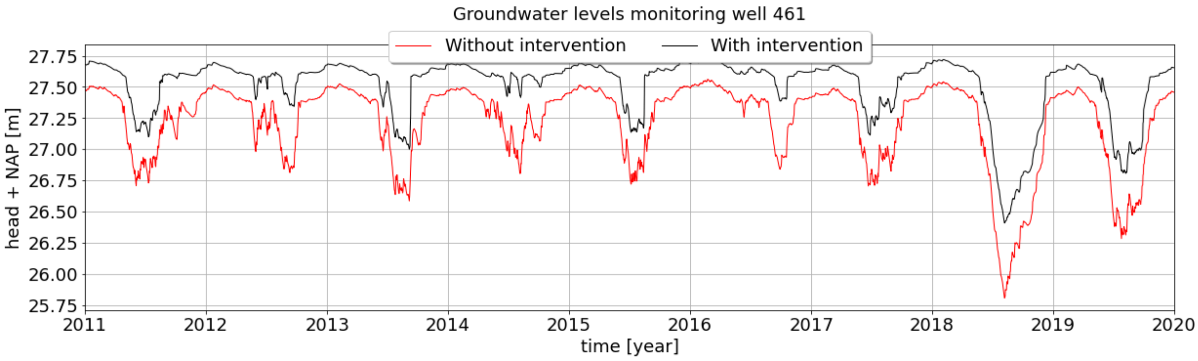

Figure 65: Forecasted groundwater levels with and without intervention monitoring well o461

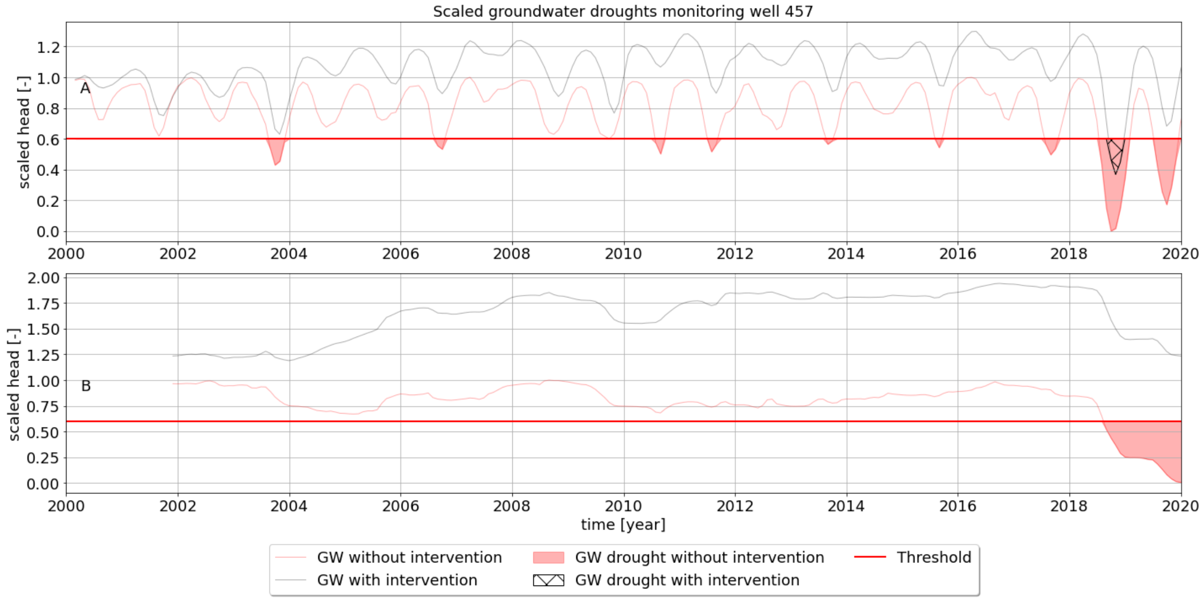

Figure 66: Scaled groundwater drought monitoring well i457 for different time scales (A = three months and B = two years)

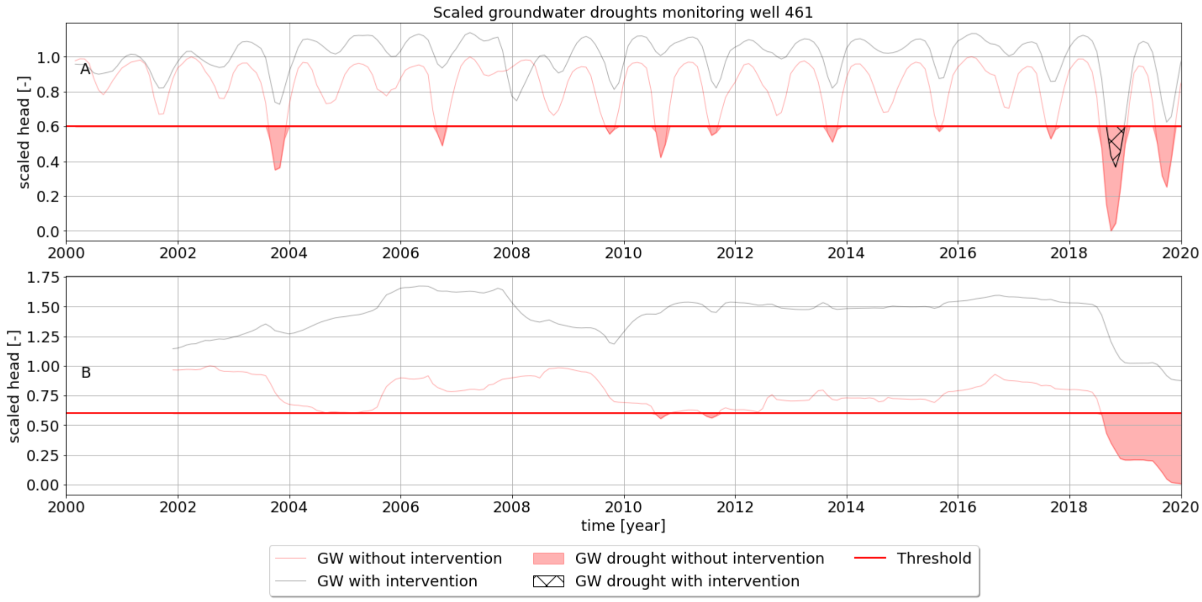

Figure 67: Scaled groundwater drought monitoring well i461 for different time scales (A = three months and B = two years)

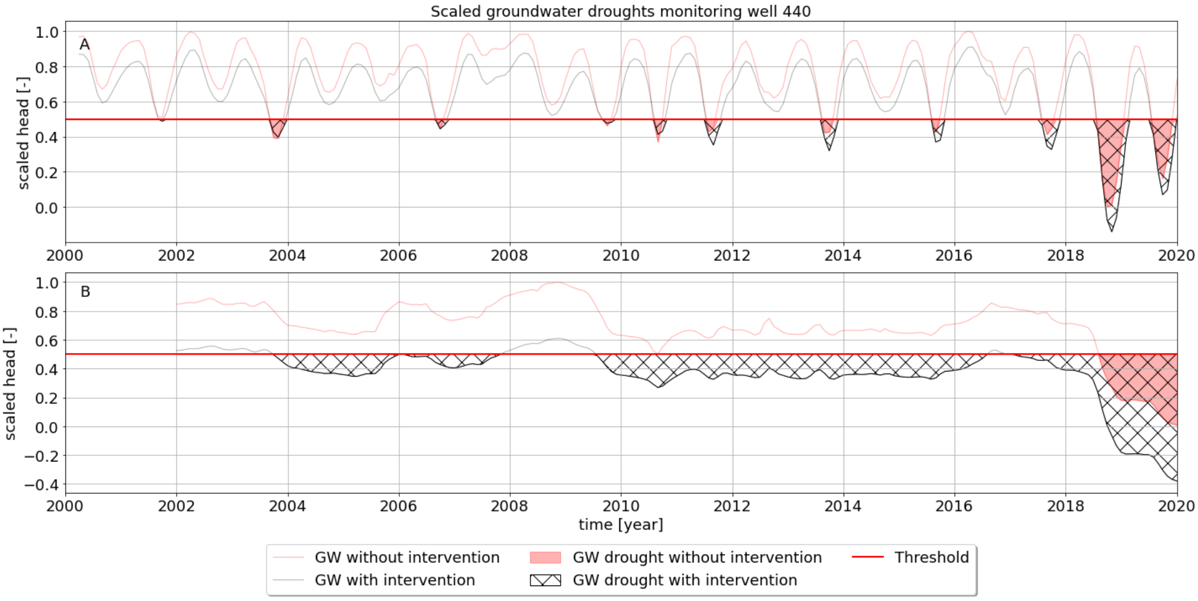

Figure 68: Scaled groundwater drought monitoring well o440 for different time scales (A = three months and B = two years)

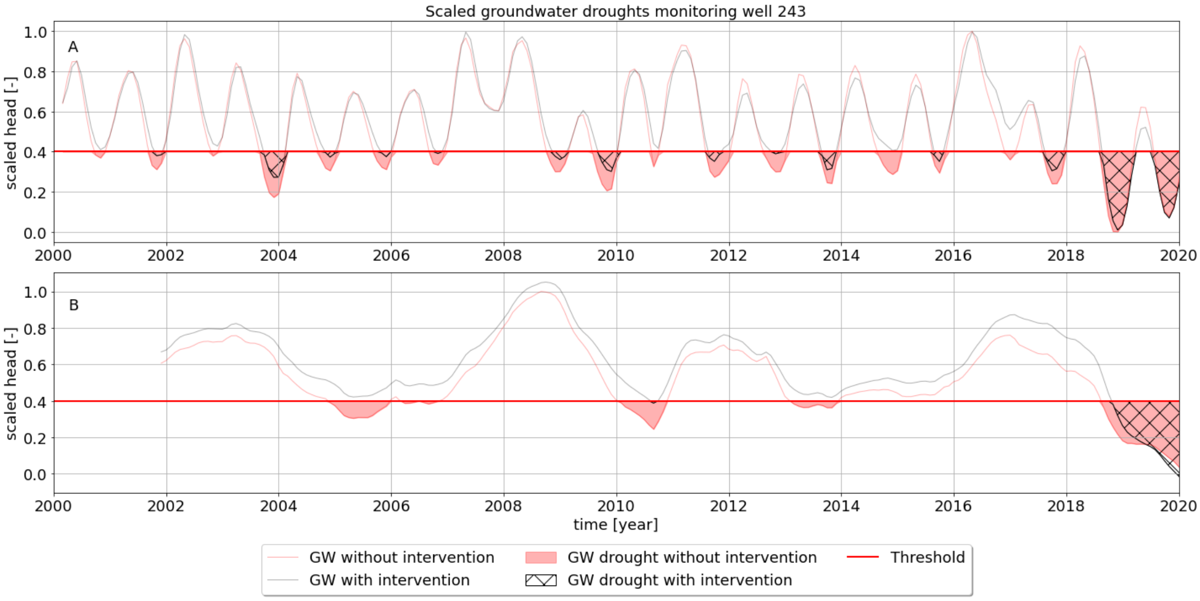

Figure 69: Scaled groundwater drought monitoring well o243 for different time scales (A = three months and B = two years)

