The effect of climate change on groundwater level variation in De Wieden, The Netherlands

MSc Thesis

Stefan van Leijsen | March 2022

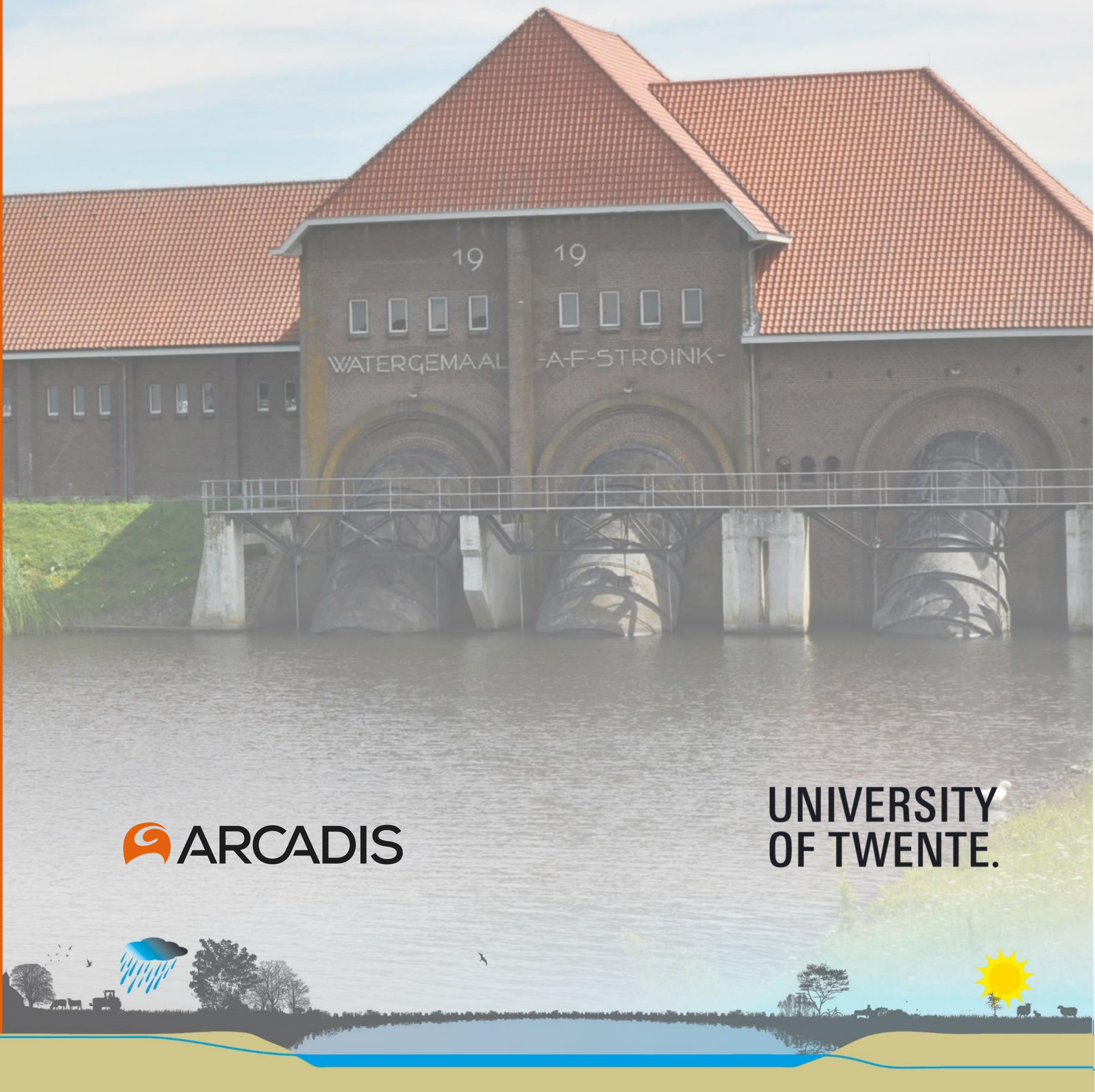

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Figure on cover page:	Pumping station Stroink, picture taken by Arjan ter Harmsel (09-03-2020)

Summary

Climate change predictions and subsequent consequences on the hydrological cycle have received increased attention over the past decades. While many studies explore climate change on global, regional, and local level the effect on groundwater levels is underexposed. However, groundwater plays an important role in meeting the demand for water availability, agriculture, and sustaining ecosystems making it is important to understand how climate change will affect groundwater levels.

The same is the case for De Wieden, a lowland peat area in the Netherlands. The area is experiencing lateral spread towards the lower situated surrounding polders and needs a supply of external water in summer to maintain the current surface water and groundwater levels in the area. How climate change predictions will influence the groundwater levels in De Wieden is highly uncertain due to the small body of knowledge surrounding climate change impact on lowland peat areas. To provide insight the following objective is formulated:

To determine the effect of climate change predictions on temporal and spatial groundwater level variation in De Wieden for 2050 and 2085 compared to a reference situation (1981-2010).

To reach this objective first the reference groundwater level (GWL) situation is determined through simulation of the 1981 to 2010 period based on spatially interpolated precipitation and potential evaporation data from daily KNMI station measurement. To simulate groundwater levels in the study area the numerical groundwater model MIPWA v3.0 is used. The model consists of the MODFLOW groundwater model coupled with the CAPSIM unsaturated zone module to simulate important hydrological processes like infiltration, capillary rise, percolation, and irrigation. Secondly, the changes in precipitation, potential evaporation, and net precipitation for 2050 and 2085 are quantified based on the four KNMI'14 climate scenarios. The KNMI'14 scenarios provide four possible future climate scenarios for the Netherlands based on the findings of the fifth IPCC assessment report focusing on the predicted change in temperature (moderate or large increase) and air current pattern (small or large change) for 2050 and 2085. Lastly, the KNMI'14 scenarios for 2050 and 2085 are simulated using the same MIPWA v3.0 model to determine the future groundwater levels and are compared to the reference situation to determine the effect of climate change predictions.

The results show that De Wieden has a shallow GWL table in the reference situation with low variation in between the years and no long-term trend. Within a year the GWL variation displays a seasonal pattern showing higher GWLs in winter and lower GWLs in summer. The KNMI'14 scenarios predict an increase in net precipitation for winter, spring, and fall but a decrease in summer for all scenarios increasing seasonality. Annually, this results in an increase in net precipitation for 2050 and 2085.

Comparing the GWL for 2050 and 2085 to the reference situation showed that there is only a small change in annual GWL and inter-annual variation with no direct relation between increased net precipitation and increased annual GWL. Within a year the seasonal GWL is expected to increase in winter and spring and decrease in summer and fall increasing seasonality for all scenarios excluding scenario 2085GL. Next to that a large decrease in net precipitation is expected to decrease GWL in multiple seasons.

Spatially, GWL variation is expected to increase slightly at the edges of the study area while the center is not influenced for all scenarios. This is a result of the large presence of surface water in the area with a constant surface level keeping variation next to the surface water to a minimum through lateral spread.

Concluding, this study showed that the effect of climate change on groundwater level variation in De Wieden, a lowland peat area with an annual precipitation surplus and large presence of surface water, is limited when the surface water level can be maintained throughout the year.

Preface

Before you lies the Master's thesis "Determining the effect of climate change on temporal and spatial groundwater level variation in lowland peat areas: A quantitative case study in De Wieden, the Netherlands". This research has been carried out to complete the master track Integrated Water Management at the University of Twente. This research was conducted part-time at Arcadis from August 2021 to February 2022.

This Master's Thesis was carried out together with support of my supervisors from Arcadis, Arjan ter Harmsel and Nico Bakker, and my supervisors from the University of Twente, Martijn Booij and Rick Hogeboom. I would like to thank my supervisors for their guidance during this process. Next to that I would like to thank Marloes Arens and all other colleagues at Arcadis for sharing their expertise and experience about the model or study area.

In hope you enjoy reading this report.

Stefan van Leijsen

February 2022

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ABBREVIATION	EXPLANATION
GWL	Groundwater level
GL	Ground level
CV	Coefficient of variation
AHG	Average highest groundwater level
ALG	Average lowest groundwater level
IPCC	Intergovernmental Panel on Climate Change
KNMI	Royal Netherlands Meteorological institute (Koninklijk Nederlands Meteorologisch Instituut)
NAP	Normal Amsterdam level (Nieuw Amsterdams peil)
RQ	Research Question

1. Introduction

1.1. Background

Climate change projections and subsequent consequences have received increased attention over the past decades. With many studies exploring climate change and its impact on global, regional, and local level. But the effect on groundwater is still underexposed (Van der Gun, 2012). Within the field of climate change research, the International Panel on Climate Change (IPCC) provides regular assessments for global climate change including the most recent climate change predictions. These reports often form a basis for the policy of many countries. However, the translation of climate change projections to groundwater is often not, or barely, addressed. For example, the IPCC Fifth Assessment report (IPCC, 2015) only states that climate change will reduce groundwater resources in most dry subtropical regions intensifying competition for water among sectors. Regional climate studies often only provide a general, qualitative, description of the resulting groundwater change. For example the KNMI'14 scenarios (KNMI, 2015) provides detailed predictions for twelve climatological variables, temperature, including precipitation, sea level rise, and wind. But these predictions are not translated to a qualitative or quantitative influence on surface water and groundwater levels. However, groundwater resources play an important role in meeting the demands for drinking water, agriculture, industrial activities, and sustaining ecosystems making it important to understand how climate change predictions will affect groundwater (Green et al., 2011).

The key interactions between groundwater and climatological variables are precipitation, temperature, and evapotranspiration affecting groundwater recharge (Dragoni & Sukhija, 2008). Therefore, climate change causing these variables to change influence groundwater levels as well. A recent study on the influence of evapotranspiration on groundwater under warming over the contiguous United States by Condon et al. (2020) showed that warming reduces the groundwater storage in which the effect is most evident in areas with shallow groundwater storages. Kotchoni et al. (2019) analyzed the relationship between rainfall and groundwater recharge in three different regions. In this, all three regions showed a strong correlation between inter-annual rainfall variation and groundwater storage. The effect of decreasing precipitation due to climate change can result in a significant increase in the abstractions of groundwater to maintain the desired water usage, amplifying the depletion of the aquifers (Romano et al., 2014). In peatland the effect of climate change was assessed by Berry & Butt (2002) on a peat bog in Britain showing that the water levels will increase in winter and spring and lower in summer and fall. Next to that Kont et al. (2007) and Kažys et al. (2015) assessed the effect of changed climatological variables on wetlands in respectively Estonia and Lithuania showing only little changes in groundwater levels. This shows that each peatland reacts differently on climate change and is mainly dependent on the local characteristics.

To assess the effect on groundwater levels in an area, models are most often used. The main ways to investigate groundwater flow using a model have been by means of a physical (scale) model, analogue model, or by means of a mathematical method (Pinder, 2000). Since than the numerical model based on the mathematical finite difference method (FDM), finite volume method (FVM), and the finite element method (FEM) has been widely used (Zhu et al., 2012). Currently the most used models are MODFLOW (USGS, 2021b), FEFLOW (Diersch, 2014), and SUTRA (Kumar, 2015).

1.2. State of the art

Climate change impact studies including or focussing on groundwater are most often focussed on a local system. Different studies focussing on South Korea (Lee et al., 2014), Punjab (Kaur et al., 2013), and the Colorado river basin (Tillman et al., 2016) show that a local focus allows the specific features of the local area (e.g. topography, subsurface, abstractions, and climate) to be included in the assessment resulting in accurate predictions of groundwater levels and flow. These location specific features are crucial in assessing the groundwater situation in an area. In these studies, a semi 3-d numerical model was combined with data from climate prediction models to simulate groundwater levels. Often the climate prediction models have a course spatial resolution requiring the application of downscaling methods as described in Trzaska & Schnarr (2014). Sophocleous & Perkins (2000) and Batelaan & De Smedt (2001) used MODFLOW to assess the effect of climate change on groundwater. Advantages from MODFLOW are the smaller input data requirements, use of readily available data and the increased flexibility in stream-aquifer interaction.

As stated in the background the knowledge is present to simulate groundwater levels and predict climate change, but the combination is highly location specific and requires a tailored approach for each new area.

1.3 Problem description

From the background and state of the art it became clear that the effects of climate change on groundwater levels in lowland peat areas have received little attention so far. There have been a few pilot studies (e.g. Santoni et al. 2021) but most studies focus on the possible emissions of greenhouse gasses or surface water in peatlands leaving groundwater level assessment undervalued. As became clear from the background, modelling approaches for assessing climate change impacts on groundwater levels are present as there are many studies focussing on groundwater levels and flow in different areas, meaning it is possible to assess the effect of climate change on groundwater levels.

To further expand the knowledge base of the effect of climate change on groundwater levels a case study is carried out in a lowland peat area in the Netherlands called De Wieden. In this area, little to no research has been carried out assessing the effect climate change will have on groundwater level variation. Due to the construction of the Noordoostpolder (1941) located to the west of De Wieden and subsidence of surrounding polders an increase in the lateral spread of groundwater leading to lowering of 0.2 to 0.8 m in the groundwater level has occurred between 1952 and 1975 (van Wirdum, 1990). The current solution to the increased lateral spread and drought during dry summers is an inflow of water from the Vollenhovermeer through pumping station Stroink. In dry summers (e.g. 2003) this inlet of water can build up to a third of the total amount of water present in De Wieden but is undesirable as the water quality parameters do not match the desired water quality of De Wieden (Natuur en Milieu, 2017).

Therefore, this research will focus on the influence medium and long-term climate change predictions for 2050 and 2085 can have on groundwater levels, using De Wieden as a case study. This will form a solid basis for further research on the influence of climate change for different user functions in the area.

1.4. Research objective and questions

Based on the background, problem description, and research gap the research objective of this study is defined:

To determine the effect of climate change predictions on temporal and spatial groundwater level variation in De Wieden for 2050 and 2085 compared to a reference situation (1981-2010).

In this study, the focus years 2050 and 2085 are chosen as these represent the near future (ca. 30 years) and far future (ca. 65 years) and are also focus years for the KNMI'14 scenarios. For assessing situations beyond 2085 the current climate change predictions include much uncertainty making it difficult to provide reliable predictions. To simulate groundwater levels in the study area, the numerical groundwater model MIPWA v3.0 is used. This model is chosen as it has a reference model covering a larger area including De Wieden and is applied in different studies in De Wieden and De Weerribben. To reach the objective of this study and guide the research, three research questions have been formulated:

RQ1. What is the temporal and spatial groundwater level variation in De Wieden during the reference situation?

RQ2. How will the current climate change predictions for 2050 and 2085 change the climatological variables influencing groundwater levels?

RQ3. How do the changed climatological variables for 2050 and 2085 influence the temporal and spatial groundwater level variation in De Wieden?

The result of this study is twofold as they provide insight in the effect of current climate change predictions on groundwater level variation in De Wieden, but the method also provides a general framework for assessing the effect of climate change predictions on groundwater level variation in any area. The scope of this research is limited to assessing the effect of climate change predictions on groundwater level variation. This specific focus leaves out the consequence(s) the simulated effect might have on the user functions in the area. This choice was intentionally made because of the limited time for this study and the complex nature and relationships between different user functions in the area.

2. Study area and model description

2.1. Study area

De Wieden is a lowland peat area of 3500 ha containing large lakes and swamps and is located in the northwest of the province of Overijssel, the Netherlands (Figure 1). The area is part of the storage basins for northwest Overijssel with more than 3000 ha of open water and has an average ground level between -0.2m NAP and -0.7m NAP (Rijkswaterstaat, 2020).

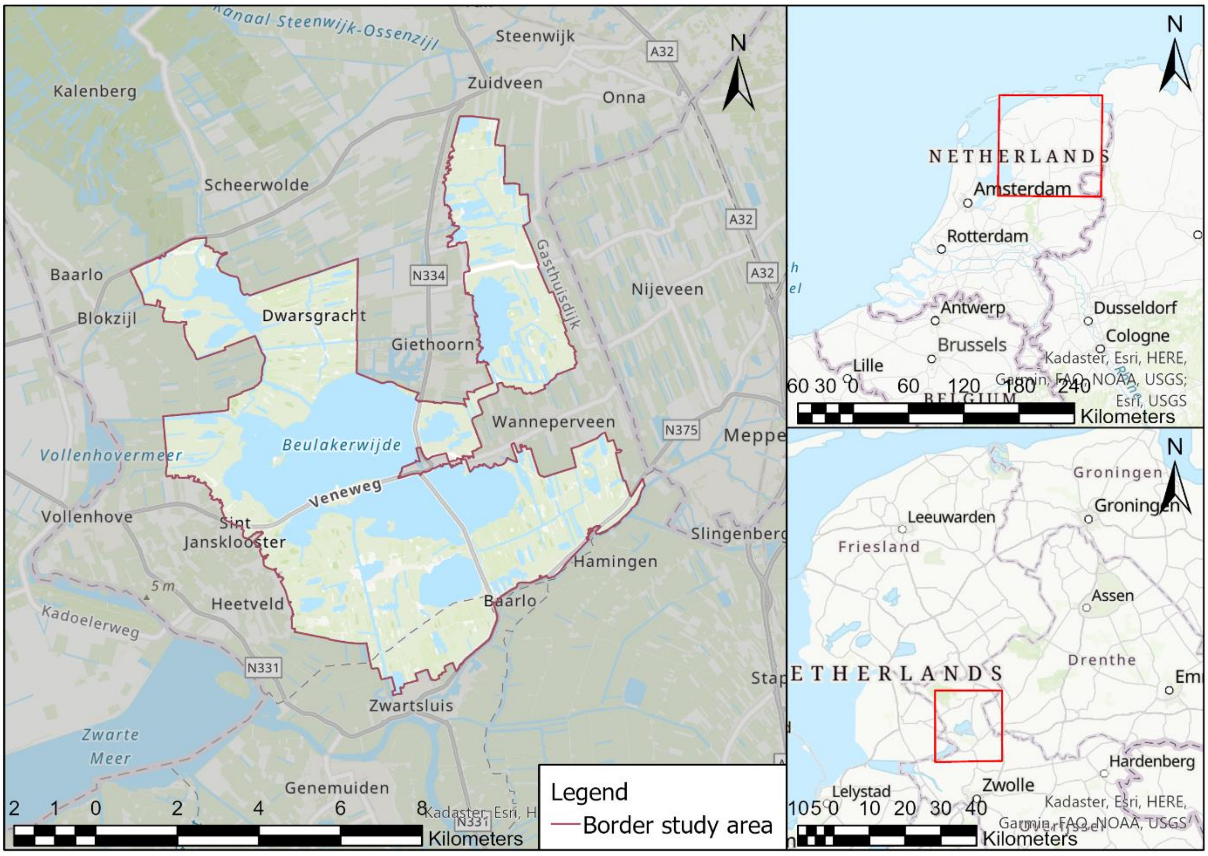

Figure 1: Location of De Wieden (left) and compared to north Netherlands (bottom right) and the Netherlands (top right)

De Wieden is part of the North Sea tectonic basin (Wood & Barton, 1983) and has a moderate maritime climate due to large influences of the north sea and the Atlantic ocean and is characterized by a rainy climate with mild winters. The area has a yearly average precipitation of around 805 mm and evaporation of around 597 mm (KNMI, 2021a) with an excess of water in winter and a shortage in summer (April-July) (van Wirdum, 1990).