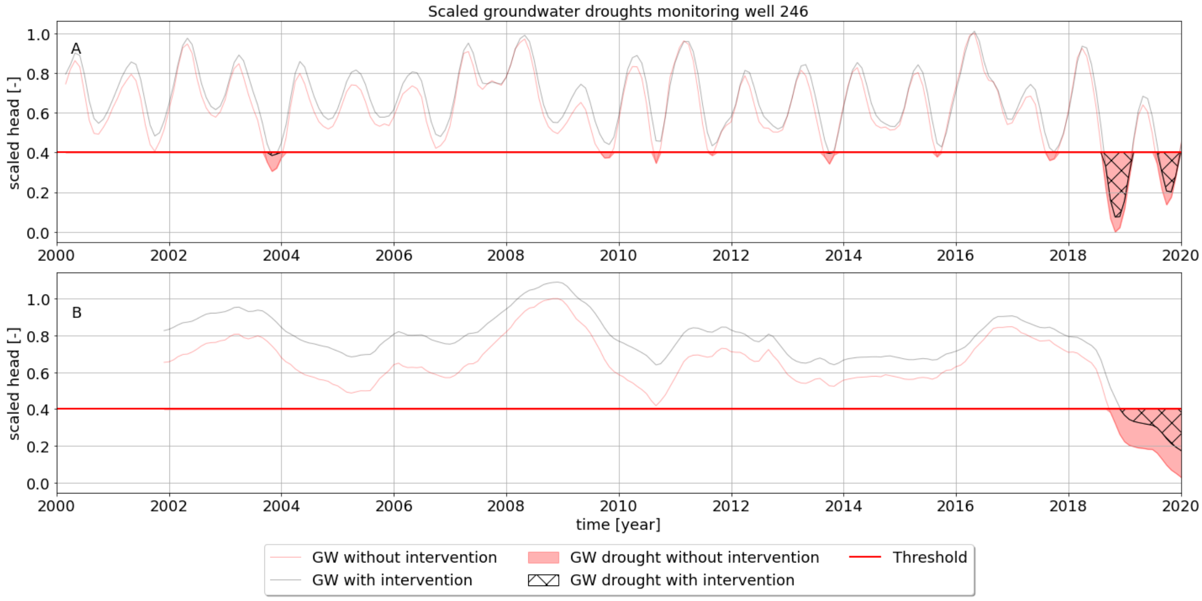

Figure 70: Scaled groundwater drought monitoring well o246 for different time scales (A = three months and B = two years)

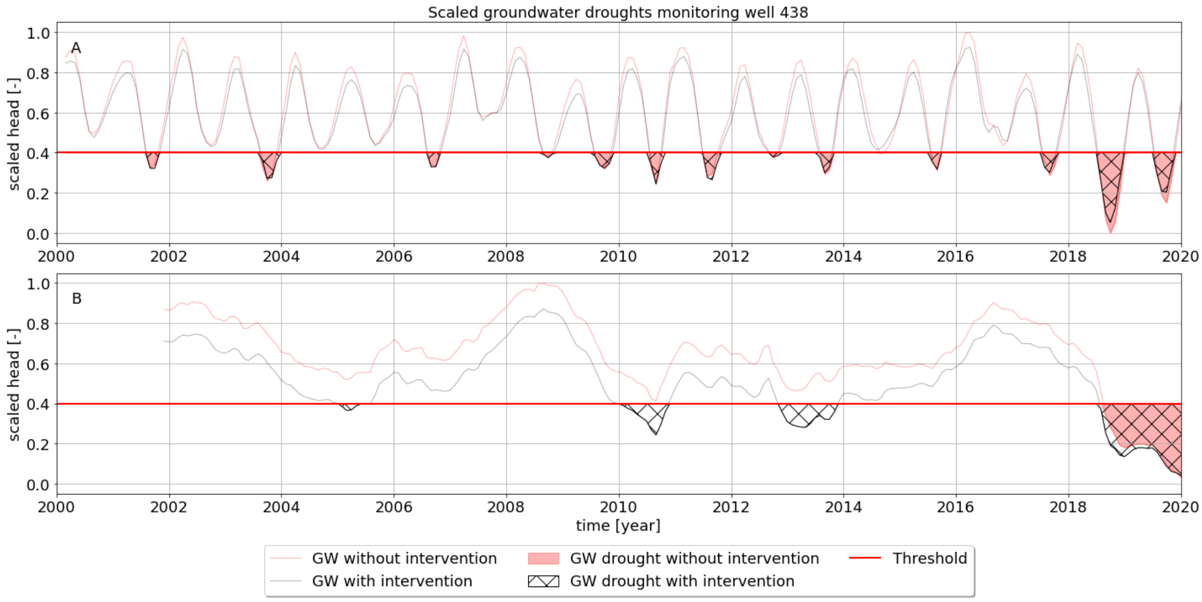

Figure 71: Scaled groundwater drought monitoring well o438 for different time scales (A = three months and B = two years)

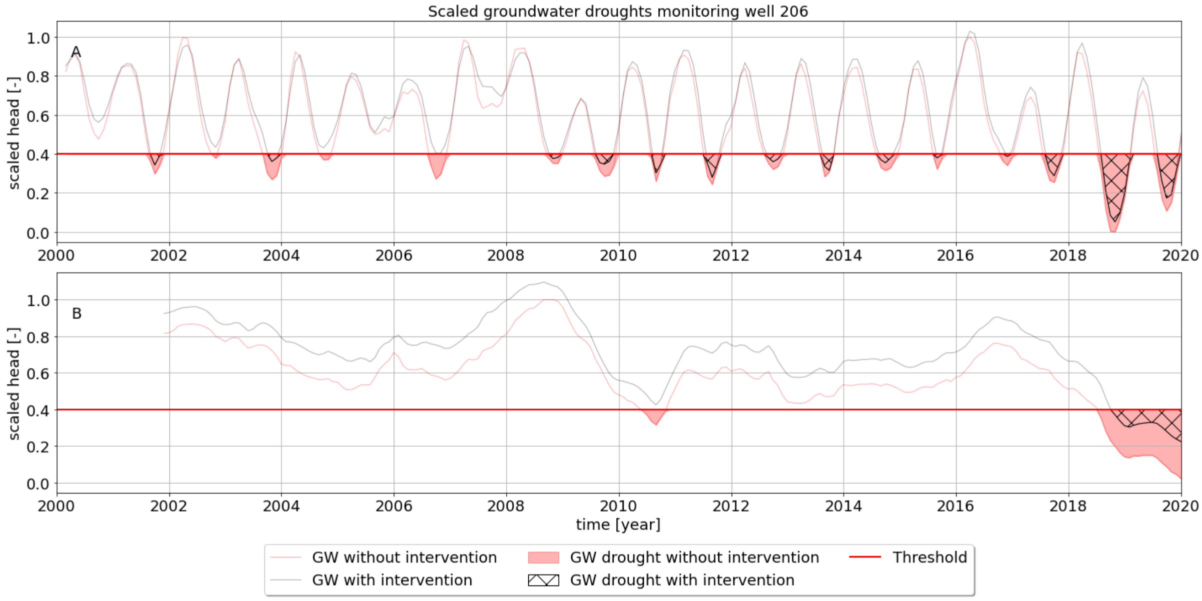

Figure 72: Scaled groundwater drought monitoring well o206 for different time scales (A = three months and B = two years)

14 Appendix C – De Doorbraak

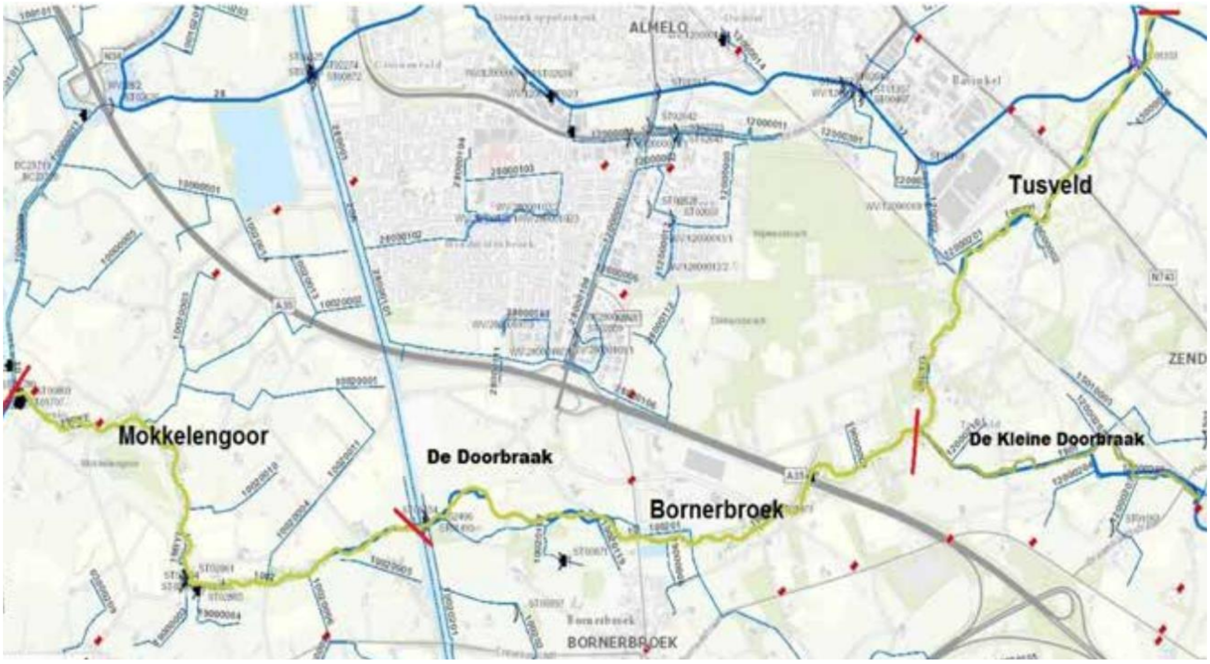

Figure 73: Faseringsoverzicht de Doorbraak (Vechtstromen, 2018)

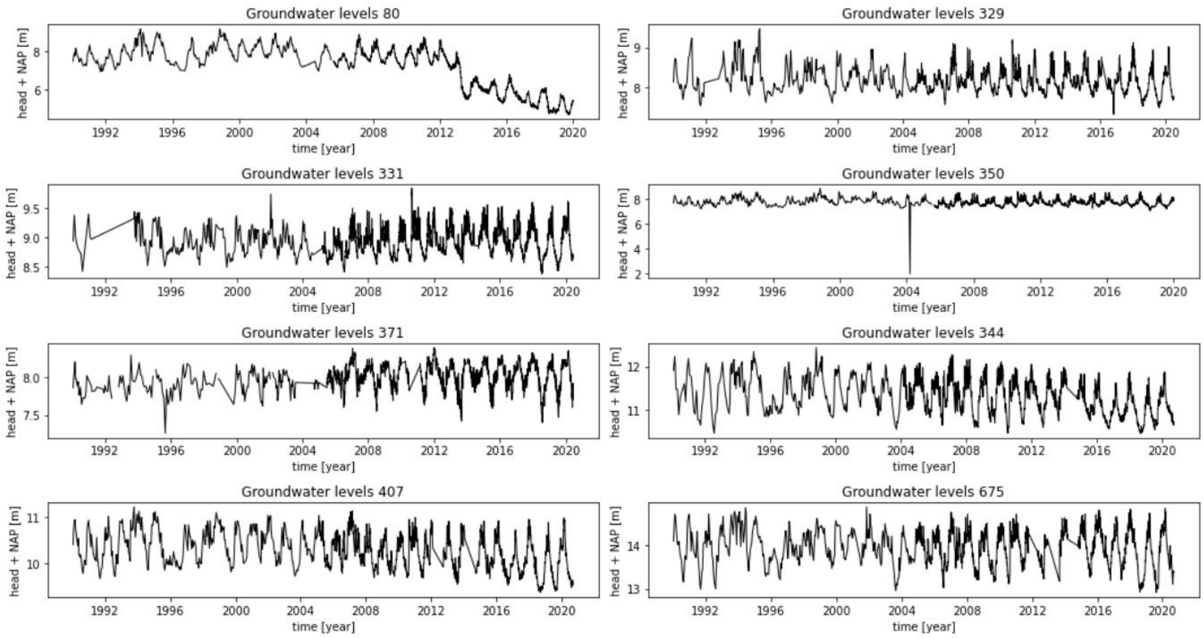

Figure 74: Observed groundwater levels De Doorbraak

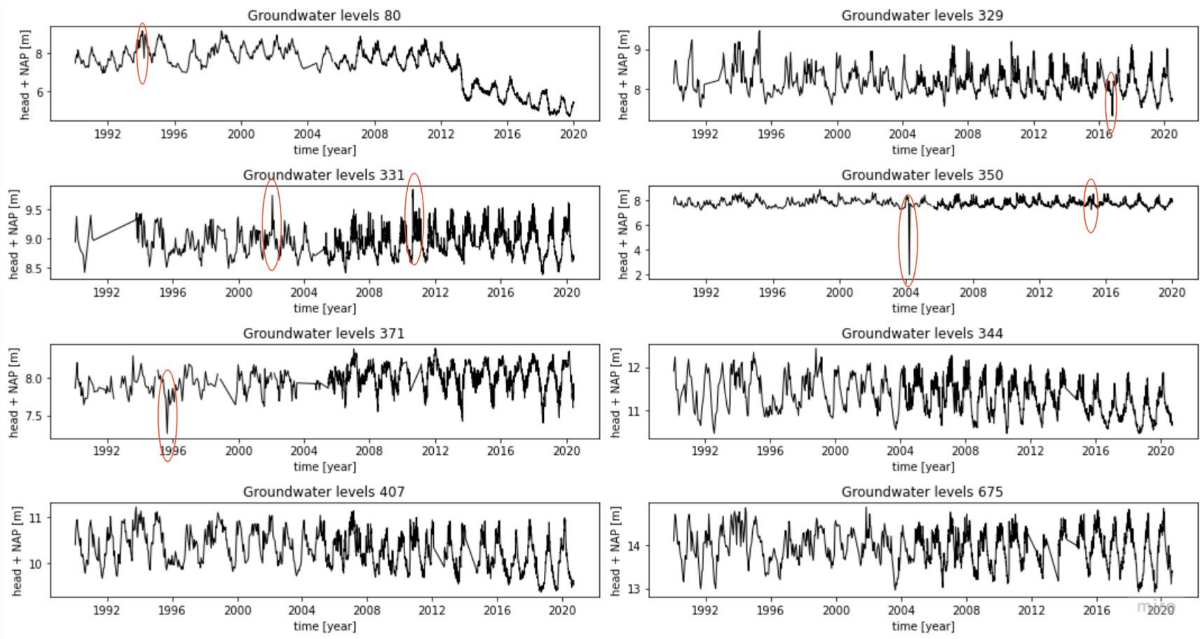

Figure 75: Distinct errors groundwater levels De Doorbraak

Table 13: Model performances De Doorbraak

Monitoring well	Calibration		Validation	
371	*RMSE*	*EVP*	*RMSE*	*EVP*
Validation	0.10	0.48	0.06	0.82
Cross-validation	0.08	0.63	0.12	0.94
Validation 2017-2020	0.06	0.86	0.10	0.93
Final model	0.09	0.55	-	-
407				
Validation	0.14	0.87	0.13	0.83
Cross-validation	0.12	0.88	0.17	0.77
Validation 2017-2020	0.13	0.86	0.16	0.79
Final model	0.14	0.85	-	-
344				
Validation	0.19	0.79	0.09	0.95
Cross-validation	0.17	0.82	0.16	0.99
Validation 2017-2020	0.19	0.68	0.15	0.89
Final model	0.18	0.80	-	-
329				
Validation	0.21	0.72	0.18	0.77
Cross-validation	0.15	0.74	0.11	0.90
Validation 2017-2020	0.10	0.86	0.12	0.89
Final model	0.17	0.76	-	-
350				
Validation	0.14	0.79	0.16	0.50
Cross-validation	0.15	0.78	0.12	0.82
Validation 2017-2020	0.10	0.81	0.10	0.85
Final model	0.15	0.78	-	-
331				
Validation	0.10	0.76	0.10	0.70
Cross-validation	0.10	0.76	0.10	0.76

Validation 2017-2020	0.08	0.83	0.07	0.91
Final model	0.10	0.76	-	-
80				
Validation	0.18	0.89	0.16	0.92
Cross-validation	0.17	0.89	0.19	0.82
Validation 2017-2020	0.18	0.76	0.20	0.80
Final model	0.17	0.89	-	-
675				
Validation	0.19	0.77	0.14	0.88
Cross-validation	0.15	0.83	0.20	0.78
Validation 2017-2020	0.10	0.92	0.16	0.88
0.13	0.18	0.78	-	-

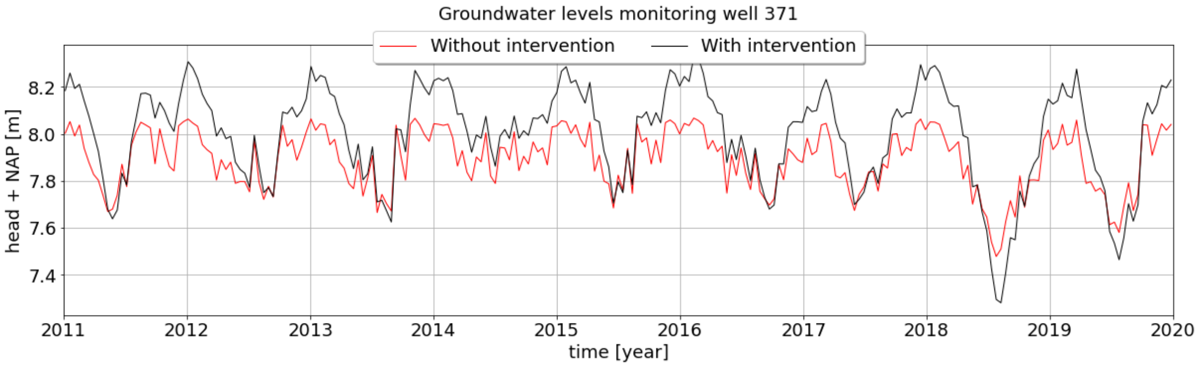

Figure 76: Forecasted groundwater levels with and without intervention monitoring well 371

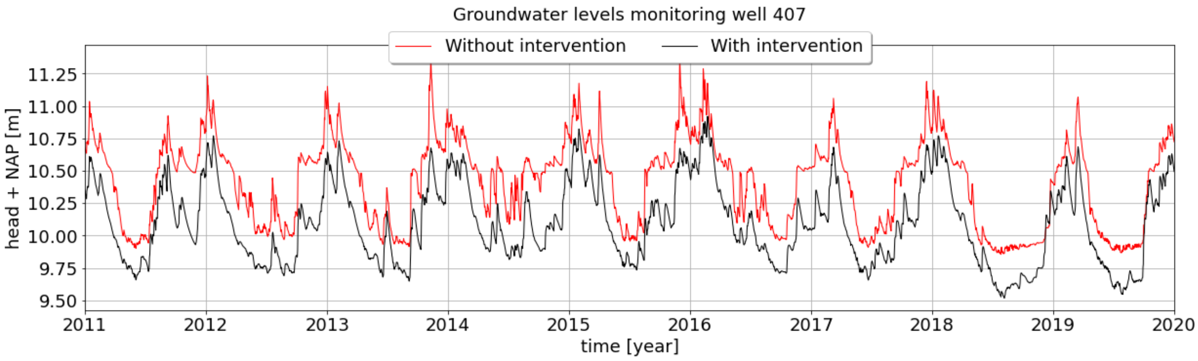

Figure 77: Forecasted groundwater levels with and without intervention monitoring well 407