2.1.1. Geomorphology

Deep subsurface

In Figure 2 a geological cross-section from the Ketelmeer to the National park Dwingelderveld is shown with the location of De Wieden illustrated. Below De Wieden, the geohydrological basis is formed by a thick sea clay layer (Breda formation) at a depth of ca. -250m NAP. Above this layer, a layer of fine to coarse sandy marine deposition up to -150m NAP is present (Oosterhout and Maassluis formation). Above this layer up to -50m NAP different river deposits from the eastern rivers containing coarse sand with local gravel deposits from the early Pleistocene is present (Peize and Appelscha formation). In the middle Pleistocene, a branch of the Rhine river system ran through the area leaving a coarse sand deposit from -50m to -30m NAP (Urk formation). After the ice age a meltwater trench formed in the area called ‘oerstroomdal van de Vecht’ from -30m to -8m NAP containing moderate to very coarse sand and locally gravel (Kreftenheye formation). At the edges of De Wieden, the Kreftenheye formation is confined by the formation of Drente also containing moderate to very coarse sand and larger rocks. On top of the Kreftenheye formation, the area is covered with a layer of fine sand between 5-10m thickness (Boxtel formation). On top of this, the Holocene cover layer consists of peat and locally clay or sand from smaller river systems. The thickness of the Holocene layer varies from 0 (absent) to several meters mainly determined by the relief of the sand layer.

As shown above there are no geohydrological significant resistant (low permeability) layers present in the deeper subsurface up to ca. -250m NAP (start of Breda formation). This results in the subsurface being a large permeable ‘sandpit’ with coarse to very coarse sand having low resistance for groundwater flow. But the top Holocene cover layer consists of peat and locally clay which have a high resistance (low permeability) for groundwater infiltration meaning this is the restricting factor in groundwater infiltration.

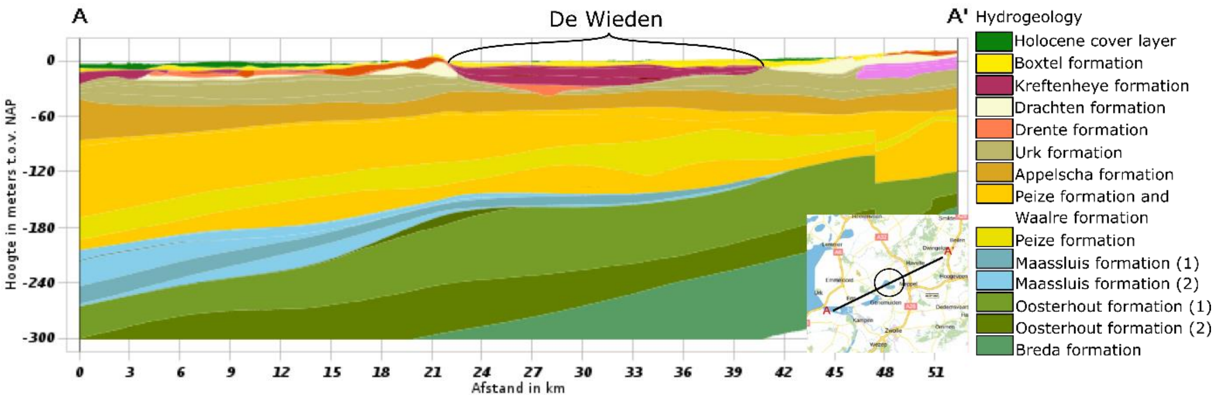

Figure 2: Geological cross section from the Ketelmeer to National Park Dwingelderveld showing De Wieden

Shallow subsurface

As explained in the previous section a peat cover layer has formed on top of the Boxtel formation. This peat layer formed due to surface water inflow from de Linde and Steenwijker Aa forming lowland and highland peat areas. Between 250 and 1500 A.D., the highland peat degraded due to climate change, sea transgression, and land use by mankind. From 1600-1900 A.D. large-scale peat excavation took place removing most of the present peat to use as stove fuel in the larger cities. Due to erosion and floods from the (at that time) Zuiderzee, clay deposition took place and larger lakes were formed. From 1919 the area started functioning as a storage basin for the surrounding (agricultural) polders. When the Zuiderzee was closed off (ca. 1930) the brackish influence disappeared from the area.

Nowadays the area mainly consists of peaty and sandy layers with a thickness of 1-3m on the southwest side and 0 to 0.5m on the northeast side. But locally the structure can be very different, for example, a peat layer can vary in thickness a lot and possibly be pierced by a waterway connecting the surface water to the water-bearing sand layers. Next to that, throughout the area, there are very impermeable layers present (gliedelagen) which often occur at the intersection of peat-sand. These large local differences in subsurface structure requires detailed information of the subsurface in the area to understand the system. The complex subsurface structure can result in large differences in the local groundwater system which can occur independently of each other.

2.1.2. Hydrological system of the study area

Since the pumping station 'Stroink' was constructed in 1919, the area of De Wieden has been used as a storage basin for surface water. Currently, the water level in the area is kept between -0.73m NAP and -0.83m NAP (Waterschap Reest en Wieden, 2007). Due to the large outflow due to lateral spread and evaporation in summer the desired water level can only be maintained due to the inlet of extra water at pumping station Stroink. Due to this difference in water inflow and outflow in summer and winter situations the flow direction in the area changes. Roughly two situations can be defined, periods with an evaporation surplus (in spring and summer) and periods with a precipitation surplus (in fall and winter). Cusell & Mandemakers (2017) provided insight in both situations based on the measurement by van Wirdum (1990) and Cusell (2014). Both situations are shown in Figure 3 and Figure 4.

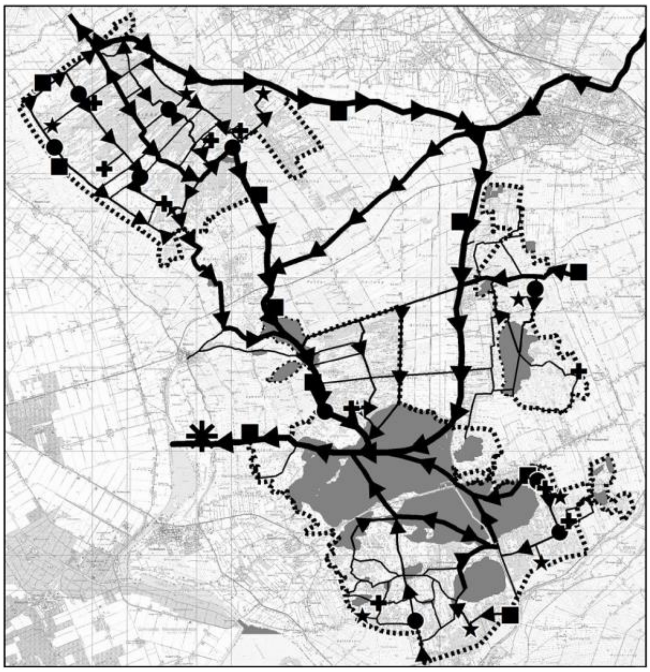

Figure 4: Flow direction and magnitude in national park Weerribben-Wieden during a precipitation surplus period (Cusell & Mandemakers, 2017)

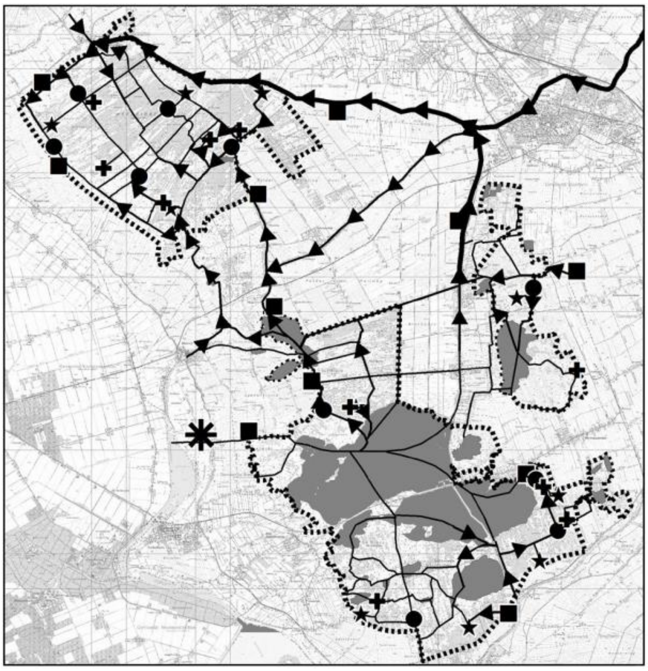

Figure 3: Flow direction and magnitude in national park Weerribben-Wieden during a evaporation surplus period (Cusell & Mandemakers, 2017)

2.1.3. Current use

Based on the LGN6 land use in De Wieden consists for 9% out of agricultural grasslands, 55% nature, 34% fresh water and 2% urban area (Hazeu et al., 2012). In and surrounding De Wieden the agricultural areas are often private property and are used for grassland, grazing livestock, or crops (Dotinga & Bodde, 2018b). From a water system perspective, these agricultural practices often abstract groundwater and surface water for irrigation. Next to the agricultural practices part of the nature area in De Wieden is used for reed cultivation. This occurs for a large part on leased land from Natuurmonumenten or Staatsbosbeheer. To grow the reed, the fields are irrigated with surface water in the summer, and in winter the water level cannot be too high to harvest the reed. Next to that, there are several villages in and surrounding De Wieden. Villages like Belt-Schutsloot and Dwarsgracht are located in the heart of De Wieden and are inseparably linked to the nature surrounding them.

2.2. Model description

2.2.1. Conceptual model

To simulate groundwater levels the regional quasi-3D MIPWA v3.0 groundwater model is used (Snepvangers et al., 2007). The MIPWA groundwater model consists of the MODFLOW groundwater model coupled with the CAPSIM unsaturated zone module. In the MODFLOW model the most important processes to simulate groundwater flow are modelled and are shown in Figure 5. By coupling these processes with the detailed CAPSIM unsaturated zone module (replacing the groundwater-surface water interaction in MODFLOW) the MIPWA model provides a detailed simulation of the groundwater-surface water interactions com.

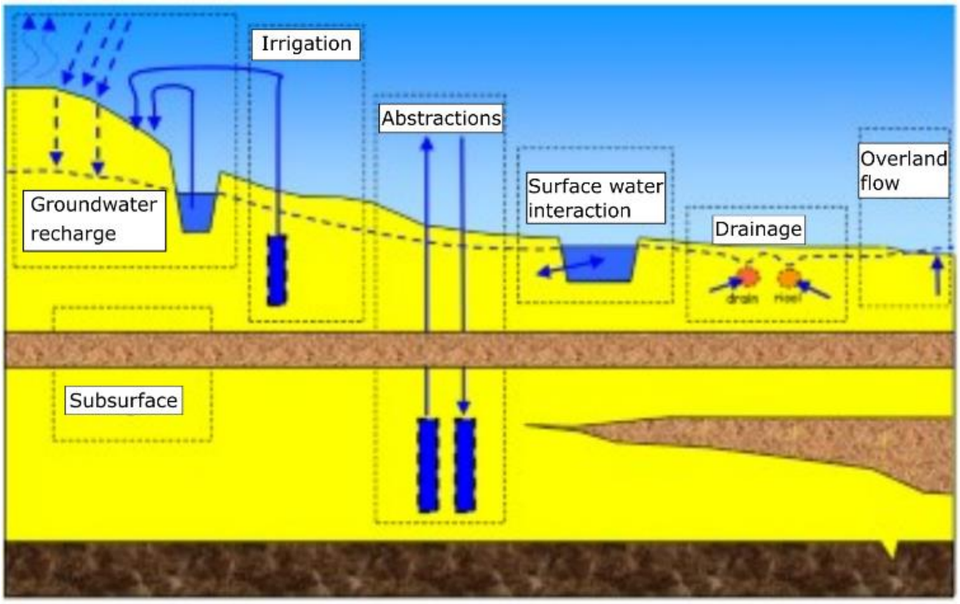

Figure 5: Modelled processes in the MIPWA/MODFLOW groundwater model

The MODFLOW model, intended as a groundwater-flow simulation code when published in 1984 provided to be a robust framework for the integration of additional simulation capabilities (USGS, 2021b). MODFLOW consists of a block-centred finite-difference model that simulates flow in two or three dimensions. The model is split up in different 'packages' which simulate a specific feature of the hydrological system (e.g. river flow, wells, drainage, etc.). The latest version is MODFLOW 6 which is an object-oriented program and framework with the possibility to combine different models and model types. Within MODFLOW 6 there are two types of hydrological models: the Groundwater flow (GWF) model focussed on water quantity and the Groundwater Transport (GWT) model focussed on water quality (USGS, 2021a). In this study the GWF model is used in which the generalized control-volume finite-difference (CVFD) based on the continuity equation is used. In this approach a cell can be hydraulically connected to any number of surrounding cells. In the GWT model three-dimensional transport of a single solute species in flowing water is simulated. This model solves the solute transport equations using numerical methods and a generalized CVFD approach.

The CAPSIM module can simulate an area including plant-atmosphere interactions, soil water, groundwater, and surface water. In this module, groundwater levels are calculated based on the conceptual model provided in Figure 6 (Snepvangers et al., 2007). In this model the driving force is the atmosphere in which precipitation and potential evaporation are input in the model.

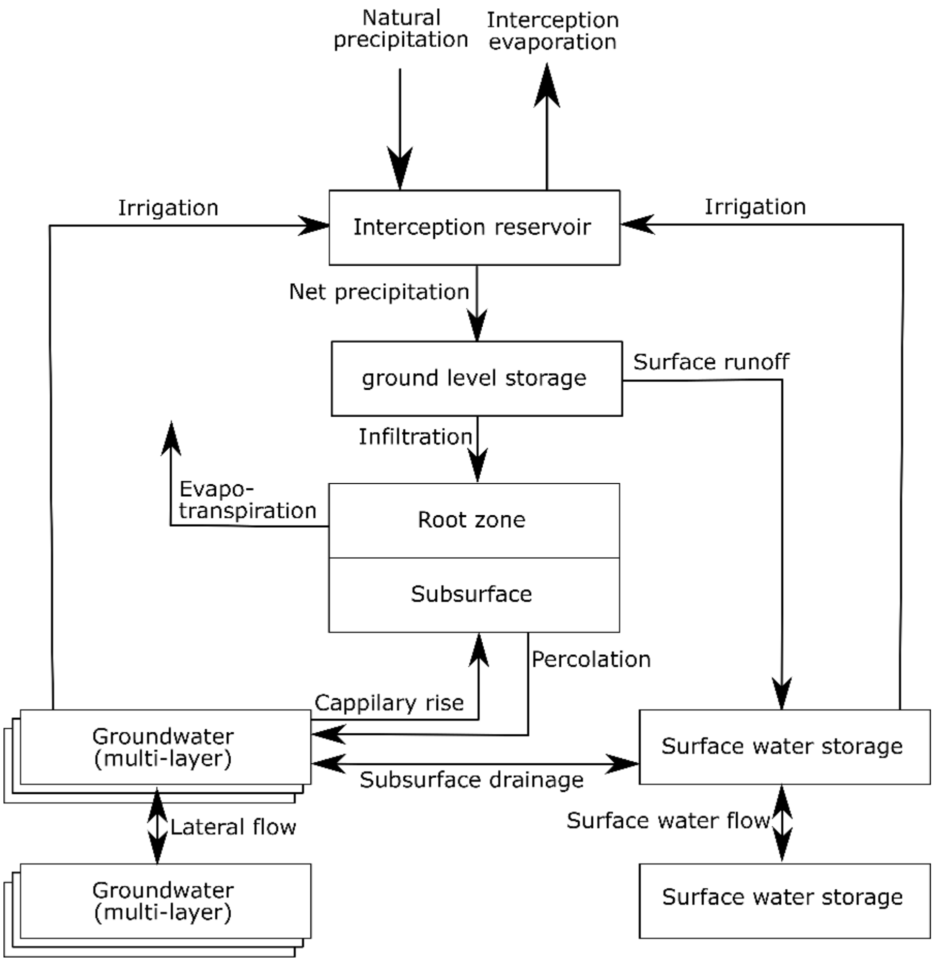

Figure 6: Conceptual model for simulating groundwater recharge using the CAPSIM module (Snepvangers et al., 2007).

2.2.2. Model assumptions and simplifications

Using a model to simulate groundwater levels inevitably results in the implementation of a set of assumptions and simplifications of reality. The main assumptions and simplifications made in this study are explained below.

Boundary conditions

Each model simulates a certain area called the model extent. At the boundary cells a value must be prescribed throughout the entire simulation time for each subsurface layer in the model. This value is determined by a stationary model simulation for the entire north-east of the Netherlands based on the input from 2000-2014 (Hunink & Borren, 2018).