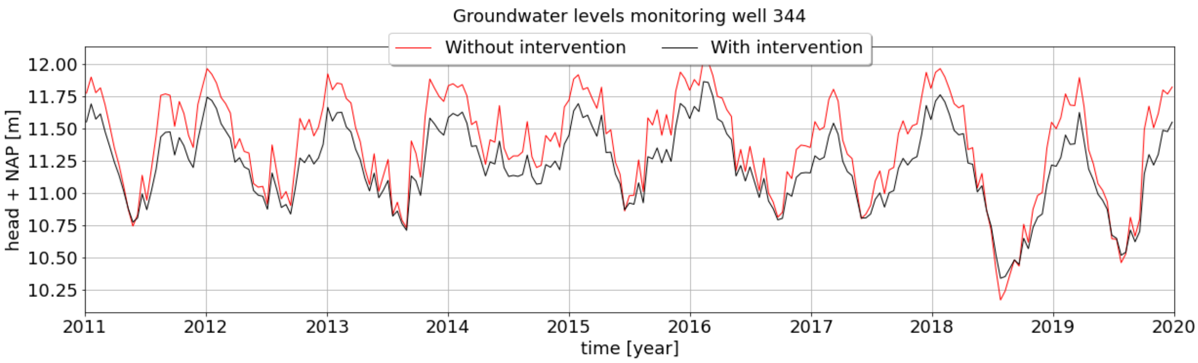

Figure 78: Forecasted groundwater levels with and without intervention monitoring well 344

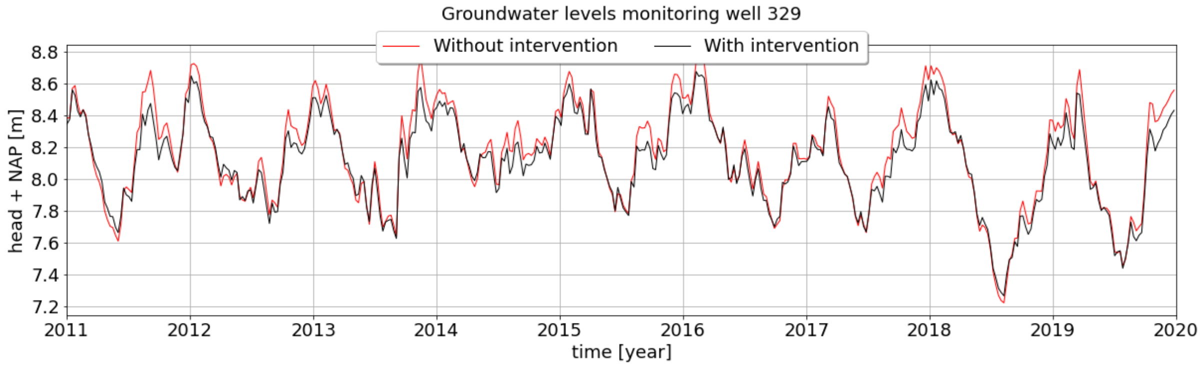

Figure 79: Forecasted groundwater levels with and without intervention monitoring well 329

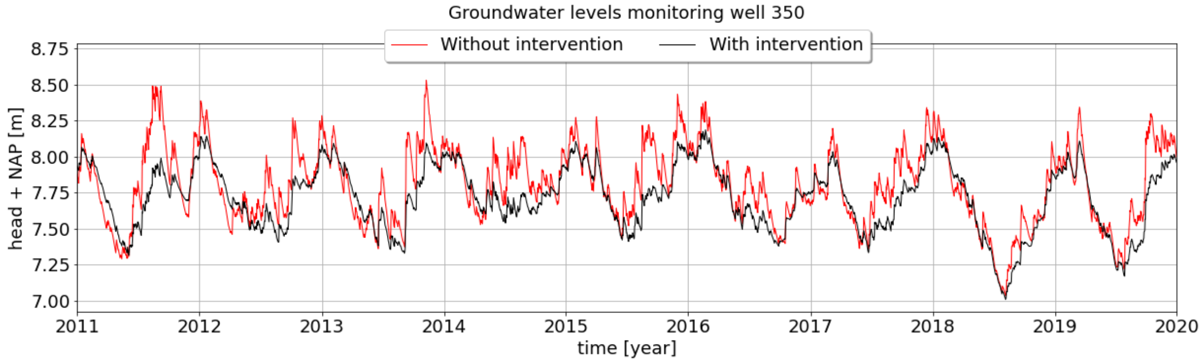

Figure 80: Forecasted groundwater levels with and without intervention monitoring well 350

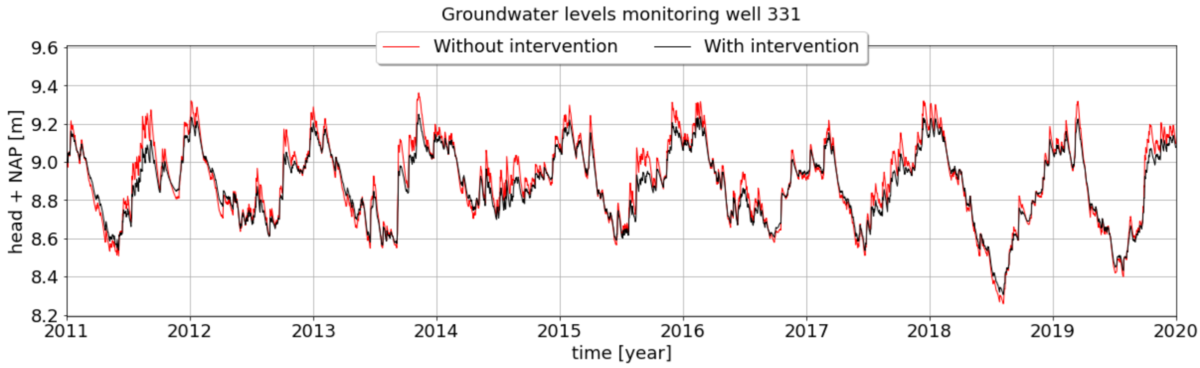

Figure 81: Forecasted groundwater levels with and without intervention monitoring well 331

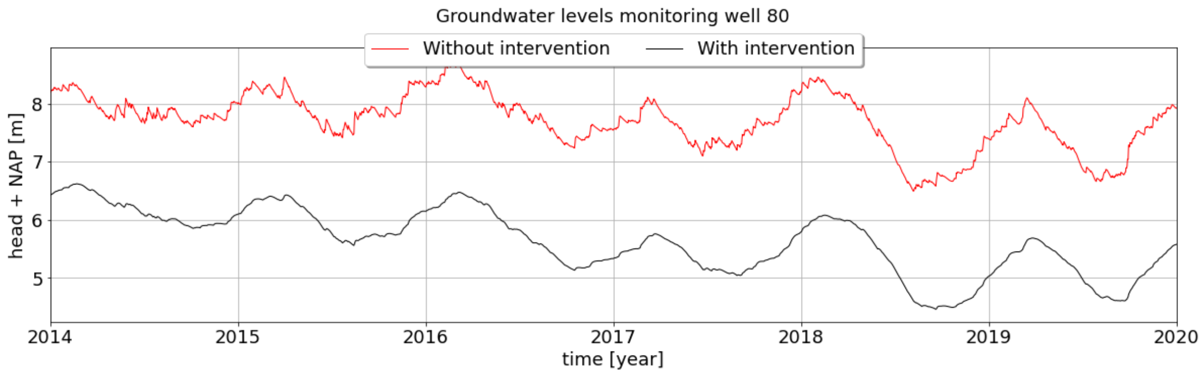

Figure 82: Forecasted groundwater levels with and without intervention monitoring well 80

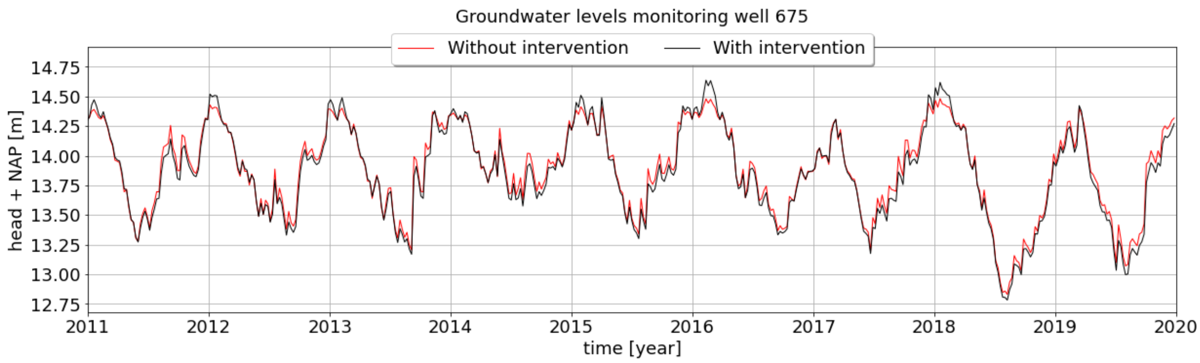

Figure 83: Forecasted groundwater levels with and without intervention monitoring well 675