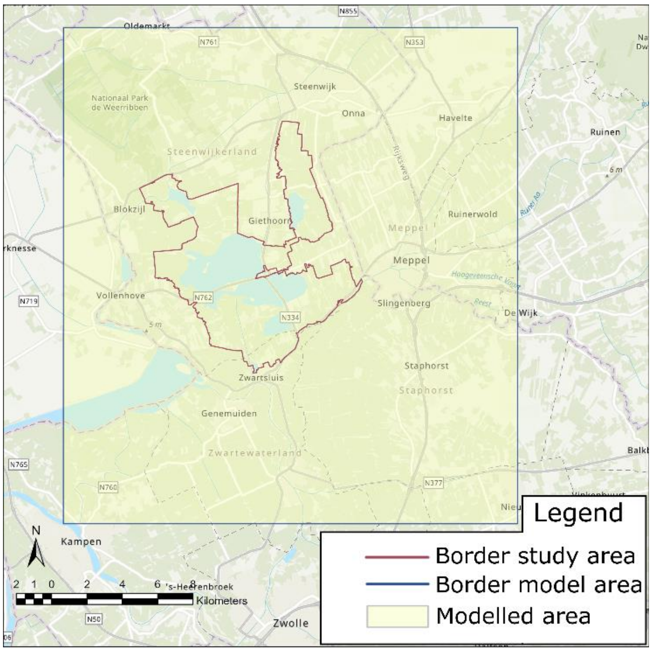

Figure 7: Study area and modelled area

To prevent the assumed boundary values influencing the simulated groundwater levels in the study area a buffer area surrounding the study area is included between the study area and the model boundary. The buffer area implemented in this study is 4 km wide (roughly a third of the study area extent). With this buffer area the entire regional surface water and groundwater system is implemented within the model area ensuring the boundary conditions do not influence the model results. This results in the model domain of 23 km horizontally and 24.5 km vertically as shown in Figure 7.

Grid

In the MIPWA model cell sizes as small as 25 m cell size can be implemented and is frequently used. In this study the cell size is set to 50 m for the entire model domain resulting in a grid of 460 by 490 cells and 9 vertical subsurface layers. The 50 m cell size is implemented due to computational and storage limitations. A comparison between the 25m and 50m cell sizes is provided in Appendix D – Model simplifications.

Initial conditions

The initial conditions in a numerical model are a set of starting-point values for the first timestep. These values are imposed upon the model for the first timestep providing a reference situation for the simulation to start. Applying accurate initial conditions is important for the model to provide correct results in the beginning of the simulation.

In this study the initial conditions consist of starting heads for each cell and each model layer. For the starting heads, the resulting heads from a stationary model run using the average precipitation and evaporation input from 2000-2014 is used. The period 2000-2014 is used as this is a period that is considered to be representative for the current situation (Hunink & Borren, 2018). To be able to compare the climate change scenarios to the reference situation the same starting heads are used for each simulation.

Surface water level

During a simulation the surface water level in lakes and waterways is assumed to maintain the desired level the waterboard has for the area. This assumption is used as implementing a variable surface water level for future scenarios is very complicated and subject to human decision making. For the reference situation there would be data available to model this but there is no such data available for the future scenarios. Therefore, the decision is made for a constant surface water level to be able to compare the different future scenarios and reference situation.

This means that the desired summer and winter surface water level will be maintained independent from the amount of precipitation and evaporation. This is a realistic assumption as pumping station Stroink can discharge or supply sufficient water to or from the IJsselmeer throughout the entire year.

Drinking water withdrawals

Within the modelled area there is one drinking water company called Vitens withdrawing water from the subsurface at 2 locations for household use, each location has multiple extraction points. The first location is to the northeast ca. 3 km outside of the study area near Meppel. The second location is to the west of the study area located against the border of the study area near Sint Jansklooster. For each location there are half year averaged abstraction volumes available from 1989-2005 and daily abstraction rates from 2006-2014.

To be able to compare the future scenarios (with no abstraction data) to the reference situation a fixed daily abstraction volume is used for the entire model period for each simulation based on the average daily abstraction volumes from 2006-2014.

3. Method

In this chapter the method used to answer the different research questions is presented. An overview of the main steps taken to answer each research question is shown in Figure 8.

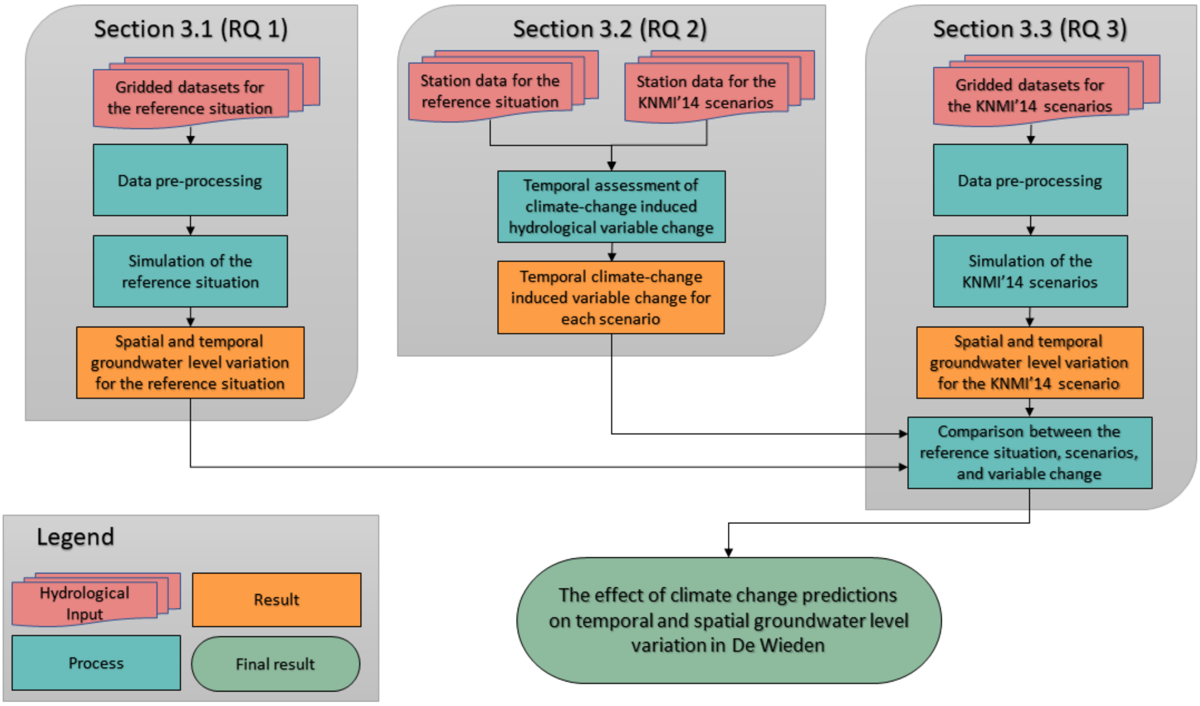

Figure 8: Flow chart representing the method used in this study in schematic steps

3.1. Simulation of the reference situation

To simulate groundwater levels in the study area for the reference situation, the MIPWA v3.0 groundwater model as described in section 2.2 is used. Daily measured precipitation and reference evaporation values from 1981-2010 (a 30-year period) by KNMI stations surrounding the study area are implemented in the model as input. The evaporation values are calculated using the Makkink equation (KNMI, 2006). The Makkink equation transforms the measured global radiation and temperature values to reference evaporation.

The daily precipitation data is measured at 294 measuring stations spread throughout the Netherlands (Sluiter, 2014). Soenario & Sluiter (2010) spatially interpolated the measured data to a 1 km cell size for the entire Netherlands using ordinary kriging and is made publicly available by the KNMI (KNMI, 2014b).

The daily temperature and global radiation data is measured at 14 locations spread throughout the Netherlands (Sluiter, 2014). This is transformed to reference evaporation using the Makkink equation by hiemstra & sluiter (2011) and spatially interpolated by Soenario & Sluiter (2010) using Thin Plate Spline Interpolation resulting in a reference evaporation dataset of 1 km cell size for the entire Netherlands and is made publicly available by the KNMI (KNMI, 2014a). The 14 locations is limited for spatial interpolation but due to the uniform distribution of reference evaporation it is sufficient (Sluiter, 2008).

Before the interpolated daily precipitation and reference evaporation datasets from the KNMI are implemented in the model, the datasets are pre-processed to check for missing values and outliers. To check for missing values, each dataset is checked for negative values and NaN values. If a NaN value occurs, the average value of that dat is taken as a new value for that cell. If a negative value occurs this value is replaced by 0. To check for outliers in the data, a more complex method is required. The main issue is that a precipitation dataset can contain mixed distributions or multiple populations which makes univariate probability distributions unsuitable to check for outliers (Amin et al., 2015). To check for outliers the Quality-Control test method is used as described by Kondragunta (2001). This method was tested by Asikoglu (2017) and resulted in the best outlier detection for extreme values series together with box-plot tests. The same method is used for reference evaporation which also occurs in accurate outlier detections. The Quality-Control test method is explained in Appendix A – Quality-Control test method (outlier detection).

After simulating the reference situation, the result is a dataset containing daily groundwater level values for each cell and each subsurface layer from 1981-2010. From this dataset the phreatic layer (top groundwater level) is extracted. As the groundwater level in an area varies in spatial and temporal dimensions, a set of statistical indicators partly taken from Ritzema et al. (2012) that allow the user to classify the simulated groundwater levels on a temporal and spatial basis. The different indicators are explained below.

3.1.1. Temporal groundwater level variation assessment

To assess the temporal GWL variation in the area the inter-annual variation and intra-annual variation are assessed. The statistical indicators used to assess both timescales are explained below.

Inter-annual variation

The annual variation is assessed by calculating the spatially averaged annual GWL, trendline over the 30-year period, and inter-annual coefficient of variation (CV).

The spatially averaged annual GWL is calculated by first averaging all grid cells in the study area for each time step excluding all surface water grid cells resulting in a single characteristic GWL value for each day. Next the annual average GWL is calculated by averaging the daily GWL values over the entire modelling period (30 years).

The trendline is calculated by fitting a linear line through the modelling period using the method described by Hussain et al. (2016). From this linear trendline it can be determined if there is an increasing, decreasing or no trend present during the modelling period. The linear trendline is chosen to prevent the influence of seasonality and noise and purely focus on the 30-year trend.

The inter-annual CV is an indicator quantifying the variation in between years by dividing the standard deviation over the average of the dataset. This results in the following formula:

$$\frac{\sqrt{\frac{\sum\left|x_i - x_{average}\right|^2}{n}}}{\frac{\sum x_i}{n}} \qquad \text{[Eq 1]}$$

In which x_i is each spatially averaged annual GWL, $x_{average}$ is the average GWL of the dataset, and n is the total number of GWL points. Using this formula, the variation in between years is calculated. In this study the inter-annual CV is calculated using the spatially averaged annual GWL for the entire modelling period (n=30).

Intra-annual variation

The seasonal variation is assessed by calculating the spatially averaged seasonal GWL and the intra-annual coefficient of variation (CV).

The spatially averaged seasonal GWL is calculated by first averaging all grid cells in the study area for each time step excluding all surface water grid cells resulting in a single characteristic GWL value for

each day. Next the seasonal average GWL is calculated by averaging the daily GWL values over each climatological season for the entire modelling period (30 years). In the climatological season division, each season is three subsequent months in which each season starts on the first date of the month. This provides the ability to compare the different seasons with each other as opposed to the astronomical calendar in which each season sometime start on a different date (e.g. winter usually starts on 21 December, but sometimes on the 20th or 21st). The climatological season division was introduced by the Societas Meteorologica Palatin in 1780 and is widely used (Cassidy, 1985).

The intra-annual CV is an indicator quantifying the variation within a year using the same formula as used for the inter-annual CV. In this study the intra-annual variation is calculated using the spatially averaged monthly GWL (Jan1981, Jan 1982, …, Jan 2010) for the entire modelling period (n=12). This results in the following formula.

The resulting seasonal GWL and intra-annual CV are assessed in detail providing an overview of the temporal variation for the reference situation.

3.1.2. Spatial groundwater level variation assessment

To assess the spatial GWL variation in the study area the average highest groundwater level (AHG) and average lowest groundwater level (ALG) are used. The AHG and ALG are indicators that characterize the average annual fluctuation in groundwater levels (ten Cate et al., 1995). In the Netherlands the AHG is an indication of the GWL situation in winter and the ALG is an indication for the GWL situation in summer.

To be able to calculate the AHG and ALG for an area the groundwater levels have to be measured every two weeks for a period of at least 8 hydrological years (1 April-31 March) in which no interventions occurred (Ritzema et al., 2012). If these criteria are met the AHG and ALG are calculated by taking the average of the three highest (or lowest) groundwater levels of a hydrological year and averaging these yearly values over the number of hydrological years simulated. As input for this calculation, traditionally, the measured groundwater level on the 14th and 28th day of each month is used (in total 24 measurements for each hydrological year).

In this study the GWLs are simulated using MIPWA resulting in daily GWL values for a 30-year period in which no interventions have occurred making the results qualified to be transformed to AHG and ALG. To calculate the AHG and ALG the simulated GWL on each 14th and 28th day of the month is used as input (in total 24 measurements for each hydrological year). Taking only the 14th and 28th day of the month neglects most of the results but provide a good image of the GWL over a period of several weeks. E.g. by using daily measurements there is a large chance that the three highest orlowest GWLs are consecutive days only showing a single extreme situation. Next to that using only the 14th and 28th day is in line with the traditional method for calculating the AHG and ALG upon which many policy documents are based. An example of the use of AHG and ALG is shown in Figure 8.

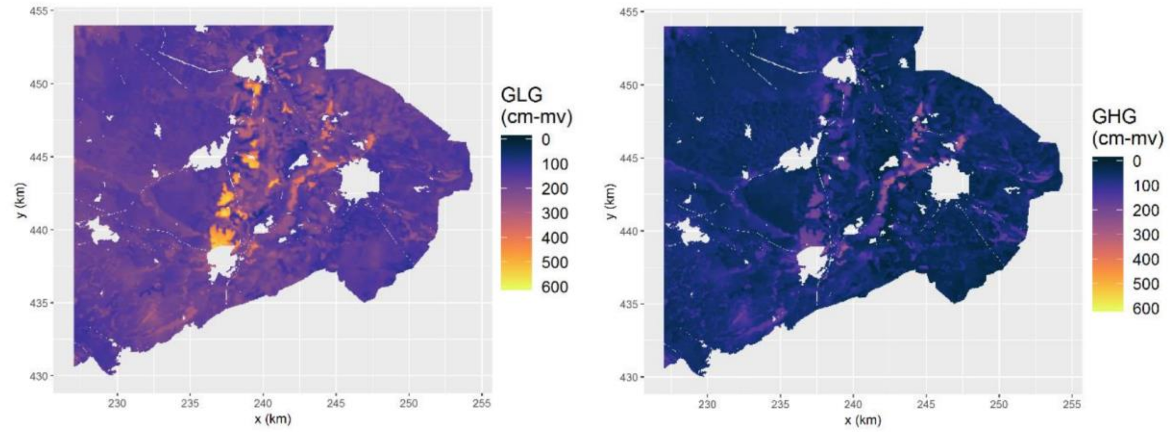

Figure 9: AHG (GHG) and ALG (GLG) in de Achterhoek near Aalten and Winterswijk from a study mapping the groundwater dynamics in the high part of the Netherlands (Knotters et al., 2018).

After the AHG and ALG are calculated for the study area, the resulting maps are assessed and compared to the summer- and winter drainage level (drooglegging) in the area. This allows for the spatial variation in GWL to be identified separate from changes in the ground level. If large differences are observed between parts of the study area that indicate that the GWL variation significantly differs between those parts, the temporal assessment must be carried out for each of these areas individually.

3.2. Influence of climate change on climatological variables

Within the large body of knowledge focussing on climate change predictions, the KNMI’14 scenarios are used as input for this study (KNMI, 2015). The KNMI’14 scenarios provide predictions on possible future climates for the Netherlands focusing on 2050 and 2085 based on the findings of the fifth IPCC assessment report (IPCC, 2015). In the KNMI’14 scenarios four possible future climates for 2050 and 2085 are formulated. Within these scenarios a distinction is made between projected temperature change (moderate increase (G) or large increase (W)) and in projected air current pattern change (low change (L) or large change (H). The four resulting scenarios are visualized in Table 1.

Table 1: Different scenario formations in the KNMI'14 scenarios

2050 & 2085	LOW AIR CURRENT CHANGE (L)	LARGE AIR CURRENT CHANGE (H)
MODERATE TEMPERATURE INCREASE (G)	GL	GH
LARGE TEMPERATURE INCREASE (W)	WL	WH

For each scenario the measured station data for the reference situation (1981-2010) is transformed to a future series based on the changes in 12 climate variables including temperature, precipitation, sea level, and wind compared to the reference situation (Bakker, 2015). In this transformation the changes in the mean climate as well as the changes in extremes are considered resulting in a 30-year dataset focussed on the time horizon 2050 and 2085. From the 12 climate variables the transformed precipitation and evaporation[1] station data is extracted for each scenario and assessed on an annual and seasonal scale.

[1] obtained by implementing the transformed temperature and global radiation data using the Makkink equation (Hiemstra & Sluiter, 2011).

On an annual scale the inter-annual CV, change in annual precipitation and evaporation, as well as the resulting change in net precipitation (precipitation-evaporation) is determined using the formulas explained in section 3.1.

For the seasonal assessment, first the change in monthly precipitation and evaporation as well as the intra-annual CV is determined for each scenario. After this the resulting change in seasonal net precipitation is determined.

The result is a set of findings quantifying how the changes in precipitation and evaporation influence the annual and seasonal net precipitation as well as the variation for each scenario compared to the reference situation. This creates a reference framework to compare the changes in GWL variation to from RQ3. Next to that, it shows what the predicted range of changes are for precipitation, evaporation, and net precipitation that can provide input for future groundwater and surface water studies in The Netherlands.

3.3. Simulation of groundwater levels for 2050 and 2085

Using the MIPWA v3.0 groundwater model the different KNMI'14 scenarios are simulated for a 30-year period. Similar to the procedures followed for the reference situation (section 3.1), for each scenario the transformed precipitation and reference evaporation series have been spatially interpolated to a 1 km cell size for the entire Netherlands using ordinary kriging by Soenario & Sluiter (2010). The result is a dataset including daily precipitation and reference evaporation values for a 30-year period and is made publicly available by the KNMI.

Sadly, the interpolated evaporation dataset for the 2085GL scenario could not be supplied by the KNMI due to human errors resulting in the loss of the dataset. In order to still be able to simulate the 2085GL scenario the transformed station data from RQ2 is spatially interpolated using the same method as used by Soenario & Sluiter (2010) for reference evaporation. To do this a model was set up in python that spatially interpolates the station data to a 1 km cell size using 2d cubic thin plate spline interpolation (SciPY community, 2015). To test if the interpolation method provides accurate results, the 2085WH reference evaporation was interpolated using the same method and compared to the dataset provided by the KNMI. To compare the two datasets a z-test is carried out comparing the average daily reference evaporation covering the modelling area. This resulted in a z value of $3.6*10^{-5}$ (threshold value = 1.96/-1.96) meaning the two datasets can be considered the same. This would mean a similar result for the 2085GL scenario is achieved.