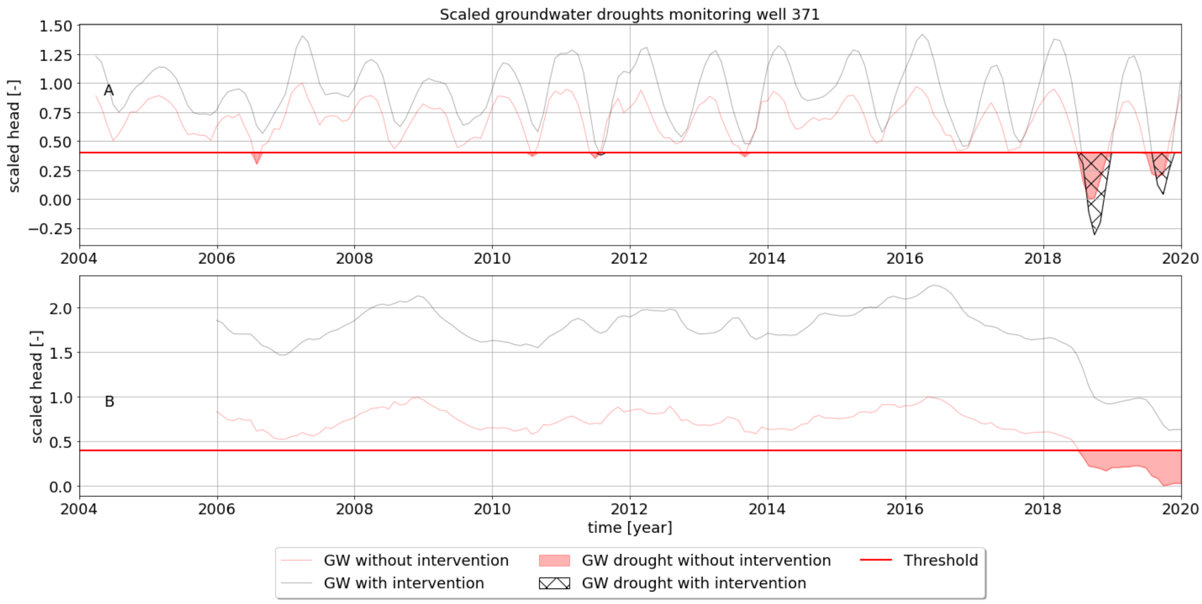

Figure 84: Scaled groundwater drought monitoring well 371 for different time scales (A = three months and B= two years)

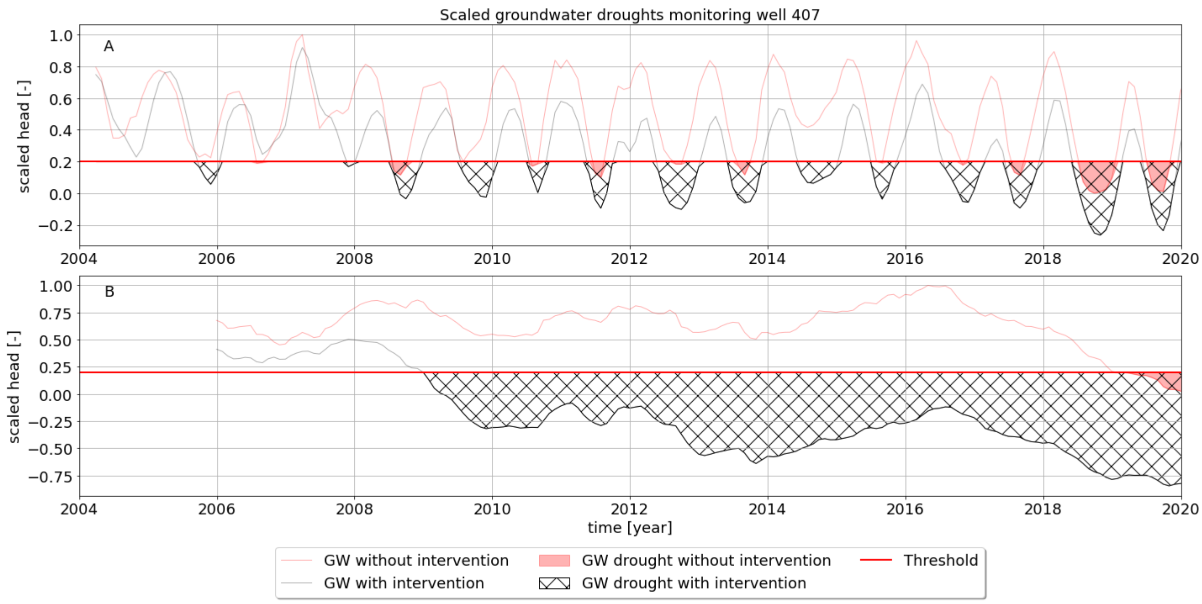

Figure 85: Scaled groundwater drought monitoring well 407 for different time scales (A = three months and B = two years)

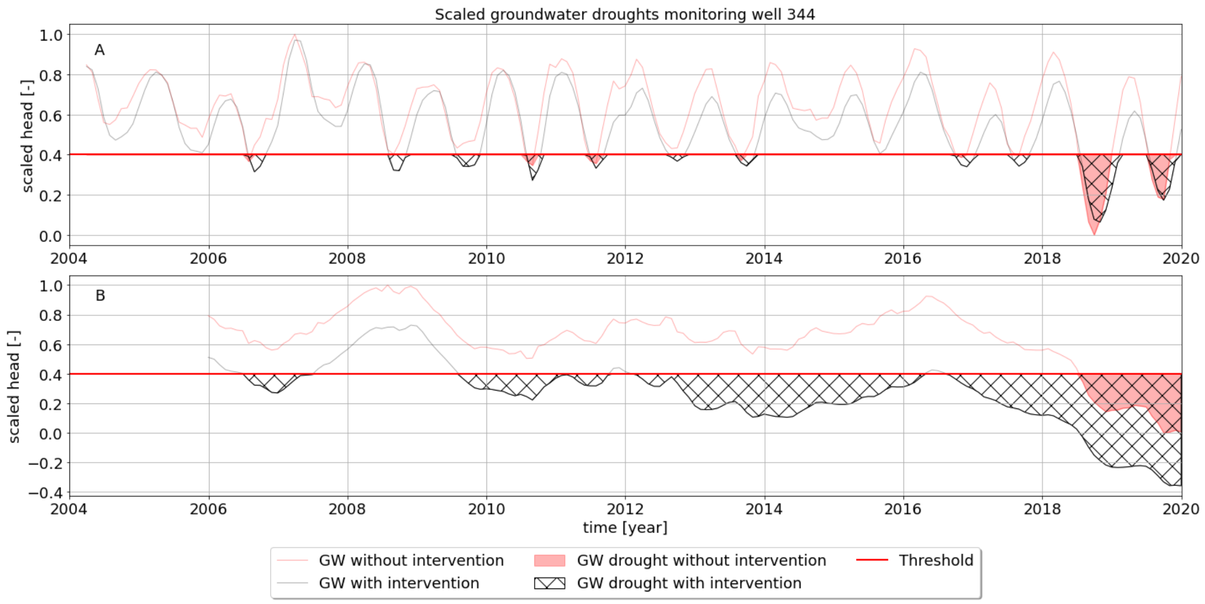

Figure 86: Scaled groundwater drought monitoring well 344 for different time scales (A = three months and B = two years)

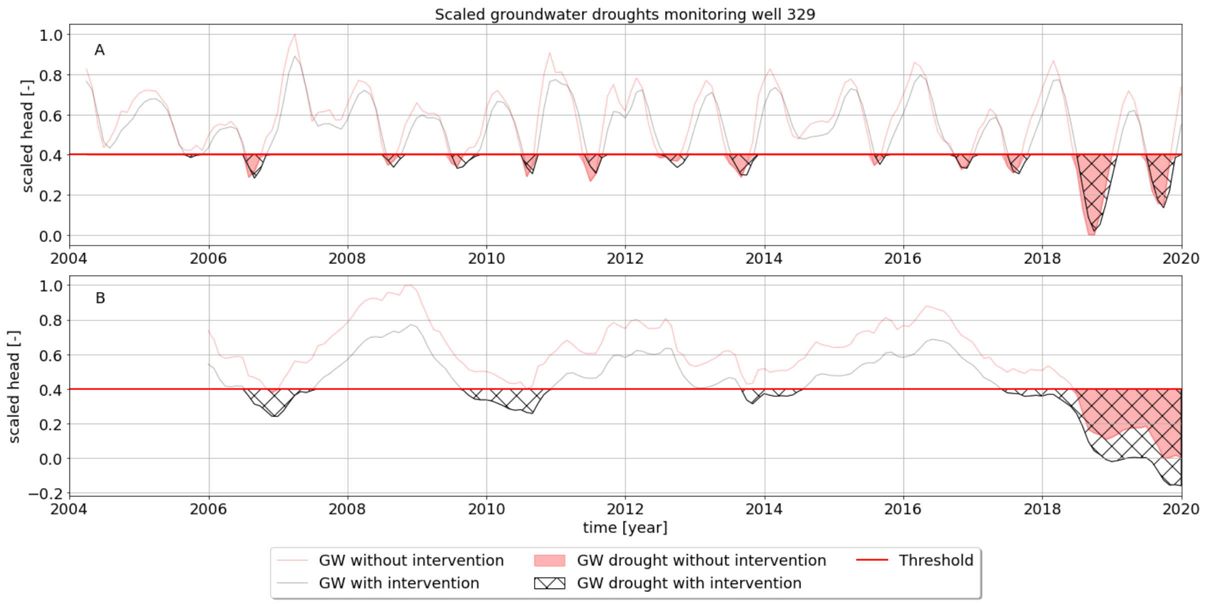

Figure 87: Scaled groundwater drought monitoring well 329 for different time scales (A = three months and B = two years)