Similar to the procedures followed for the reference situation, each daily dataset is pre-processed to check for missing values and outliers. A detailed explanation is provided in section 3.1.

After simulating the scenarios, the expected result is a 50m cell size for the study area containing daily groundwater levels for a 30-year period. The resulting GWL for each scenario is assessed using the same indicators used in section 3.1.1 and 3.1.2. After this the scenarios can be compared to the reference situation (RQ1) and change in net precipitation (RQ2) quantifying the change in GWL variation that has occurred due to the predicted climate change for each scenario. The result is a set of findings quantifying how the temporal and spatial GWL variation is influenced by climate change predictions.

4. Results

4.1. Temporal and spatial groundwater level variation in the reference situation

In the reference situation the climatological conditions from 1981-2010 are simulated using the MIPWA v3.0 hydrological model and model settings as described in section 2.2. The resulting temporal and spatial groundwater level variation are presented and discussed below.

4.1.1. Temporal groundwater level variation

Annual variation

In Figure 10, the spatially averaged groundwater level variation (excluding all surface water) over a 30-year period is shown for the reference situation in the area.

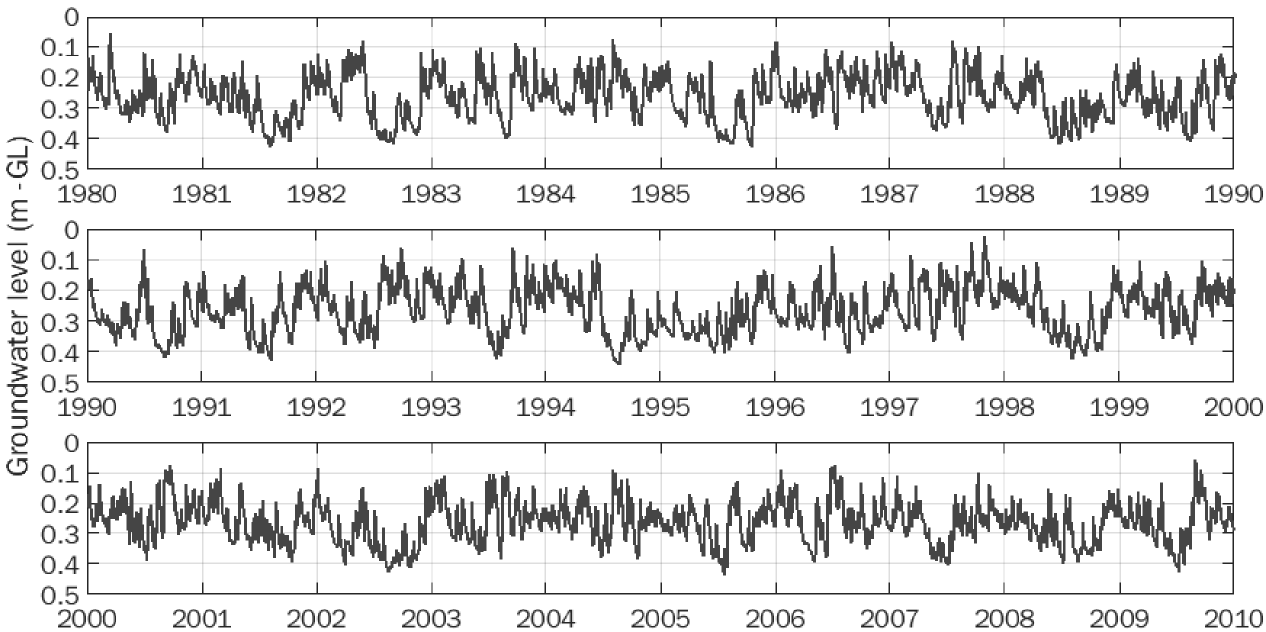

Figure 10: Spatially averaged groundwater level (m – GL) for the reference situation (1981-2010) excluding all surface water.

From Figure 10 it can be derived that the average GWL in De Wieden is 0.27 m – GL. The GWL remains steady during the reference period showing no increasing or decreasing trend. During the driest year of the reference situation (2003) the average GWL lowered with 0.05 m and in the wettest year (1998) the average GWL rose with 0.05 m compared to the average GWL. This relatively low variation in between the years results in an inter-annual CV of 0.09 (n=30) meaning the study area has low inter-annual variation.

Seasonal variation

Next to the fluctuations in GWL in between the years the GWL also fluctuates within a year (intra-annual). During the reference period the intra-annual CV is 0.09 (n=12) showing low intra-annual variation. To characterize the variation within a year the average GWL per season is shown in Table 2.

Table 2: Average GWL (m - GL) for each season during the reference situation (1981-2010)

Season	*Winter*	*Spring*	*Summer*	*Fall*
Average GWL [m- GL]	0.24	0.27	0.30	0.27
Net precipitation [mm]	+178	-7	-48	+154

Table 2 shows that the average variation within a year is 0.06 m indicating a steady GWL. The average GWL is highest in winter and lowest in summer with spring and fall forming transitional seasons. Compared to the net precipitation it becomes clear that the average GWL is directly connected to the amount of net precipitation and that a net precipitation surplus is required to maintain the current GWL levels. Figure 9 also shows that under extreme conditions the GWL can reach low values of 0.44 m -GL in summer or high values of 0.03 m -GL in fall.

Findings

From this assessment it becomes clear that the study area has a shallow GWL with low variation throughout the reference situation as both inter-annual and intra-annual CV are low. The low variation is a result of the balance between net precipitation surplus in winter and fall increasing the GWL and the net precipitation deficit in spring and fall lowering the GWL.

4.1.2. Spatial groundwater level variation

To show the spatial variations within the study area, the AHG and ALG for the reference situation are shown in meter below ground level in Figure 11. Next to that the drainage level (difference between surface water level and ground level) for the summer and winter is shown in Figure 12.

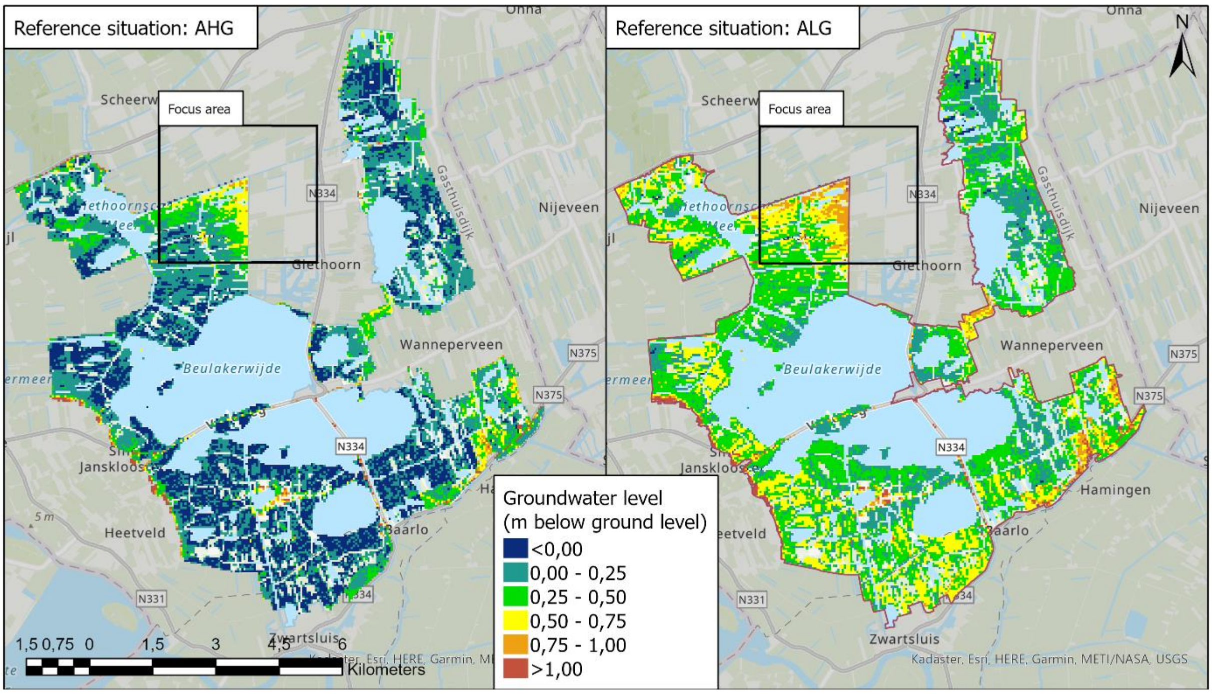

Figure 11: AHG and ALG for the reference situation (m – GL). The focus area represents an area with different GWL and is clarified below.

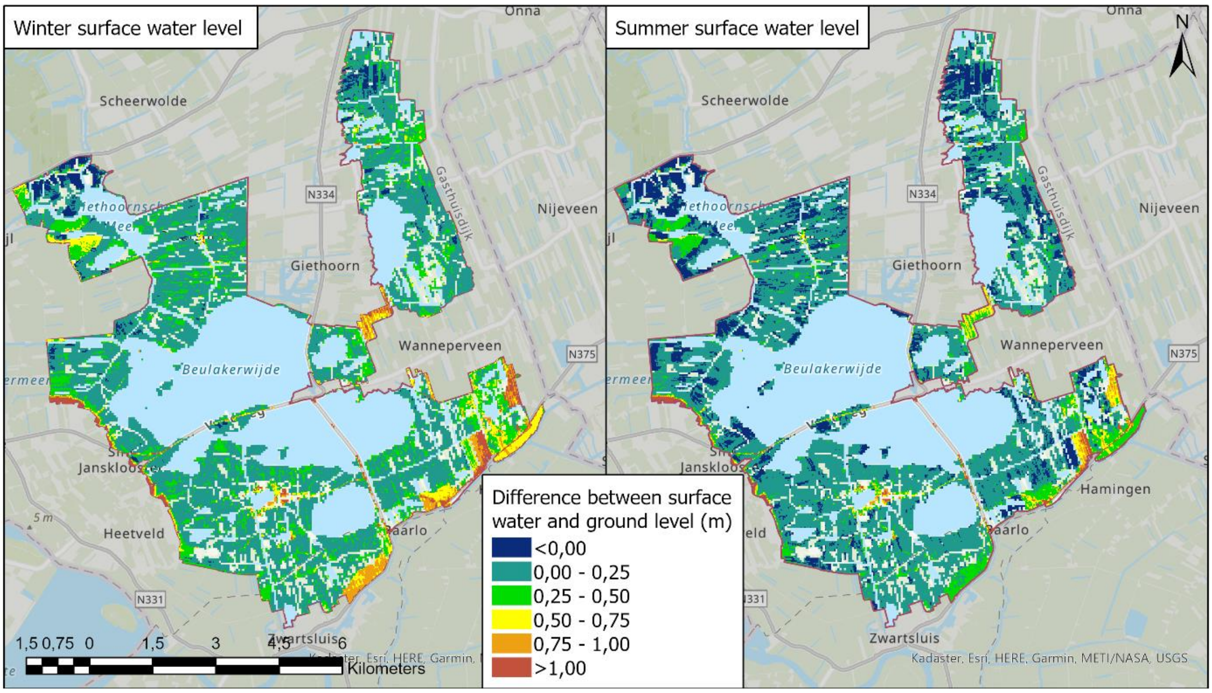

Figure 12: Summer and winter drainage level (difference between surface water level and ground level) in meter.

From Figure 11 it becomes clear that the AHG is often the same as the ground level indicating the ground is fully saturated and the area is flooded during wet periods. In the area the AHG is between 0 and 0.50 m - GL. The ALG has roughly the same spatial pattern as the AHG but is on average 0.25 m to 0.50 m lower. Overall, the AHG and ALG are closer to the ground level near open water and tend to be lower towards the edge of the study area. This is due to the increased drainage level toward the edges of the study area (Figure 12) showing that the GWL remains constant, but the ground level increases. One exception is the focus area showing abnormal behavior, this is explained below.

When comparing Figure 11 and Figure 12 one area shows a decreasing AHG and ALG compared to the ground level while the difference between surface water and ground level remains the same (focus area in Figure 11). In Figure 13 and Figure 14 this focus area is enlarged and the adjacent area outside of the study area is also shown.

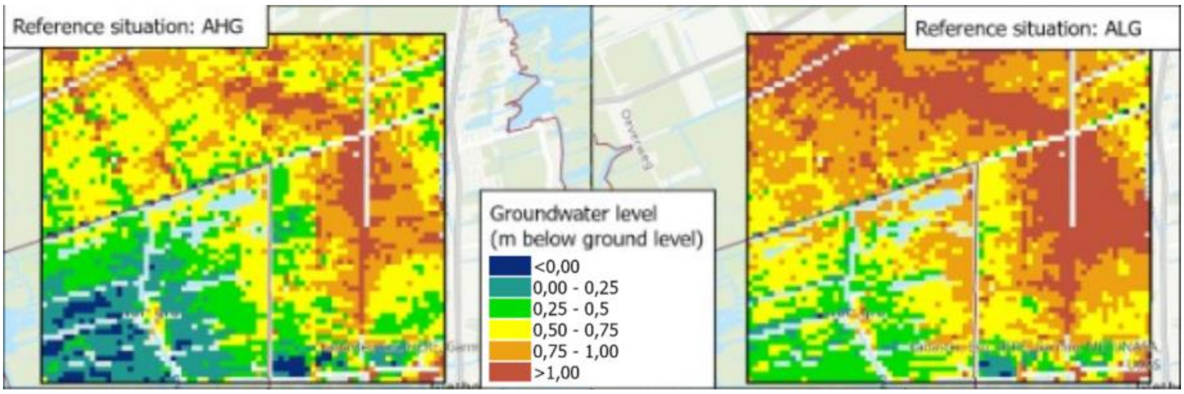

Figure 13: Close up of the focus area showing the AHG and ALG for the reference situation (m – GL).

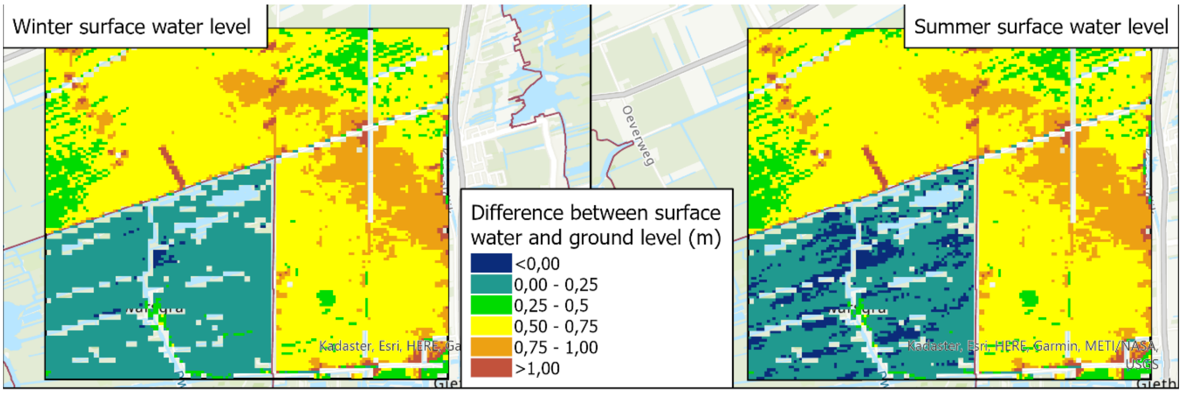

Figure 14: Close up of the focus area showing the difference in winter and summer drainage level in meter.

As can be seen in Figure 14, the difference between surface water and ground level makes a sudden drop of 0.5 m at the study area border. This is mainly due to a lower ground level outside of the study area which is currently used for agriculture. From an assessment of the subsurface layers in the model it became clear that the thickness of the first subsurface layer (peat layer) reduces in thickness from 0.5 m in the study area to 0.1 m in the agricultural area. Next to that the agricultural area has a water level of -2.40m NAP in summer and -2.75m NAP in winter as opposed to the study area having a water level of -0.73m NAP in summer and -0.83m NAP in winter.

The large differences between the two areas causes lateral flow of groundwater from the study area to the agricultural area which results in the groundwater level pattern displayed in Figure 13.

Findings

The assessment indicated that the spatial distribution of GWL in the area is relatively homogeneous. The AHG ranges between the 0 and 0.50 m – GL and shows that a large part of the subsurface is saturated (flooded) during wet periods. The ALG ranges between the 0.25 and 1.00 m – GL and follows the same pattern as the AHG. The large presence of surface water (47% of the total study area), which is artificially maintained at the desired level throughout the year, keeps the variation in areas close to open water to a minimum by providing a constant source of water (through lateral spread).

Assessing the focus area in detail showed that part of the study area is strongly influenced by lateral spread. Lower situated areas adjacent to the study area cause a withdrawal of water lowering GWL in the study area.

4.2. Predicted influence of climate change on climatological variables

The Netherlands experiences, on average, a surplus of precipitation from September to April and a deficit from May to August (KNMI, 2021b). On average there is 849 mm precipitation and 573 mm evaporation in the Netherlands (average of 102 measuring stations spread throughout the Netherlands for the reference situation 1981 to 2010) resulting in an annual surplus of precipitation. In areas dependent on rainfall for groundwater net precipitation this should result in a lower groundwater level in summer and an increased groundwater level in winter.

4.2.1. Predicted changes in the KNMI'14 scenarios

Annual variation

In Table 3 the annual precipitation, evaporation, and net precipitation and change compared to the reference situation is shown based on the KNMI'14 scenario predictions for 2050 and 2085. Next to that the inter-annual CV (n=30) is shown for precipitation and evaporation. The CV cannot be calculated for net precipitation as this is an arbitrary scale with both positive and negative values resulting in false CV values.

Table 3: Inter-annual coefficient of variation (CV) and annual precipitation, evaporation, and net precipitation for the reference situation and the change for each KNMI'14 scenarios compared to the reference situation. In the table blue represents an increase, grey no change, and red a decrease.

Focus year	*1995*			*2050*				*2085*	
Scenario	**Reference situation**	**GH**	**GL**	**WH**	**WL**	**GH**	**GL**	**WH**	**WL**
Precipitation									
Inter-annual CV	0.13	0.13	0.13	0.14	0.13	0.13	0.13	0.14	0.14
Annual [mm]	850	877	889	893	898	892	898	910	911
Change [mm]	-	+27	+39	+43	+48	+42	+48	+60	+61
Evaporation									
Inter-annual CV	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Annual [mm]	573	602	591	614	595	604	588	634	607
Change [mm]	-	+29	+18	+41	+22	+31	+15	+61	+34
Net precipitation*									
Annual [mm]	+277	+275	+298	+279	+303	+288	+310	+276	+304
Change [mm]	-	-2	+21	+2	+26	+11	+33	-1	+27

**Net precipitation is calculated by subtracting evaporation from precipitation.*

From Table 3 it becomes clear that the annual precipitation and evaporation will increase in all scenarios. This results in a net precipitation that ranges between the -2 and +33 mm showing that the annual net precipitation will increase. This should result in a slight increase in the average annual GWL, but this is highly dependent on the seasonal changes within a year. The inter-annual variation barely changes for precipitation and evaporation which means the intensity of extreme wet or dry years, compared to an average year, will not change.

Seasonal variation

In Figure 15, Figure 16, Figure 17, and Figure 18 the average monthly precipitation, evaporation, and net precipitation (precipitation-evaporation) are shown for the reference situation and as projected by each scenario for 2050 and 2085. The monthly timescale is chosen to show the pattern within a year before summarizing the results per season.

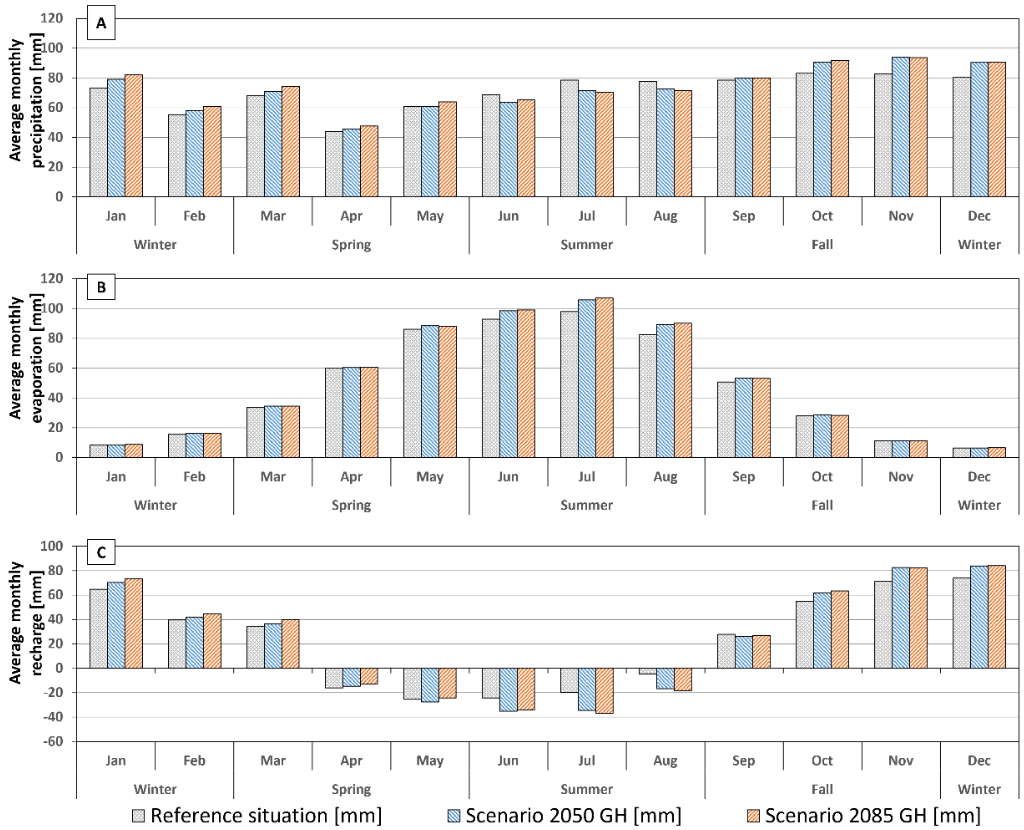

Figure 15: Average monthly precipitation, evaporation, and net precipitation for the reference situation and scenarios 2050GH and 2085GH

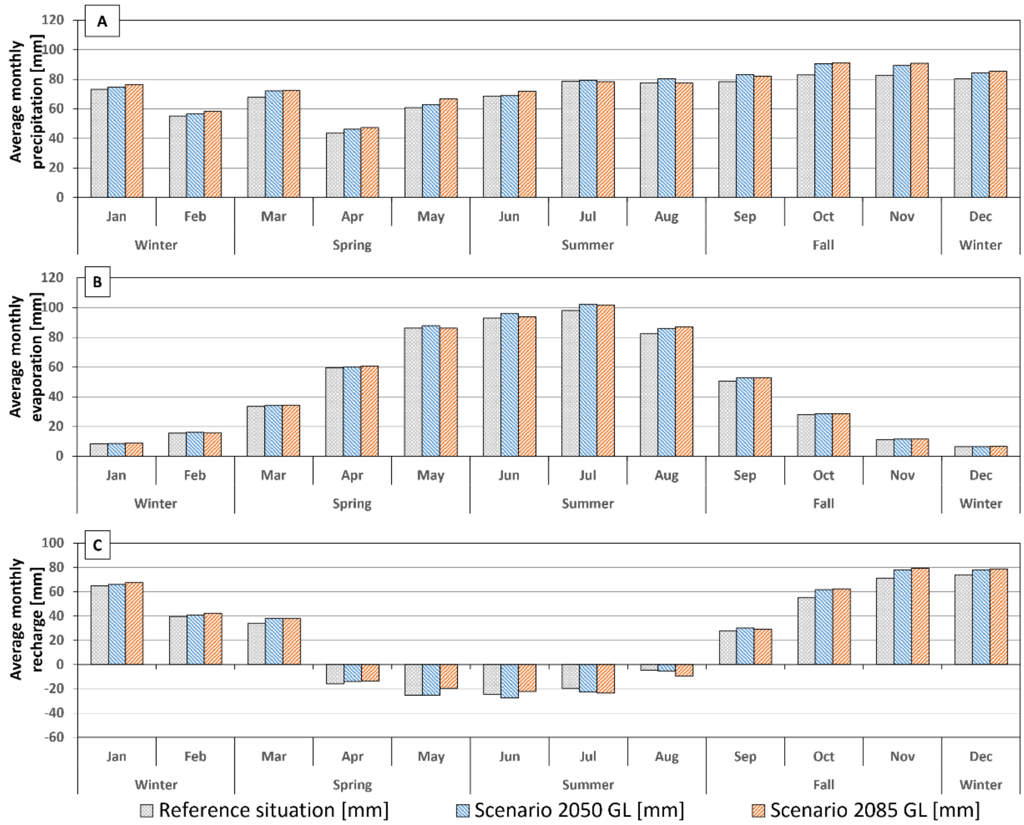

Figure 16: Average monthly precipitation, evaporation, and net precipitation for the reference situation and scenarios 2050GL and 2085GL

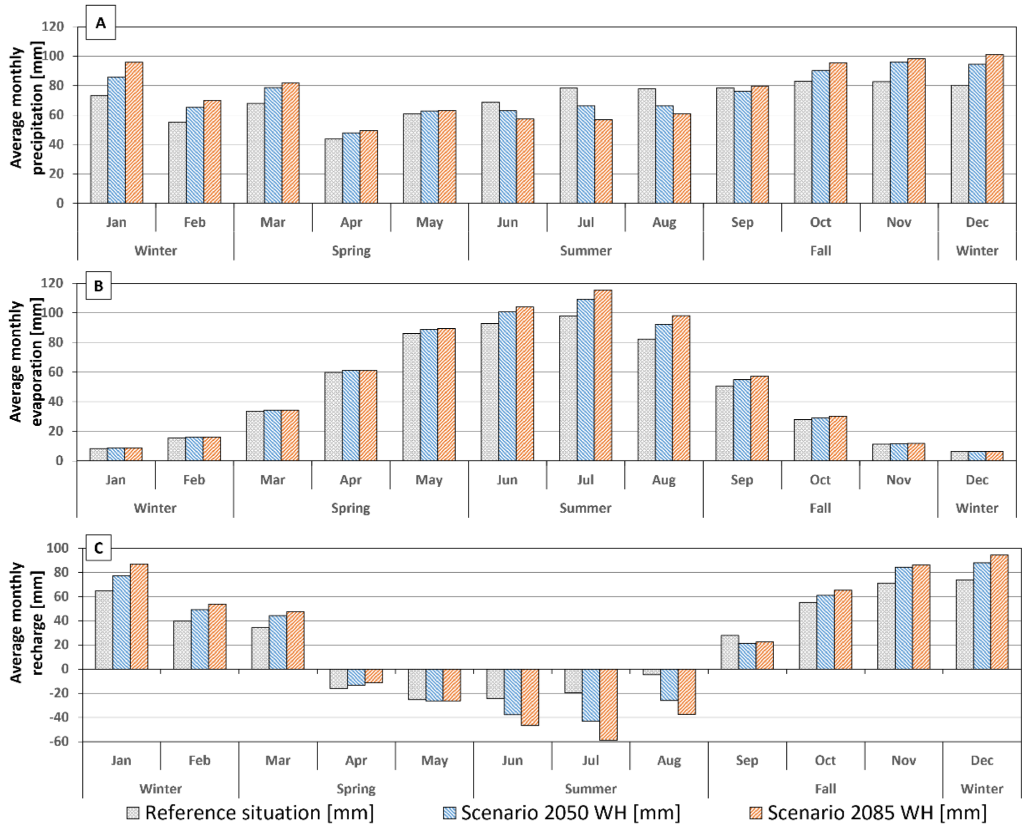

Figure 17: Average monthly precipitation, evaporation, and net precipitation for the reference situation and scenarios 2050WH and 2085WH

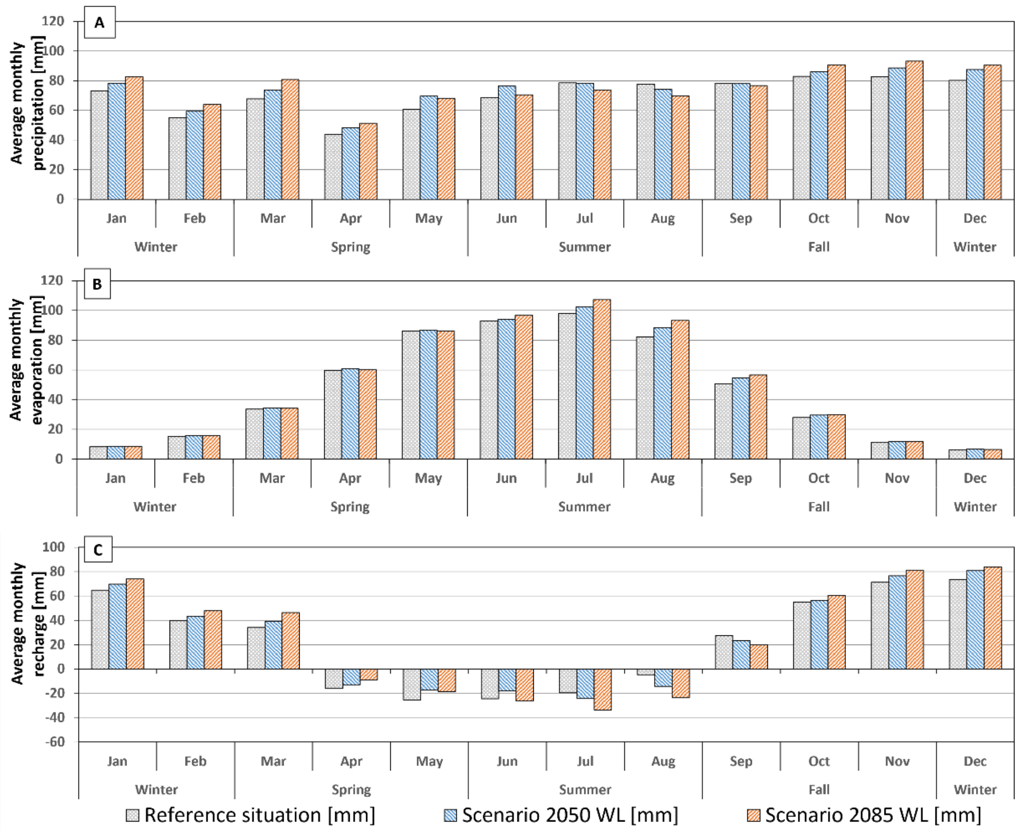

Figure 18: Average monthly precipitation, evaporation, and net precipitation for the reference situation and scenarios 2050WL and 2085WL

The figures show that the monthly precipitation will decrease in June, July, and August (summer) and increase in all other months for both 2050 and 2085. The monthly evaporation will increase in all months but increase most (absolute and relative) in July, August, and September. The combined effect (precipitation – evaporation) is a large decrease in net precipitation for June, July, and August. In all other months the precipitation increases, and evaporation slightly increases resulting in an increase in net precipitation. The intra-annual (n=12) coefficient of variation (CV) based on the average monthly precipitation and evaporation values is shown in Table 4.

Table 4: Intra-annual coefficient of variation (CV) for the precipitation and evaporation of each scenario compared to the reference situation. In the table blue represents an increase, grey no change, and red a decrease.

Focus year	*1995*	*2050*				*2085*			
Scenario	**Reference situation**	**GH**	**GL**	**WH**	**WL**	**GH**	**GL**	**WH**	**WL**
Precipitation									
Intra-annual CV [-]	0.17	0.19	0.17	0.19	0.15	0.18	0.16	0.23	0.16
Evaporation									
Intra-annual CV [-]	0.71	0.72	0.71	0.72	0.70	0.72	0.70	0.73	0.71

From Table 4 it becomes clear that the intra-annual CV increases for the GH and WH scenarios but decreases or does not change for the GL and WL scenarios. The increase for the GH and WH scenarios is the result of increased precipitation in winter and fall and a large decrease in summer whereas the evaporation shows a large increase in summer and small increase in winter and fall. The decrease in GL and WL scenarios is a result of a less pronounced seasonal precipitation change and increase in winter and fall evaporation reducing the difference between seasons. In Table 5 the seasonal net precipitation is summarized for the reference situation and each scenario. This allows the results of RQ3 to be compared to the change in net precipitation and assess how the system behaves.

Table 5: Seasonal net precipitation for each scenario and the change compared to the reference situation. In the table blue represents an increase, grey no change, and red a decrease.

Focus year	*1995*	*2050*				*2085*			
Scenario	**Reference situation**	**GH**	**GL**	**WH**	**WL**	**GH**	**GL**	**WH**	**WL**
Winter									
Net precipitation [mm]	+178	+196	+185	+214	+194	+202	+189	+235	+206
Change [mm]	-	+18	+7	+36	+16	+24	+11	+57	+27
Spring									
Net precipitation [mm]	-7	-6	-1	+5	+9	+3	+5	+10	+20
Change [mm]	-	+1	+6	+12	+16	+10	+12	+17	+26
Summer									
Net precipitation [mm]	-48	-86	-56	-107	-56	-89	-55	-143	-83
Change [mm]	-	-38	-7	-58	-8	-41	-6	-94	-35
Fall									
Net precipitation [mm]	+154	+171	+170	+167	+156	+173	+171	+174	+162
Change [mm]	-	+17	+16	+13	+2	+19	+17	+20	+8

Findings

In all scenarios (except 2050GH and 2085WH) the average annual net precipitation will increase while the inter-annual CV remains similar showing that there is no expected increase in wet or dry years compared to the average. Within a year the differences between seasons are expected to increase showing a decrease in net precipitation in summer and increase in fall, winter, and spring. The intra-annual CV is expected to increase for the GH and WH scenarios but decreases or does not change for the GL and WL scenario.

4.3. Temporal and spatial groundwater level variation for 2050 and 2085

For each KNMI'14 scenario the simulated change in temporal and spatial groundwater level variation compared to the reference situation is assessed.

4.3.1. Temporal groundwater level variation

Annual variation

In Figure 19 the spatially averaged groundwater level (excluding all surface water) for the reference situation and each KNMI'14 scenario is shown for the 30-year simulation period.

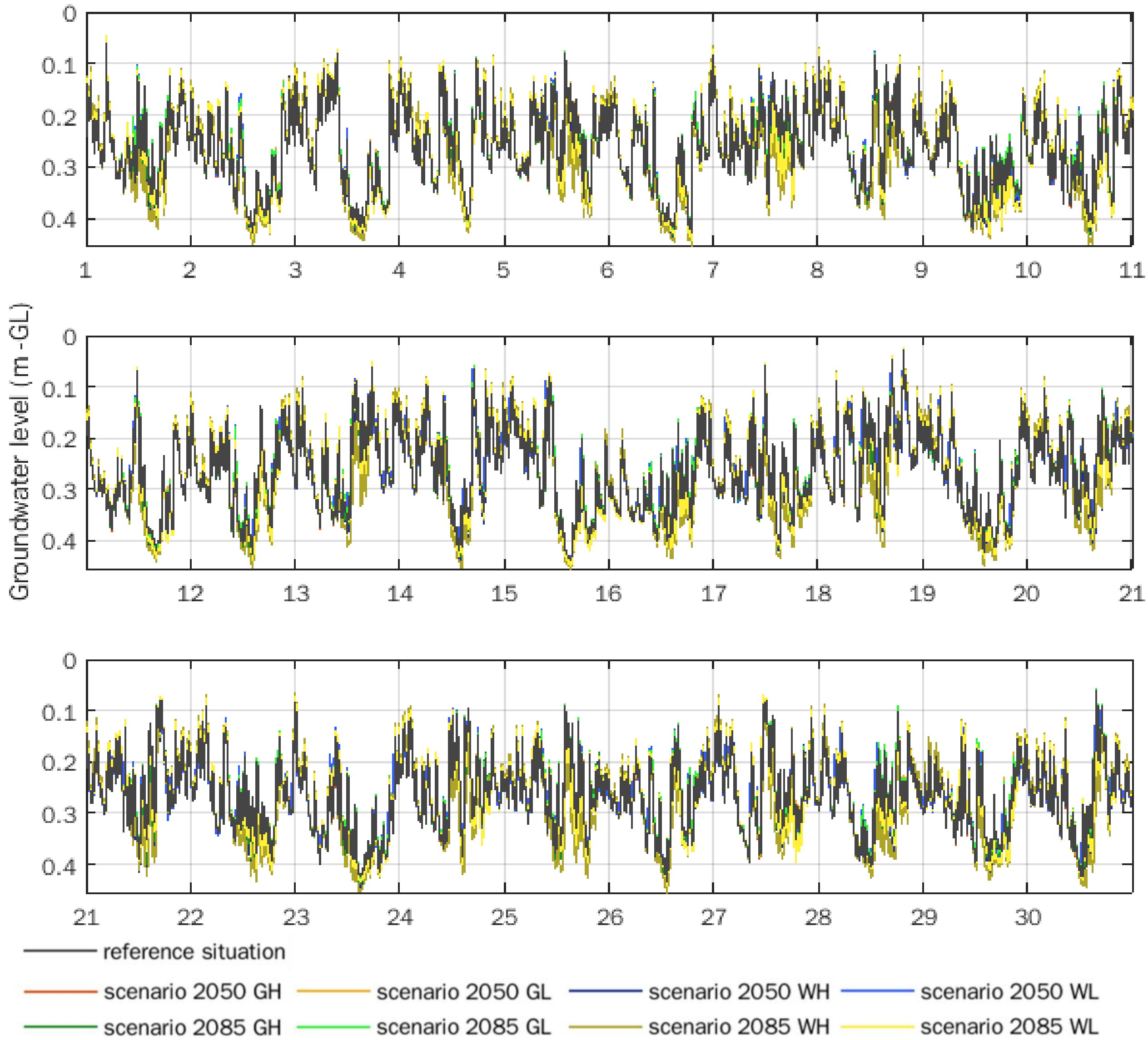

Figure 19: Spatially averaged groundwater level (excluding all surface water) for the reference situation and each KNMI'14 scenario for a 30-year period.