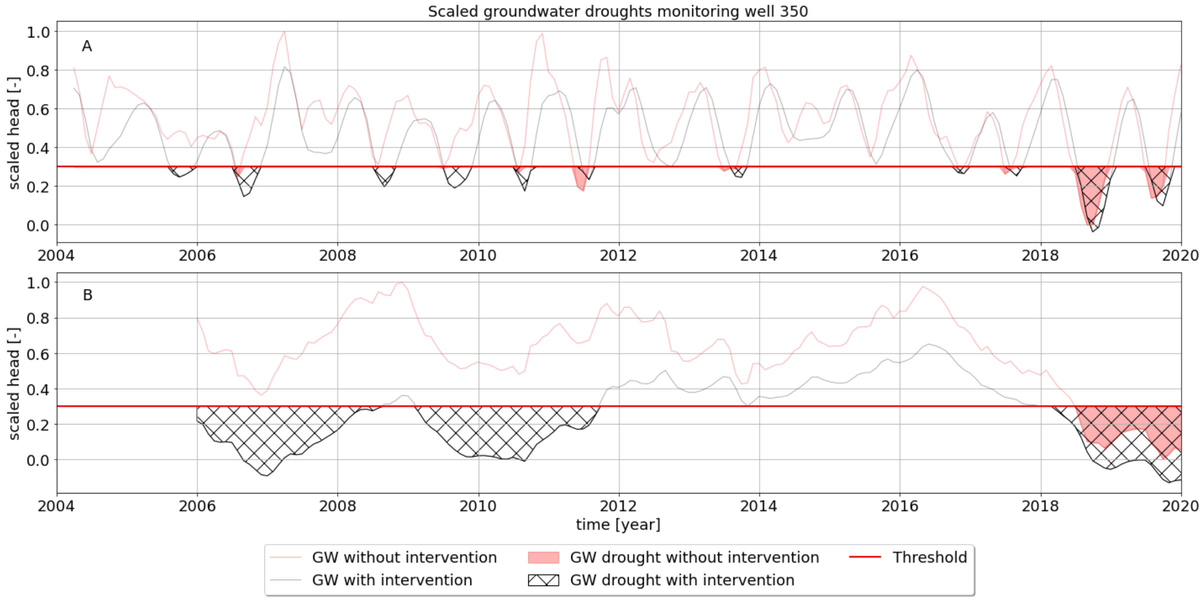

Figure 88: Scaled groundwater drought monitoring well 350 for different time scales (A = three months and B = two years)

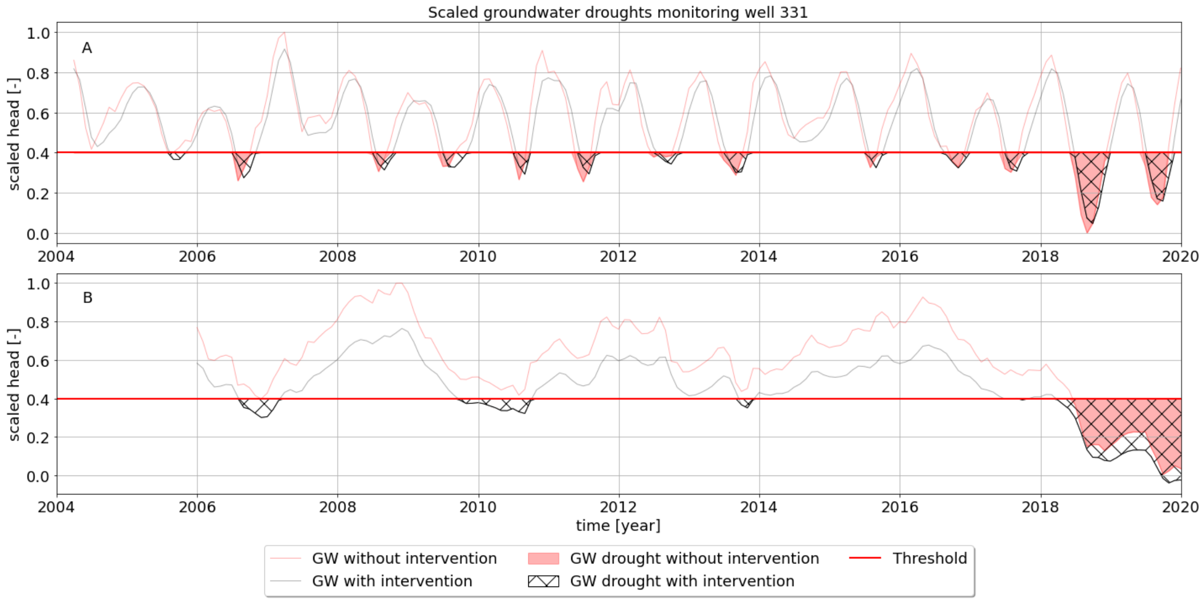

Figure 89: Scaled groundwater drought monitoring well 331 for different time scales (A = three months and B = two years)

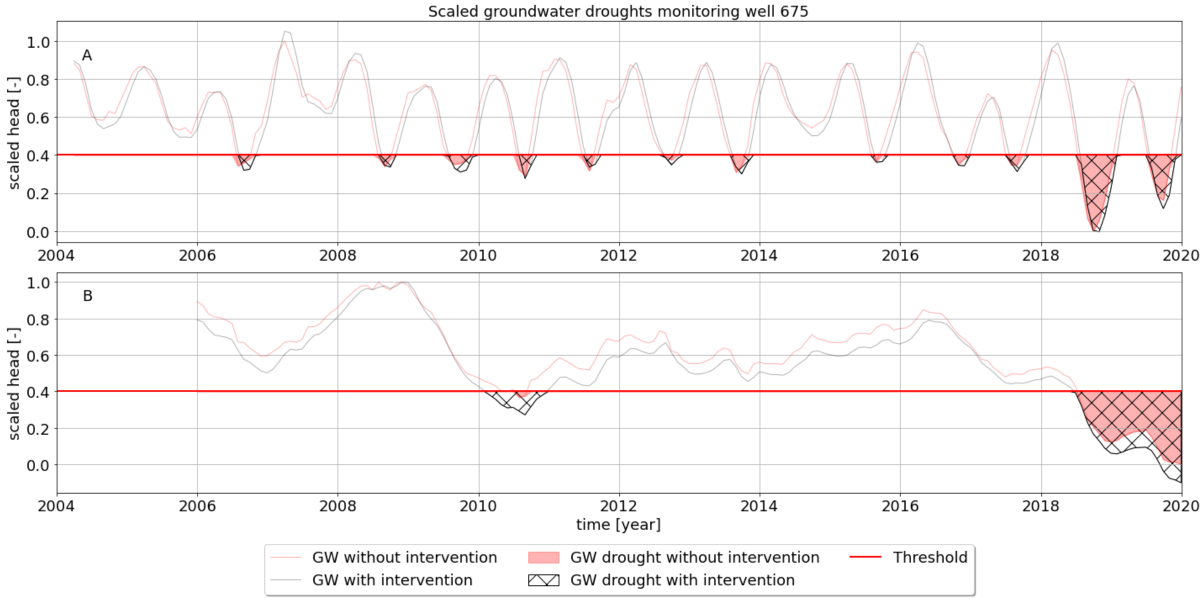

Figure 90: Scaled groundwater drought monitoring well 675 for different time scales (A = three months and B = two years)

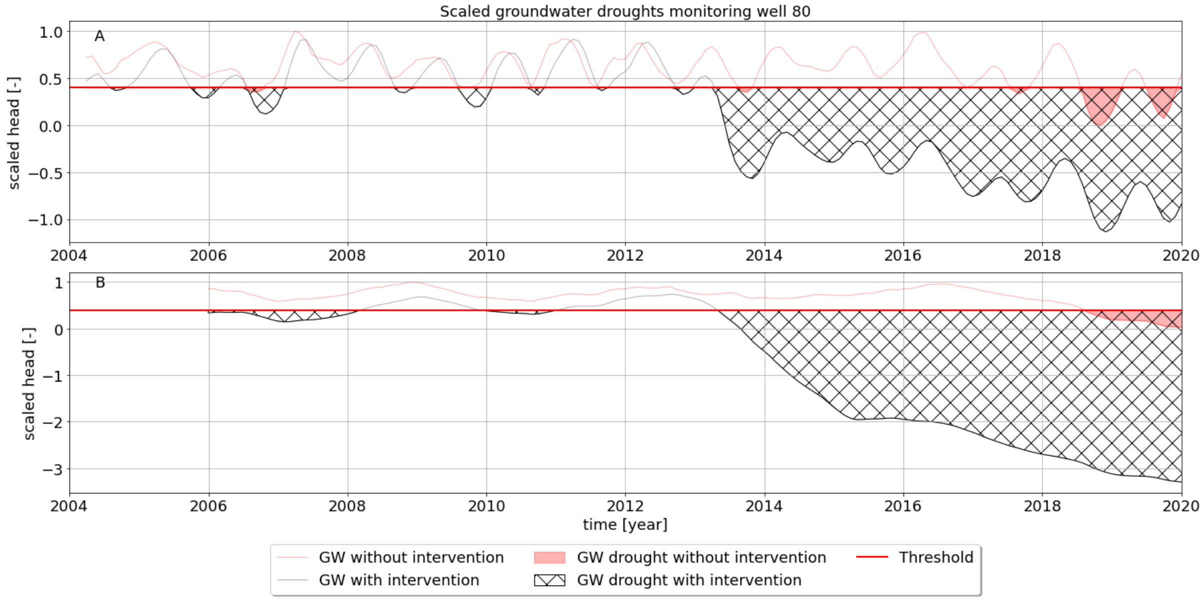

Figure 91: Scaled groundwater drought monitoring well 80 for different time scales (A = three months and B = two years)

15 Appendix D – Scheller and Oldeneler buitenwaarden data pre-processing

In this Section, the results of data pre-processing are provided for the intervention at Scheller and Oldeneler buitenwaarden.

15.1 Correlation input series

Analysing the correlation of input series could result in useful information for further analysis. In Figure 92 the normalized series of the observed groundwater levels (well 260), abstraction data (Het Engelse Werk) and surface water levels (Wijhe) are shown. A correlation between surface and groundwater is visible, but a correlation between abstraction data and the other two is difficult to determine.

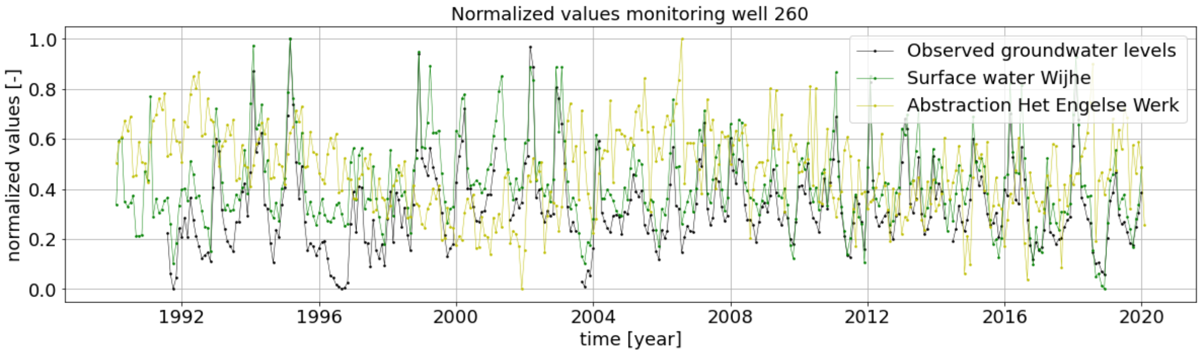

Figure 92: Correlation input series Scheller and Oldeneler buitenwaarden

The correlation between recharge and surface water is also determined but resulted in simulations with EVP < 30%. Therefore, surface water is not designated as a confounding variable.

Additionally, it could be useful to know the relation between the absolute values of the groundwater and surface water levels near the intervention. Therefore, the surface water series is transformed based on the slope of the IJssel of 1/10km to imitate the surface water levels near the intervention (Clemens, 2016). This highly simplified transformed series includes quite some uncertainty but does indicate that the IJssel switches from gaining to losing stream during the year.

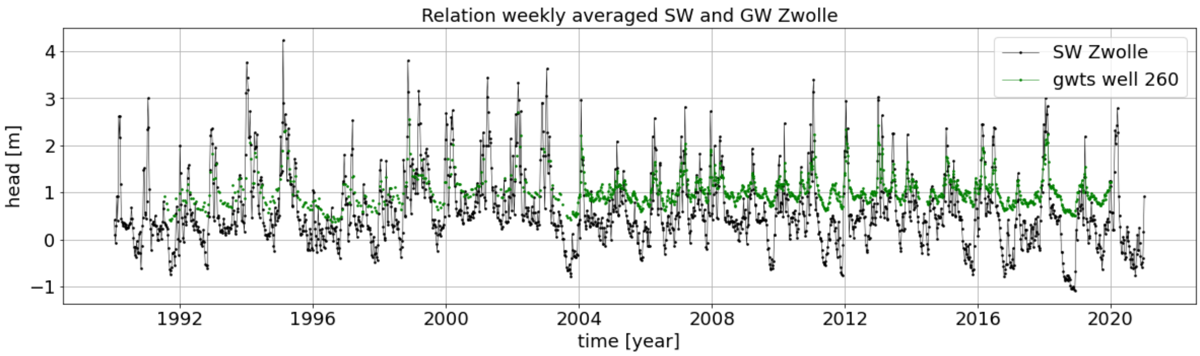

Figure 93: Absolute weekly averaged relation SW and GW Zwolle

16 Appendix E – Scheller and Oldeneler buitenwaarden

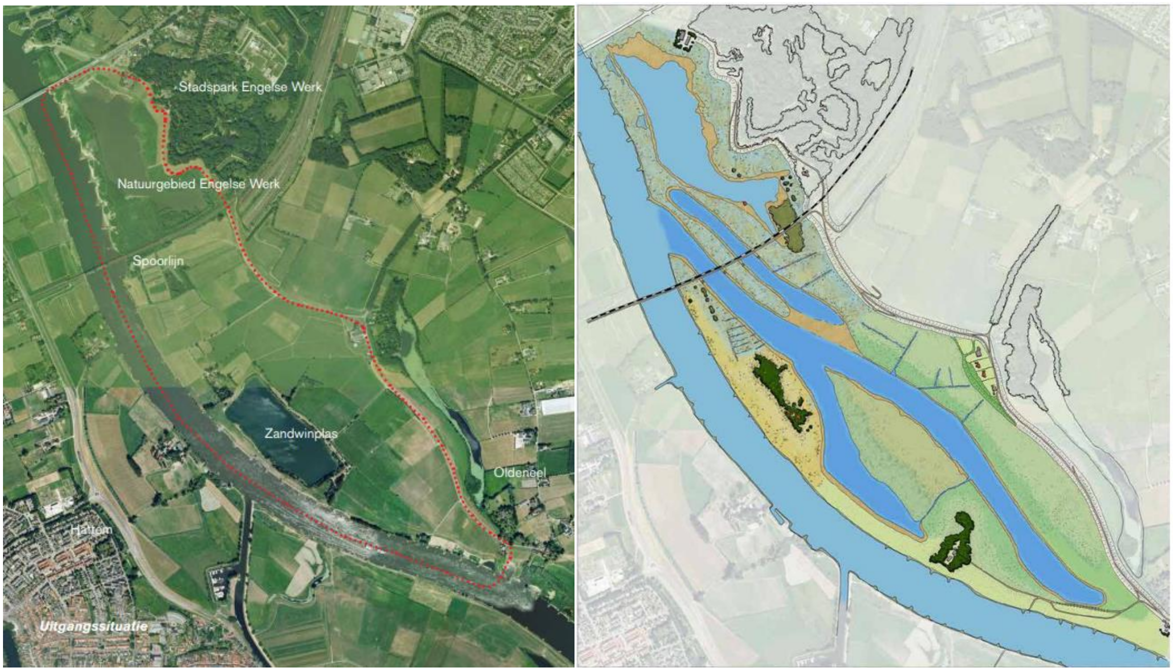

Figure 94: Left) Original situation and right) final design high-water channel Scheller and Oldeneler buitenwaarden (T. van Loon, 2018)

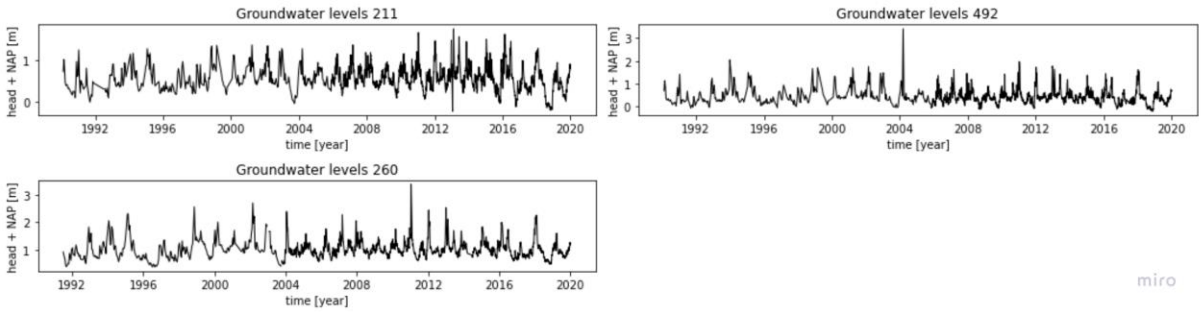

Figure 95: Observed groundwater levels Scheller and Oldeneler buitenwaarden

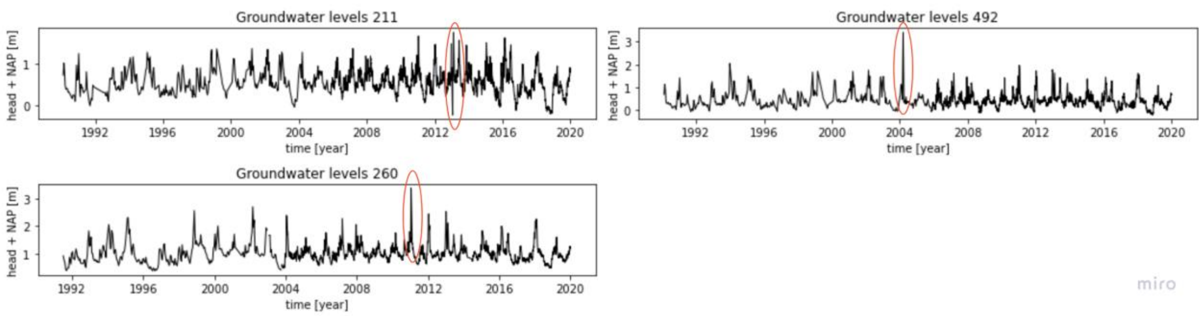

Figure 96: Distinct errors groundwater level Scheller and Oldeneler buitenwaarden

Table 14: Model performances Scheller and Oldeneler buitenwaarden

Monitoring well	Calibration		Validation	
211	*RMSE*	*EVP*	*RMSE*	*EVP*
Validation	0.07	0.91	0.14	0.76
Cross-validation	0.09	0.86	0.11	0.78
Validation 2017-2020	0.09	0.94	0.11	0.95
Final model	0.10	0.85	-	-
492				
Validation	0.09	0.91	0.07	0.94
Cross-validation	0.09	0.92	0.06	0.96
Validation 2017-2020	0.07	0.95	0.07	0.96
Final model	0.09	0.92	-	-
260				
Validation	0.12	0.86	0.12	0.84
Cross-validation	0.12	0.87	0.18	0.73
Validation 2017-2020	0.09	0.91	0.09	0.91
Final model	0.12	0.87	-	-

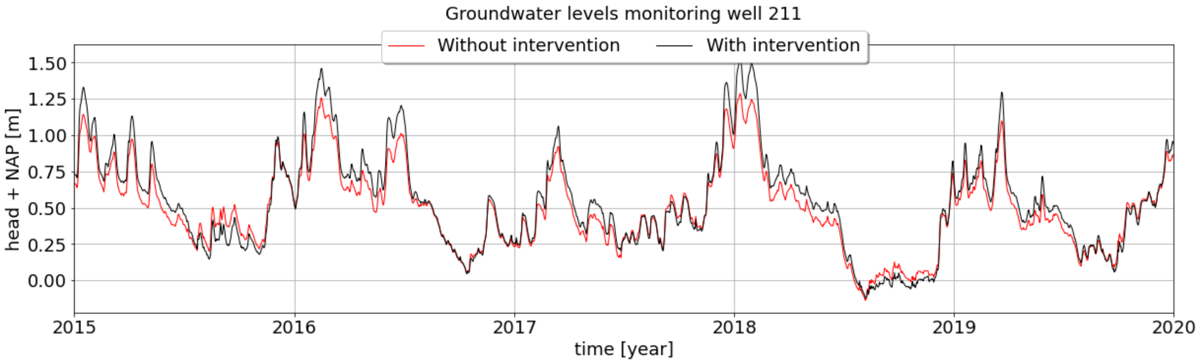

Figure 97: Forecasted groundwater levels with and without intervention monitoring well 211