From Figure 19 it becomes clear that the scenarios show little change compared to the reference scenario. Only the 2085WH and 2085WL scenarios show consistently higher and lower GWLs indicating increased variation between seasons. In all scenarios the GWL shows no increasing or decreasing trend during the simulation period. The timeseries is transformed to the spatially averaged annual GWL and inter-annual CV (n=30) and is shown with the annual net precipitation from Table 4 in Table 6.

Table 6: Spatially averaged annual groundwater levels (GWL) and inter-annual coefficient of variation (CV) (n=30) for a 30-year period and the annual net precipitation and net precipitation change from Table 4. In the table blue represents an increase, grey no change, and red a decrease.

Focus year	*1995*		*2050*				*2085*		
Scenario	**Reference**	**GH**	**GL**	**WH**	**WL**	**GH**	**GL**	**WH**	**WL**
Average annual GWL [m -GL]	0.27	0.27	0.27	0.27	0.27	0.27	0.26	0.28	0.27
Inter-annual CV [-]	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.10
Net precipitation									
Annual [mm]	+277	+275	+298	+279	+303	+288	+310	+276	+304
Change [mm]	-	-2	+21	+2	+26	+11	+33	-1	+27

Table 6 shows that the average annual GWL and inter-annual CV show no change in 2050 and little change in 2085 compared to the reference situation. Compared to the annual net precipitation it can be concluded that the change in average annual GWL is not directly correlated with a change in annual net precipitation. For example, the 2050GH, 2050WH, and 2085WH scenarios have a small change in net precipitation, however the 2085WH scenario shows a decrease in GWL and inter-annual CV while the 2050GH and 2050WH scenarios do not show a change. Next to that the 2085WL scenario shows an increase in inter-annual CV while similar net precipitation changes for the 2050GL, 2050WL, and 2085GL scenario do not cause a change in inter-annual CV.

Although the changes might seem negligible small it is important to note that this is a 30-year averaged value masking more detailed temporal and spatial changes. This is elaborated in the next sections.

Seasonal variation

In Table 7 the average seasonal GWL and intra-annual CV (n=12) are shown for the reference situation and each scenario combined with the seasonal net precipitation and net precipitation change from Table 5.

Table 7: Spatially averaged seasonal groundwater levels (GWL) and intra-annual coefficient of variation (CV) (n=12) for a 30-year period and the seasonal net precipitation and net precipitation change from Table 5. In the table blue represents an increase, grey no change, and red a decrease.

Focus year	*1995*		*2050*				*2085*		
Scenario	**Reference**	**GH**	**GL**	**WH**	**WL**	**GH**	**GL**	**WH**	**WL**
Intra-annual CV [-]	0.09	0.12	0.10	0.14	0.10	0.13	0.09	0.18	0.12
Winter									
Average seasonal GWL [m -GL]	0.24	0.23	0.23	0.23	0.23	0.23	0.23	0.22	0.23
Net precipitation [mm]	+178	+196	+185	+214	+194	+202	+189	+235	+206
Change in net precipitation [mm]	-	+18	+7	+36	+16	+24	+11	+57	+27
Spring									
Average seasonal GWL [m -GL]	0.27	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Net precipitation [mm]	-7	-6	-1	+5	+9	+3	+5	+10	+20
Change in net precipitation [mm]	-	+1	+6	+12	+16	+10	+12	+17	+26
Summer									
Average seasonal GWL [m -GL]	0.30	0.32	0.30	0.33	0.30	0.32	0.29	0.35	0.31
Net precipitation [mm]	-48	-86	-56	-107	-56	-89	-55	-143	-83
Change in net precipitation [mm]	-	-38	-7	-58	-8	-41	-6	-94	-35
Fall									
Average seasonal GWL [m -GL]	0.27	0.27	0.26	0.28	0.27	0.27	0.26	0.29	0.28
Net precipitation [mm]	+154	+171	+170	+167	+156	+173	+171	+174	+162
Change in net precipitation [mm]	-	+17	+16	+13	+2	+19	+17	+20	+8

Table 7 shows that the intra-annual CV increases for all scenarios (except scenario 2085GL) indicating an increase in seasonality. The average seasonal GWL shows an increase in winter and spring and decrease in summer and fall for both 2050 and 2085. An exception to this is the 2050GL and 2085GL scenario showing no change or increase for all seasons. The seasonal pattern of the reference situation is enhanced in the scenarios showing larger differences between winter and summer while the average annual GWL does not change. The largest changes are predicted by the 2085WH scenario showing a decrease in the average GWL of 0.05 m in summer and an increase of 0.02 m in winter. This might seem small but as this is an average of the entire study area and three months this is a notable change.

Compared to the seasonal changes in net precipitation it becomes clear that large decreases in net precipitation in a single season can still influence GWL in the next season. This is observed in the 2050 WH, 2085WH and 2085WL scenarios in which a large summer net precipitation deficit results in lower average seasonal GWL in summer and fall even though a net precipitation surplus is present in fall.

Comparing 2050 to 2085 it becomes clear that the GH and GL scenarios show no continued trend whereas the WH and WL scenarios do. This corresponds to the changes in net precipitation for each scenario.

Findings

Overall, the average annual and seasonal GWL change is limited. The inter-annual CV showed little change indicating there is no change in extreme high or low GWL years which corresponds with the little change in inter-annual CV for precipitation and evaporation input. The average annual GWL showed that a change in annual net precipitation does not directly result in a similar change of the average annual GWL and is dependent on the seasonal distribution of net precipitation.

The intra-annual CV showed increasing values for each scenario indicating increased seasonality. This translates to an average seasonal GWL increase in winter and spring and decrease in summer and fall. Next to that, large decreases in net precipitation in a single season can result in lower GWL for the next season. This indicates that the study area is partially dependent on rainfall to maintain its current GWL.

4.3.2. Spatial groundwater level variation

To show the spatial GWL variation in the study area the AHG and ALG for each scenario are determined. In this section the WH scenario is assessed in detail as this scenario shows the largest change in AHG and ALG compared to the reference situation for both 2050 and 2085. The AHG and ALG for all other scenarios are provided in Appendix B – Change in AHG for all KNMI’14 scenariosand Appendix C – Change in ALG for all KNMI’14 scenarios. These scenarios show similar, but less pronounced, changes in AHG and ALG compared to scenario WH. In Figure 21 the predicted change in AHG for scenario WH in 2050 and 2085 compared to the reference situation is shown.

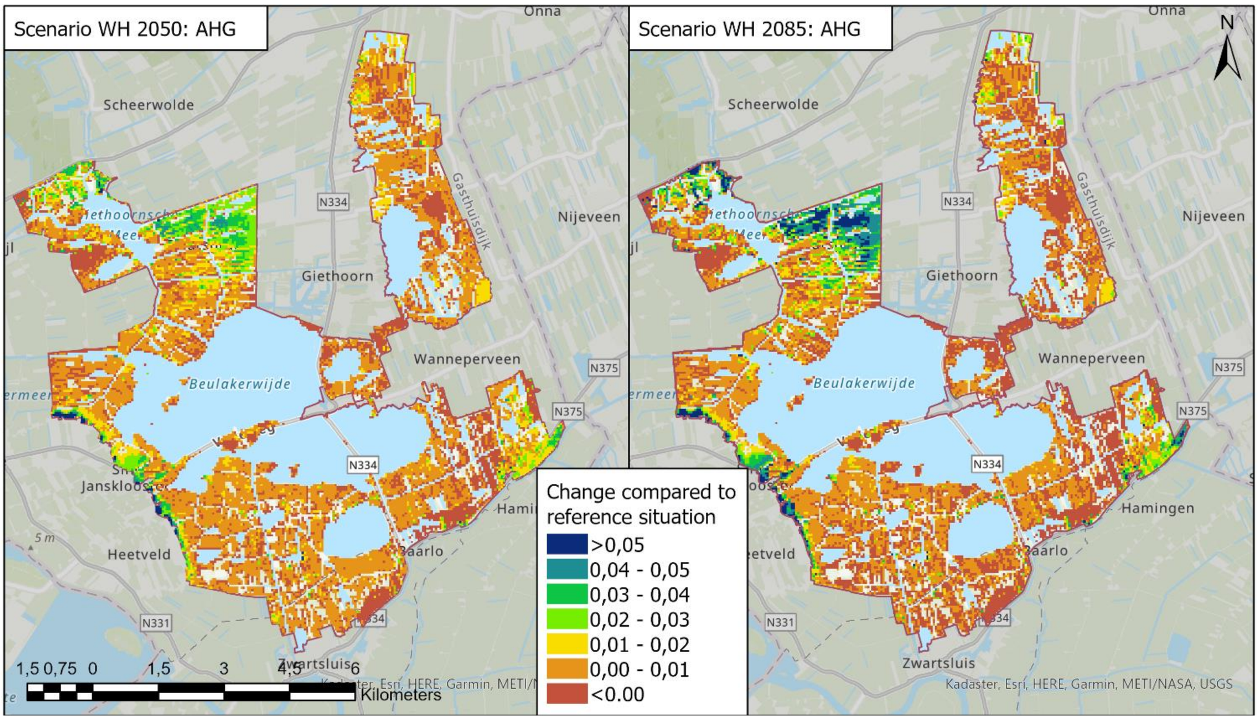

Figure 20: Predicted change in AHG (m) for scenario WH in 2050 and 2085 compared to the reference situation. A negative value means that the AHG decreases (further away from ground level).

From Figure 20 it becomes clear that the largest part of the study area is not affected by the scenarios (between 0.00 m and 0.01 m change) for both 2050 and 2085. Only towards the southeast, southwest, and northeast edges of the area a small increase is simulated between 0.01 m and 0.05 m. The focus area as described in section 4.1 shows the largest increase in AHG. This increase shows that areas with a lower AHG compared to the average become less pronounced resulting in reduced spatial varaiton. This is mainly due to the increased net precipitation surplus in winter.

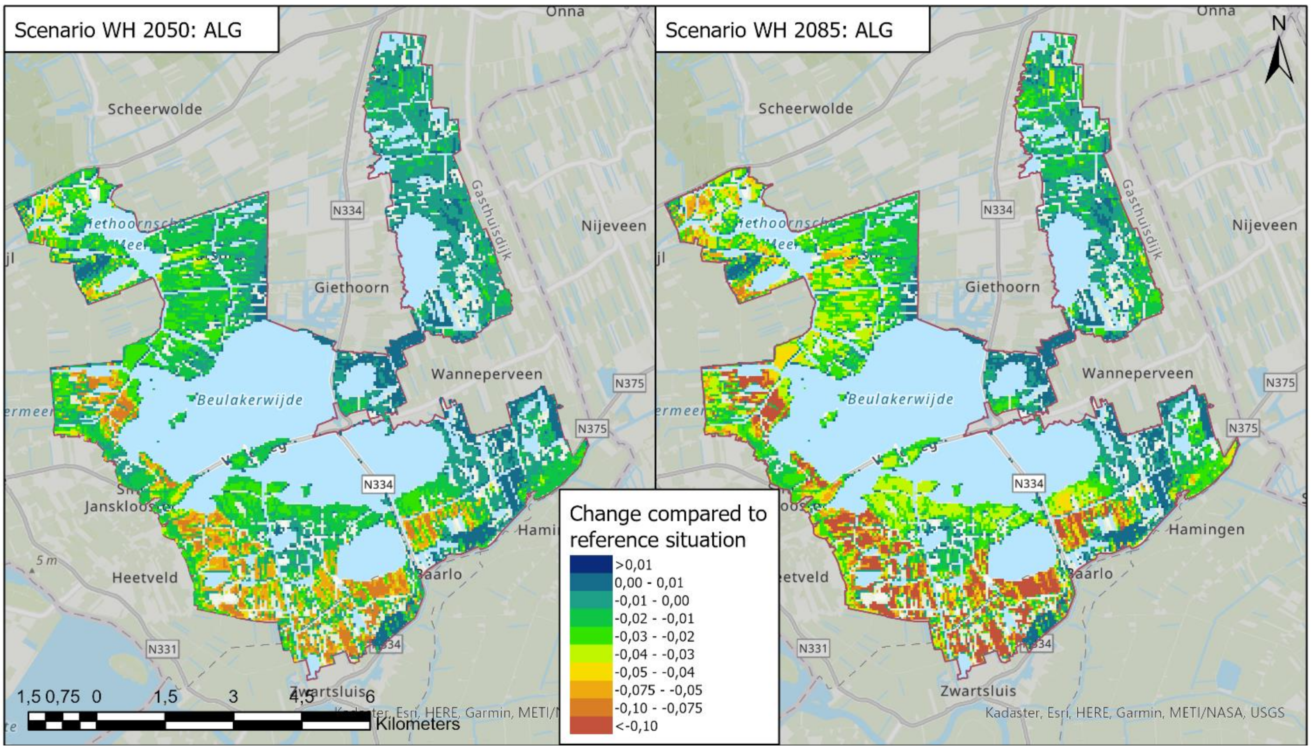

Figure 21: Predicted change in ALG (m) for scenario WH in 2050 and 2085 compared to the reference situation. A positive value means that the ALG increases (closer to ground level).

Figure 21 shows a decrease in the ALG for both 2050 and 2085. In the northeastern part of the area the ALG decreases with 0.00 m to 0.03 m. To the south and west of the central lake the ALG decreases between 0.03 m and 0.10 m. Why specifically this part of the study area is influenced more is still unknown and requires further investigation. Surprisingly, the focus area does not show any specific changes.

Findings

From the spatial assessment it became clear that the scenarios have little influence on the AHG and ALG. The difference between AHG and ALG slightly increases, resulting in a larger range of possible GWLs in the area. The focus area as described in section 4.1 shows a slight increase in AHG but no change in ALG. The relatively large decrease in ALG in the south and east of the study area cannot be explained as the subsurface, drainage level, ground level, and land use show no large changes. To further investigate this the groundwater flow in this area should be made insightful to find out why this decrease occurs.

5. Discussion

5.1. Method and data

The method used during this study was designed to form a general approach for assessing the groundwater level variation in different areas. Strong features are the focus on the temporal and spatial variation in the study area resulting in a spatio-temporal variation assessment comparable to Delbari et al. (2013) and Ahmadi & Sedghamiz (2007). Using the AHG and ALG provides a spatial overview frequently used in the Netherlands but this is limited to specific data on the 14th and 28th of each month leaving out much of the available data (Knotters et al., 2018). The focus on an annual and seasonal timescale prevented the ability to assess how the system responses to extreme rainfall events or droughts. Liu et al. (2016) showed that extreme rainfall events can increase groundwater levels in areas with a shallow GWL up to 20% making it a valuable addition to this study. However, as the surface water level is maintained at a constant level in the model the effect of extreme rainfall events and droughts on the GWL variation would be underestimated.

The use of a numerical model results in a certain level of uncertainty due to imperfections resulting from simplifications and assumptions which are often the most important source of uncertainty (Cui et al., 2021). In this study the most important simplifications and assumptions are explained in section 2.2.2. The main simplifications are the cell size (50 m) and the present model layers (9 subsurface layers). In Appendix D – Model simplifications an assessment comparing 25 m and 50 m cell size is carried out showing that the model uncertainty (spatially averaged GWL values) does not increase with the different cell sizes. combined with the spatial resolution of input data (e.g., land use, subsurface) a decrease in cell size will not improve results keeping similar uncertainty. But, as all scenarios use the same model, and the focus is on annual and seasonal averages this uncertainty is less relevant when comparing the different scenarios with the reference situation. For the model layers the top model layers are most important as the study area has a shallow GWL regime. The first model layer represents the existing peat and the second layer the sand from the formation of Boxtel. The lower model layers represent different sand layers which are subject to regional GWL flow from the northwest to the southeast as described in section 2.1.1. The thickness of these layers is based on the REGIS II subsurface layer model described by Hummelman et al. (2019) and boreholes (Dotinga & Bodde, 2018a). Due to local Gliede, Gyttja or cemented soil layers in De Wieden which are often poorly characterized the resistance of the peat layer can locally be underestimated locally influencing the results. An increase in the resolution of the top model layer, both in resistance and presence of cemented soil layers would improve local results increasing the accuracy of the AHG and ALG.

To simulate the predicted climate change for 2050 and 2085 the KNMI'14 scenarios are used as input. The KNMI'14 scenarios provide spatially interpolated station data for precipitation (using ordinary kriging) and evaporation (using this plate splines) based on 194 station and 14 stations respectively spread throughout the Netherlands. The spatially interpolation is explained in detail by Sluiter (2014) in which also some important dataset limitations are provided. Relevant limitations to this study are that local factors (e.g. presence of gliede layers, sand pop-ups) are not taken into account, that the values are no 'real' representation for a specific date, and that the extreme statistics might be lower than statistics derived from source data. As the study area has a relatively uniform ground level and the focus is on average GWL variation (annual average, seasonal average, AHG, and ALG) it can be concluded that all three limitations will probably not influence the results. But it is important to note that, if a more detailed assessment is wanted (e.g., extreme rainfall events) a critical assessment of the KNMI'14 prediction data for the future scenarios is required to assess whether the datasets properly represent the precipitation and evaporation.

The MIPWA model used to simulate GWL variation in the reference situation (1981-2010) and KNMI'14 scenarios (2050 & 2085) is identical except for the precipitation and evaporation input. This ensures that solely the effect of climate change is assessed but leaves out developments in- and outside the area between 2010 and 2050 or 2085. These developments can consist of changes in the surface water system, land use or (local) subsidence and influence the future GWL variation. These developments are not considered in this study as there is currently limited to no information present on the matter and are subject to a highly complex and elaborate decision-making process. This results in a simulation of the scenarios on the precondition that there are no developments in the area between 2010 and 2050 or 2085 limiting the practical applicability. Important development influencing GWL variation is a change in the desired surface water level due to the strong connection with GWL. This would result in different outcomes making the results of this study outdated. However, by implementing future developments in the numerical model when known and re-assessing the temporal and spatial effect, the results of this study can be updated, and changes can be made insightful.

5.2. Results

This study simulated the flow of groundwater in De Wieden under different climate change scenarios. The results showed that the change in average annual and seasonal GWL change is limited. Similar results were obtained in a study by Kont et al. (2007) assessing the impact of climate change on coastal and inland wetlands in Estonia between 1956-2002 focusing on seasonal GWL and using intra-annual CV as an indicator for variance. In this study (observing a similar system as De Wieden) it became clear that the effect of climate change has a relatively small influence on the different seasons (-0.07 to + 0.11 m change) showing a steady system. The intra-annual CV showed low change ranging between 0.16 and 0.25.

Spatially, the study showed that the influence of climate change predictions on the AHG and ALG is limited to a maximum change of 0.10 m. It became clear that close to the surface water the change is limited due to the constant surface water level providing a constant source of water through lateral spread. A study by Kažys et al. (2015) explored the effect of temperature change on groundwater level fluctuation in a peatbog in Lithuania. In this study a set of measurement points ranging in distance from lake Rèkyva showed that in the warm season measurement points closer to the lake showed larger fluctuation (higher maxima and lower minima) compared to measurement point further away. In the cold season the opposite effect was found. The results differ from this study as the opposite effect is observed for the warm season characterized by the ALG. This is mainly due to the fluctuating surface water level while this was assumed constant in this study. Currently, the constant surface water level can be maintained in the area but it is uncertain if this is still the case for the future scenarios as in dry periods the external inlet accounts for a third of the present water. This emphasizes the large influence of fluctuating surface water levels on GWL variation implying that, if the surface water level cannot be maintained the effect of climate change predictions will be larger than determined in this study.

The focus of this study is to evaluate how the study area reacts to changes in precipitation and evaporation caused by climate change, this focus introduces 'predictive uncertainty' in the results. Predictive uncertainty assesses how well the model can evaluate the effect of changes in the system and is determined by how accurate the conceptual model is defined, how well the data and scenarios are understood, and how well the model is calibrated (Cui et al., 2021). In this study the MIPWA groundwater model is used in which the conceptual model is based on MODFLOW combined with the CAPSIM module, the MODFLOW model has been widely used in the world and is generally accepted to provide accurate groundwater level modelling (Babakhani et al., 2018). The used data is well understood and accurate enough to assess De Wieden as an area (Dotinga & Bodde, 2018b). The model used in this study was calibrated for the precipitation and evaporation distribution from 1980-2010 (Dotinga & Bodde, 2018a). In this study the same model settings were implemented to simulate the KNMI'14 scenarios but the precipitation and evaporation input was altered. The change in precipitation and evaporation distribution for the KNMI'14 scenarios compared to the reference situation is provided in Appendix F – Precipitation and evaporation distribution showing small changes. This results in a low predictive uncertainty meaning that if the predicted climate change occurs it is likely that the resulting change in groundwater level variation will also occur.

5.3. Generalization of the method used and practical application

The method and model used in this study was designed to be easily applicable to different areas and results in a comprehensive temporal and spatial assessment. However, there are certain aspects of the method that are area specific and require specific attention. For example, the temporal analysis in this study used the GWL below ground level averaged over the entire project area to provide representative daily GWL values. This resulted in accurate results due to the rather uniform ground level, surface water level, subsurface, and GWL characteristics of the area. This cannot be applied to every study area as these characteristics can differ greatly within a project area resulting in daily GWL values that would not provide a representative image for the entire area. If this occurs the project area should be divided into sub-areas with similar characteristics and the results should be assessed for each individual sub-area. When to divide the project area into sub-areas should be determined based on the characteristics combined with expert knowledge. The numerical model used in this study provided accurate results of the GWL regime in the study area due to the application of the right assumptions and simplifications (section 2.2.2). These model settings might not provide accurate results in different areas and should be assessed or tested for each project area. Next to that, the climate predictions used in this study (KNMI'14 scenarios) are only available for the Netherlands. To simulate areas outside of the Netherlands other quantified climate predictions for precipitation and evaporation from the IPCC or scientific studies should be used.

This study showed that it is possible to assess the quantitative effects of climate change on GWL both temporally and spatially. Although the results showed a small change in GWL regime it is of large importance to assess the impact of climate change on an area. The result of this assessment provides valuable information for decision making processes concerning the area as it can quantify the predicted influence of climate change and identify possible challenges that will occur in the future. These challenges can range from water shortages in local areas or increased dependency on other systems possible putting these systems under too much stress. Next to that each study contributes to the body of knowledge regarding the influence of climate change on different areas.

6. Conclusion and recommendations

6.1. Conclusion

In section 1.5 a research objective was formulated and split up in three research questions. In this section a short answer for each research question is presented and an answer for the research objective is provided based on the results from this study.

RQ1. What is the temporal and spatial groundwater level variation in De Wieden during the reference situation?

The temporal results showed that the study area has a relatively shallow GWL table (on average 0.27m -GL) with low variation in between the years and no long-term trend. Within a year the GWL variation displays a seasonal pattern showing higher GWLs in winter and lower GWLs in summer with low variation in between seasons (average variation of 0.06m between winter and summer).

The spatial results showed that the GWL remains between 0m and 1.0 m -GL indicating parts of the area are fully saturated during wet periods and the area is subject to lateral spread resulting in the small range. The large presence of surface water (which is artificially maintained at the desired level) combined with the large influence of lateral spread reduces temporal and spatial GWL variation in areas close to open water to a minimum.

RQ2. How will the current climate change predictions for 2050 and 2085 change the climatological variables influencing groundwater levels?

The results show that the annual net precipitation will increase while the inter-annual CV for precipitation and evaporation remain similar showing no increase in extreme wet or dry years compared to the average. All scenarios predict an increase in net precipitation in winter, spring and fall but a decrease in summer increasing seasonality. The intra-annual CV for precipitation and evaporation only slightly increases for scenario GH and WH and slightly decreases or does not change for scenario GL and WL.

RQ3. How do the changed climatological variables for 2050 and 2085 influence the temporal and spatial groundwater level variation in De Wieden?

The temporal results show that there is only a small change in average annual GWL and inter-annual CV. The change in average annual GWL did not always correspond with the change in annual net precipitation showing that an increase in net precipitation does not directly also result in an increase in average annual GWL. Within a year the intra-annual CV increased for all scenarios (except for scenario 2085GL showing no change) indicating increased seasonality. This is a result of increased average seasonal GWLs in winter and spring and a decrease in summer and fall. Next to that it became clear that the large decreases in net precipitation in summer (e.g., scenario 2050WH, 2085WH, and 2085WL) still resulted in lower GWL in fall even though a net precipitation surplus was present. The spatial assessment showed that the different scenarios have little influence on the AHG and ALG only slightly increasing the possible GWL range.

The objective of this study was to determine the effect of climate change predictions on the temporal and spatial groundwater level variation in De Wieden for 2050 and 2085 compared to a reference situation representing 1981-2010

From the results of this study, it can be concluded that the current climate change predictions for 2050 and 2085, based on the KNMI'14 scenarios, will have a small (-0.03 m to + 0.02 m) but significant effect on the temporal and spatial groundwater level variation in De Wieden[2]. On an annual timescale there is a small change in average GWL and inter-annual variation and no long-term trendline was observed.

Within a year the average GWL is expected to increase in winter and spring (0 to 0.02 m) and decrease in summer and fall (0 to 0.03 m) increasing seasonality resulting in an increased intra-annual CV for all scenarios (excluding scenario 2085GL in which the GWL increases or does not change in all seasons). A large net precipitation deficit in summer is expected to decrease the average GWL in summer and fall even though a net precipitation surplus is expected in fall. The spatial GWL variation is expected to increase at the edges of the study area while the centre of the study area is not influenced. This is a result of the large presence of surface water in the area with a constant surface water level keeping variation next to the surface water to a minimum through lateral spread.

The results obtained in this study are comparable to other studies focussing on the effect of climate change in peatlands showing that the results can be attributed to the effect of climate change. Going forward, the strong influence of the surface water body and constant surface water level should be addressed and, if possible, implemented as a variable surface water level.

6.2. Recommendations

6.2.1. Recommendations for future research

During this study it became clear that the constant surface water level assumption had a large influence on the results. In lowland peat areas subject to a variable surface water level, it is essential to implement this variable surface water level in the model. Therefore, it is recommended when simulating future scenarios that a surface water model is coupled that can determine the surface water level based on the scenario input as well as the changed GWL variation. The large lateral spread of a single area to an adjacent, lower situated, agricultural area (described in section 4.1.2) showed the importance of accurately modelling the areas surrounding the study area. Therefore, it is recommended that the direct surroundings of a lowland peat area are also assessed in detail to provide adequate simulation of the interaction between the study area and surrounding area.

The results of this study are based on the most recent climate change predictions (KNMI'14 scenarios) for the Netherlands. These predictions are periodically updated by the KNMI including the most recent predictions. The next update is expected mid 2023 replacing the current predictions called KNMI'23-climate scenarios. To keep the predicted influence on groundwater level variation in De Wieden relevant it is recommended that the results of this study are updated using these KNMI'23 scenarios.

During this study it became clear that the number of studies focusing on the effect of climate change predictions on GWL variation in lowland peat areas is limited. Most studies focusing on lowland peat areas are directed to surface water or water quality leaving GWL variation underexposed. Therefore, it is recommended to apply the method and lessons learned from this study to other lowland peat areas enlarging the body of knowledge on the influence of climate change predictions on GWL variation in lowland peat areas.

For future research continuing this study for De Wieden it is recommended to focus on what influence the changed groundwater level variation can have on the different user functions present in the area. To do this, first the influence of climate change on the quantitative surface water balance of the area and consequently the effects on water quality have to be made insightful. For instance, an increase in summer water inlet through pumping station Stroink to maintain the surface water level changes the

[2] Taking the assumptions in this study into account.

water quality possibly influencing the present flora and fauna. By carrying out this research an integral view of how climate change will affect the area is created which supports policy making for the area.

6.2.2. Recommendations for policy makers

This study showed that the KNMI'14 climate change predictions on GWL remains low mainly due to the constant surface water level. Whether this constant surface water level can be maintained in the future is uncertain as fresh surface water supply is threatened by climate change (Kwadijk et al., 2007; Stuurman et al., 2008). In case of a water shortage the priority of users in the Netherlands is determined by the Dutch Water Management act by four categories. De Wieden falls in category 1 (highest) as surface water shortages would result in irreparable damage to the present nature (Kort & Teunis, 2020). But how De Wieden would be affected during a shortage is still uncertain. Therefore, it is recommended to compose a monthly surface water balance of the study area from which the external water dependencies and water surplus periods become clear. Subsequently, similar to RQ2 of this study, the most recent climate change predictions can be implemented in the water balance and the expected change in dependencies becomes clear.

Even though the results show a low change in GWL variation in De Wieden for the KNMI'14 scenarios, it is important that assessing the effect of climate change predictions on GWL variation is considered when establishing policy documents for a nature area. Therefore, it is recommended to include the assessment of climate change predictions on temporal and spatial GWL variation in different policy documents focusing on the future development of De Wieden but also in nature areas in general.

Finally, it is important to note that the results of this study show a general overview of the effect climate change predictions will have on groundwater level variation in the Wieden. The results for different parts of De Wieden cannot be directly used by policy makers because of the focus on the entire area. An additional assessment in which the numerical model is tailored to a certain part of De Wieden (e.g., by locally refining the layer characteristics or grid size) can show the effect of climate change on a certain part of De Wieden.

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Appendices

Appendix A – Quality-Control test method (outlier detection)

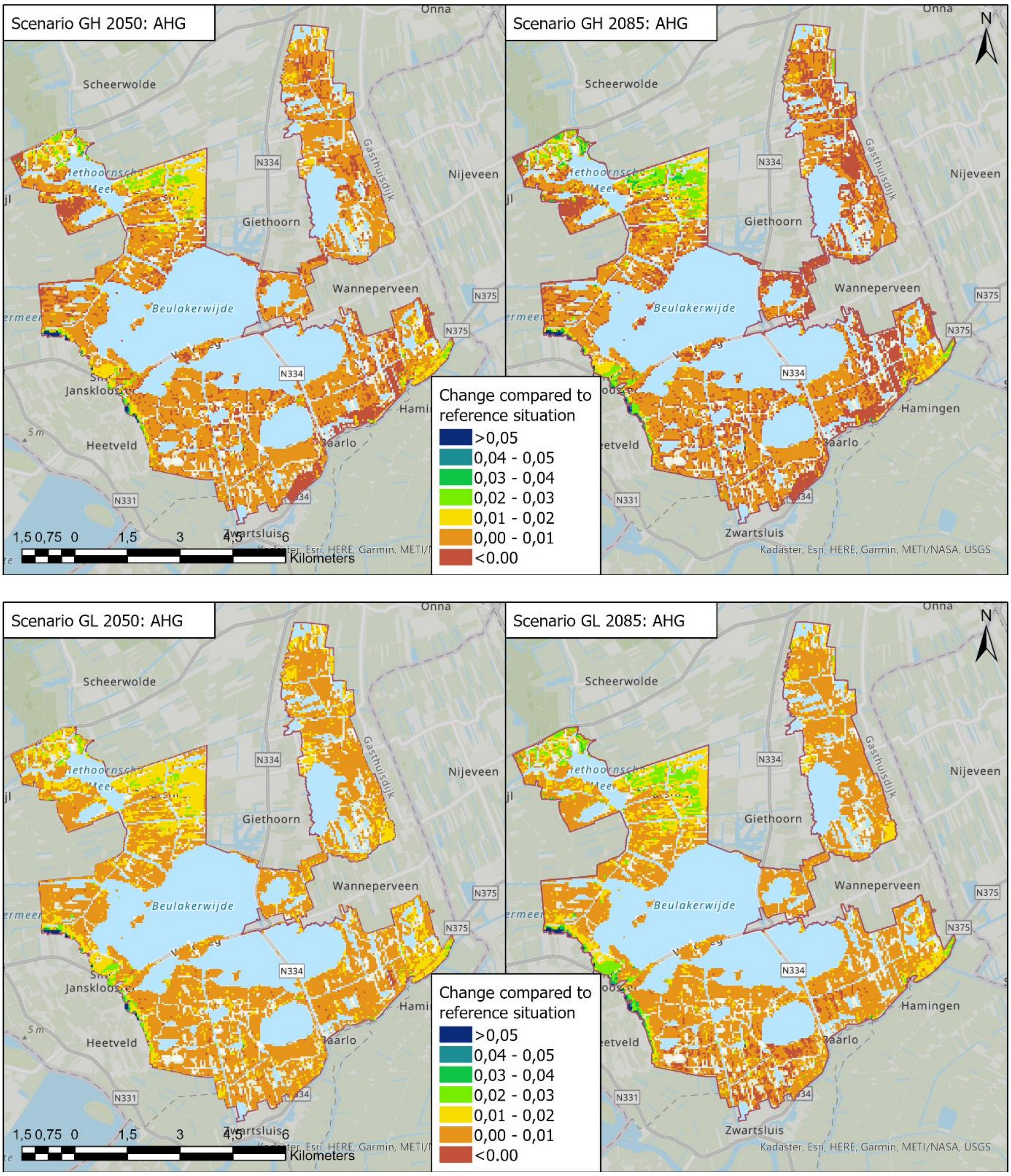
The Quality-Control test method consists of four steps (Asikoglu, 2017):

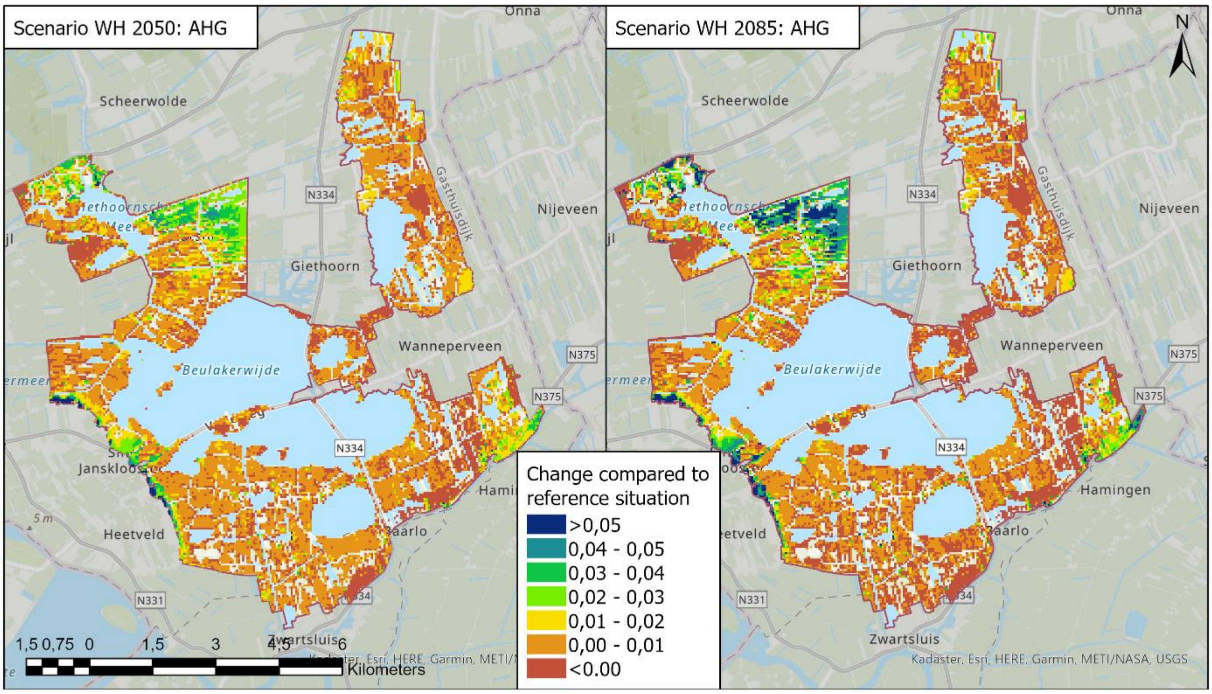
1. Calculation of the median ($x_{0,50}$), and the quartiles ($x_{0,25}$ $x_{0,75}$) of the data.
2. Calculation of the median absolute deviation (MAD): $MAD = \frac{1}{N}\sum_{i=1}^{N}|x_i - x_{0.50}|$
3. Calculation of the test index as follows:
    a. If MAD = 0, the test index = 0
    b. Else if $x_{0.75} \neq x_{0.25}$, the test index = $|x_i - x_{0.50}|/(x_{0.75} - x_{0.25})$
    c. Else the test index = $|x_i - x_{0.50}|/MAD$
4. Compare the calculated test index with a predefined threshold value (typically 2). If the test index turns out to be higher than the threshold, the value is categorized as an outlier.