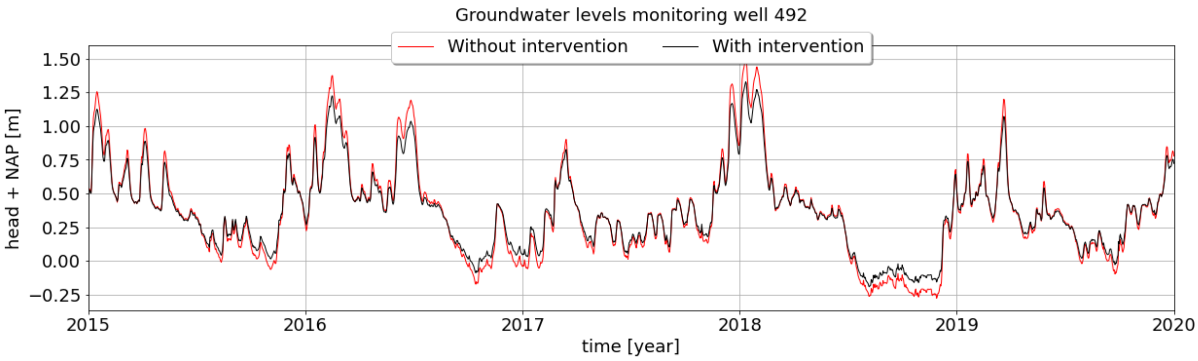

Figure 98: Forecasted groundwater levels with and without intervention monitoring well 492

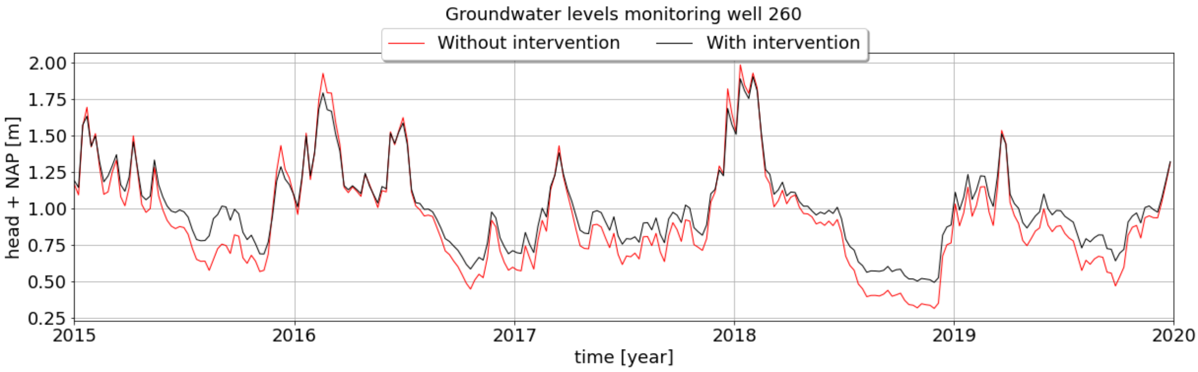

Figure 99: Forecasted groundwater levels with and without intervention monitoring well 260

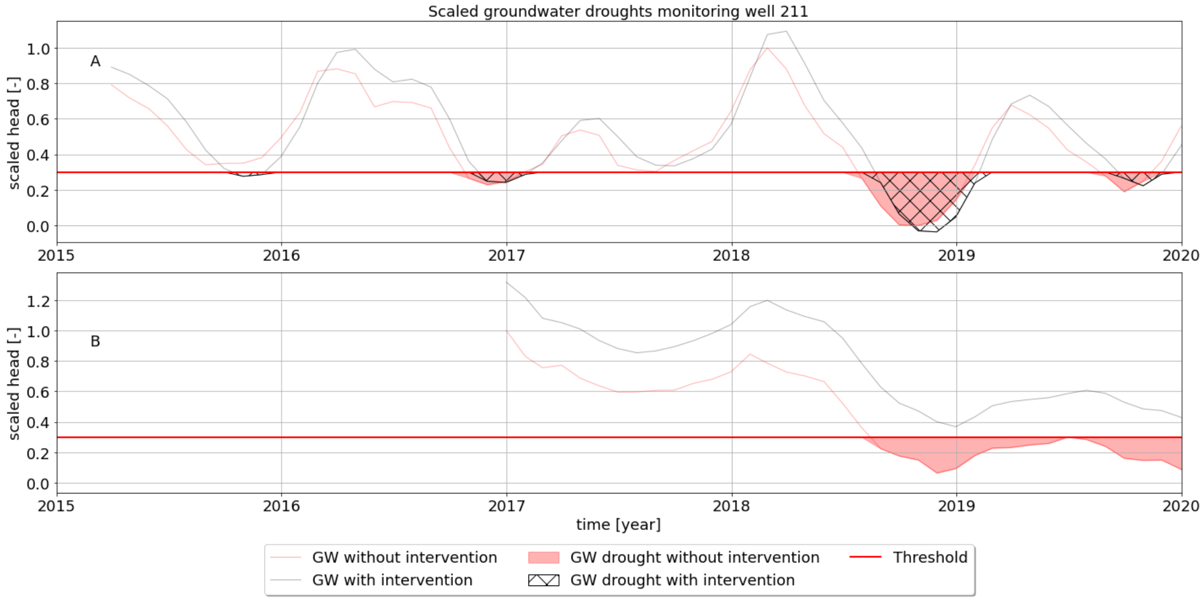

Figure 100: Scaled groundwater drought monitoring well 211 for different time scales (A = three months and B = two years)

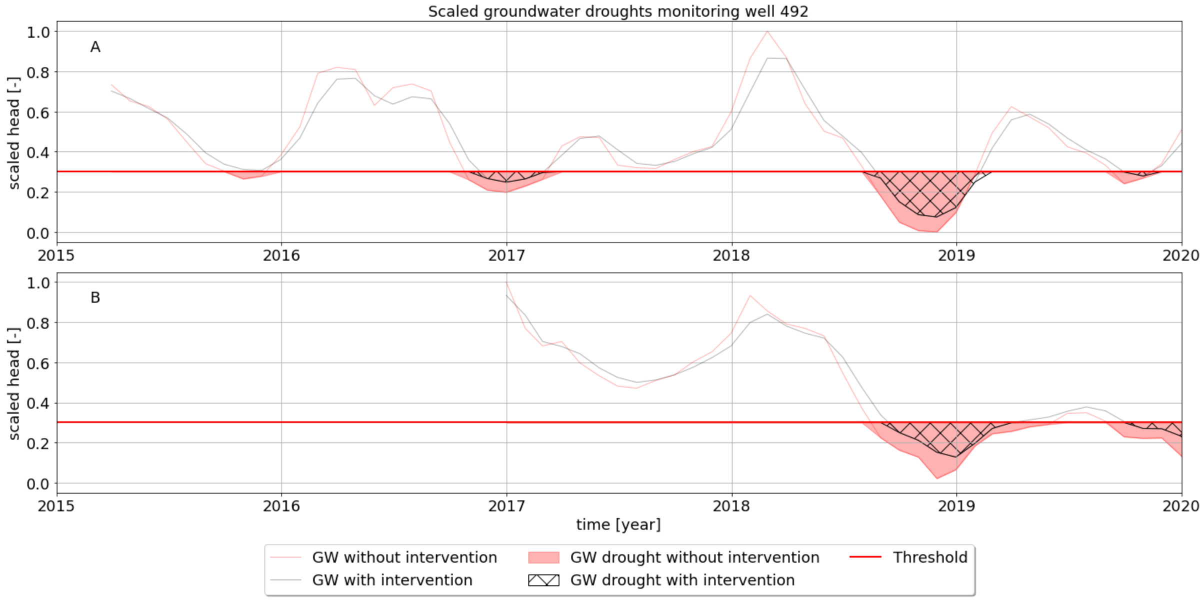

Figure 101: Scaled groundwater drought monitoring well 492 for different time scales (A = three months and B = two years)

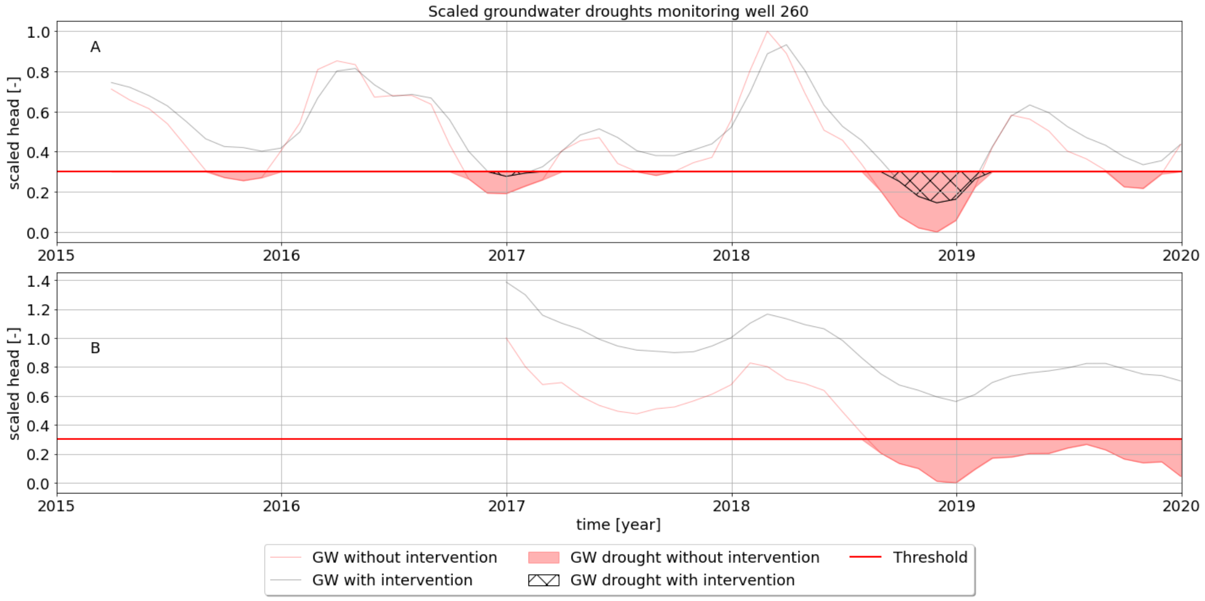

Figure 102: Scaled groundwater drought monitoring well 260 for different time scales (A = three months, B = six months, C = one year and D = two years)