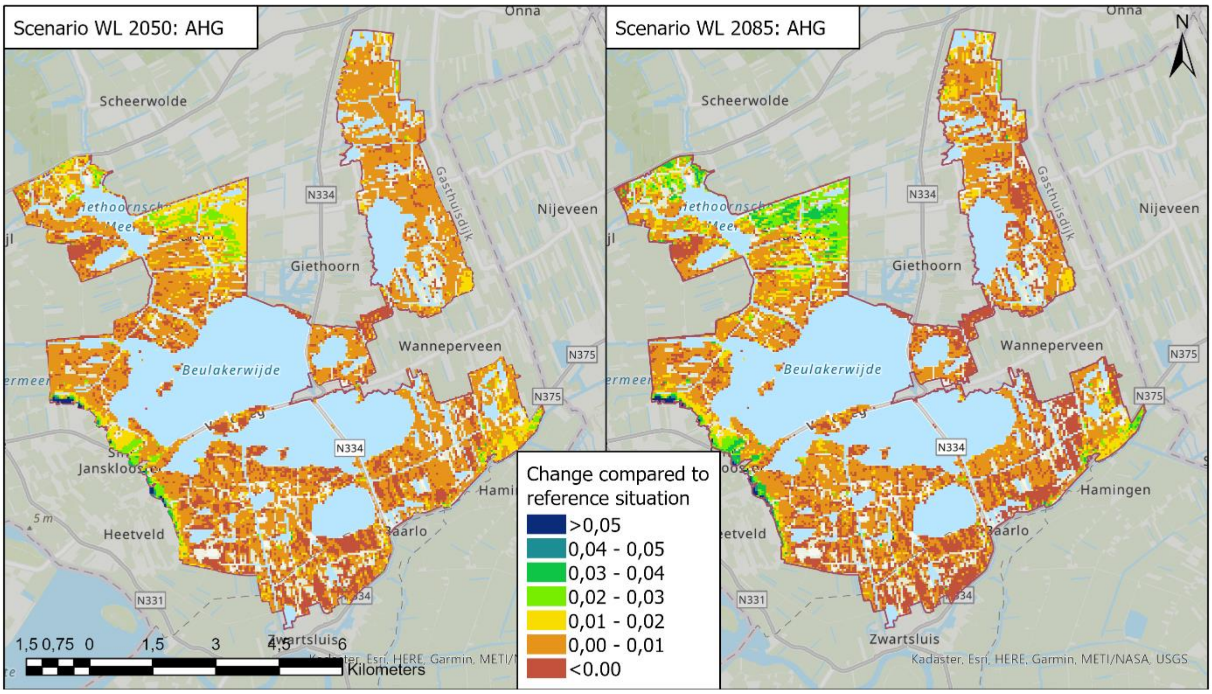
Due to possible local rainfall events (especially in summer) in the Netherlands only the top 1% (483 cells containing the highest values) of rainfall cells are considered. This prevents the false labelling of outliers due to the local nature of rainfall events. For potential evapotranspiration the top 10% (4830 cells) of evaporation cells are considered. The threshold value for the test index in this study is set to 2 for reference evaporation and to 3 for rainfall due to the local rainfall events.

When outliers are detected, these values are replaced by the average value of the assessed cells excluding the outliers. E.g., if a precipitation dataset contains three outliers these values are replaced by the average value of the remaining 480 cells.

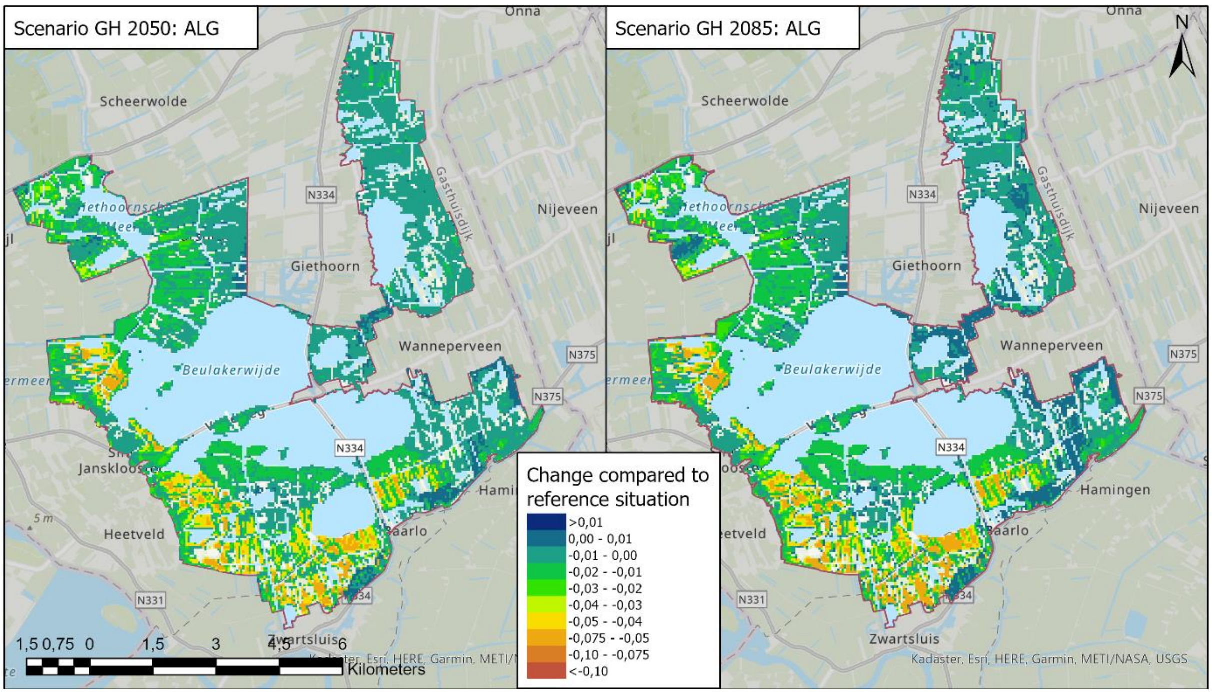
Appendix B – Change in AHG for all KNMI’14 scenarios

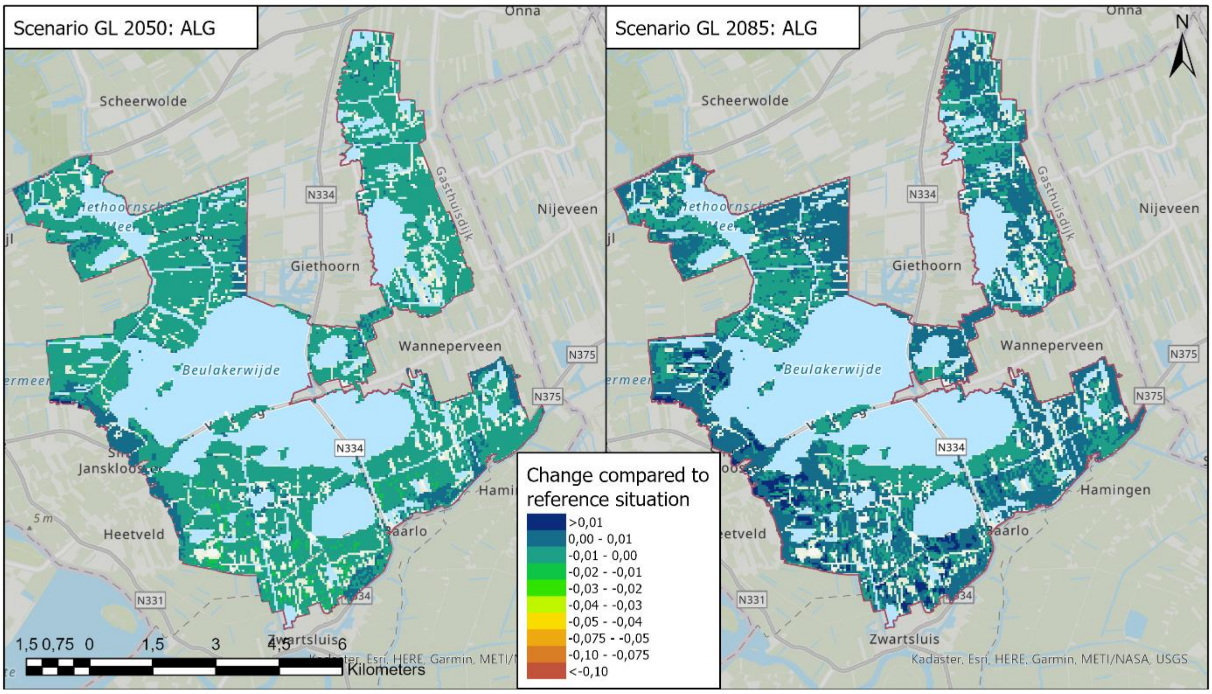


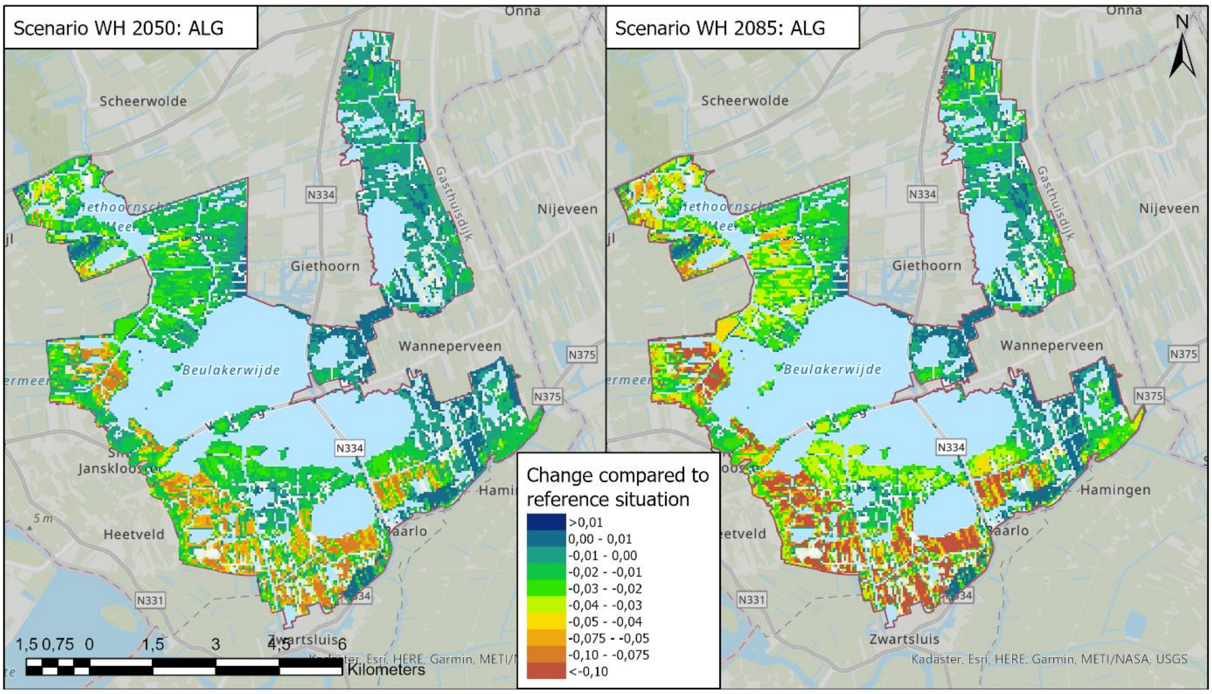

Scenario WH 2050: AHG
Scenario WH 2085: AHG
N
Onna
Scheerwolde
Nijeveen
Giethoorn
Gasthuisdijk
Wanneperveen
Beulakerwijde
Heetveld
Hamingen
Zwartsluis
N334
N375
N331
Change compared to reference situation
>0,05
0,04 - 0,05
0,03 - 0,04
0,02 - 0,03
0,01 - 0,02
0,00 - 0,01
<0.00
1,5 0,75 0 1,5 3 4,5 6
Kilometers
Kadaster, Esri, HERE, Garmin, METI/NASA, USGS

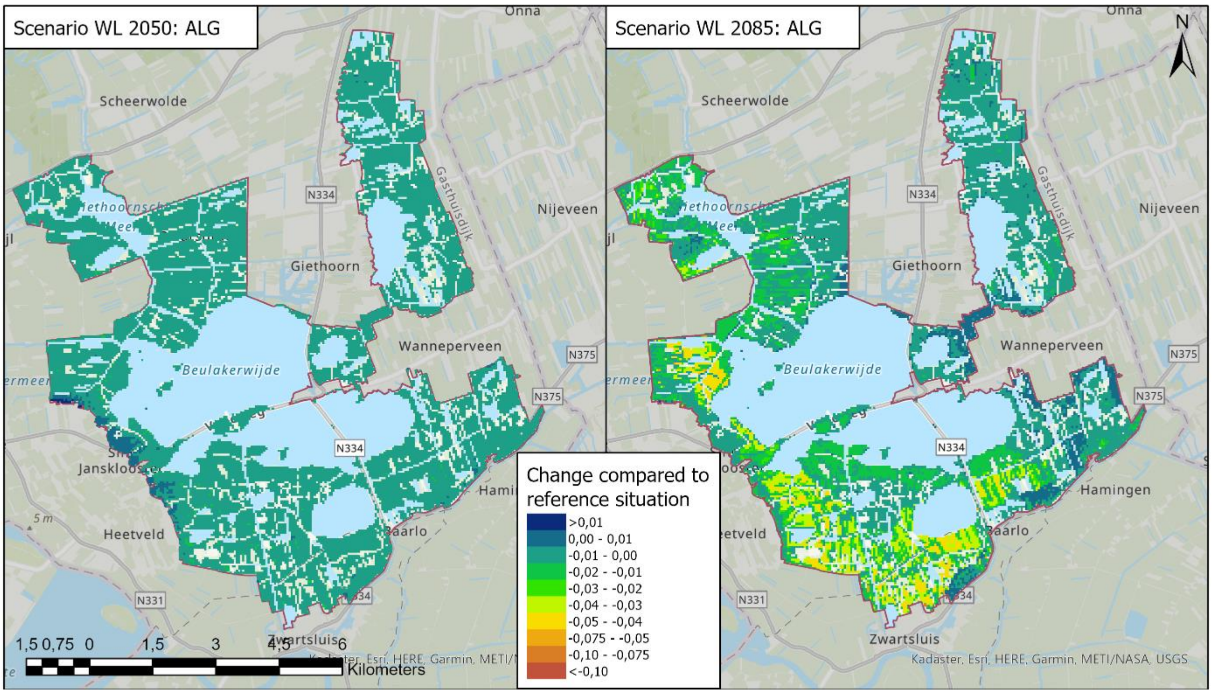

Scenario WL 2050: AHG
Scenario WL 2085: AHG
N
Onna
Scheerwolde
Nijeveen
Giethoorn
Gasthuisdijk
Wanneperveen
Beulakerwijde
Heetveld
Hamingen
Zwartsluis
N334
N375
N331
Change compared to reference situation
>0,05
0,04 - 0,05
0,03 - 0,04
0,02 - 0,03
0,01 - 0,02
0,00 - 0,01
<0.00
1,5 0,75 0 1,5 3 4,5 6
Kilometers
Kadaster, Esri, HERE, Garmin, METI/NASA, USGS

Appendix C – Change in ALG for all KNMI’14 scenarios






Scenario WH 2050: ALG
Scenario WH 2085: ALG
Scheerwolde
Giethoorn
Nijeveen
Wanneperveen
Beulakerwijde
Jansklooster
Heetveld
Zwartsluis
Hamingen
Gasthuisdijk
N334
N375
N331
Onna
N
Change compared to reference situation
>0,01
0,00 - 0,01
-0,01 - 0,00
-0,02 - -0,01
-0,03 - -0,02
-0,04 - -0,03
-0,05 - -0,04
-0,075 - -0,05
-0,10 - -0,075
<-0,10
1,5 0,75 0 1,5 3 4,5 6
Kilometers
Kadaster, Esri, HERE, Garmin, METI/NASA, USGS


Scenario WL 2050: ALG
Scenario WL 2085: ALG
Scheerwolde
Giethoorn
Nijeveen
Wanneperveen
Beulakerwijde
Jansklooster
Heetveld
Zwartsluis
Hamingen
Gasthuisdijk
N334
N375
N331
Onna
N
Change compared to reference situation
>0,01
0,00 - 0,01
-0,01 - 0,00
-0,02 - -0,01
-0,03 - -0,02
-0,04 - -0,03
-0,05 - -0,04
-0,075 - -0,05
-0,10 - -0,075
<-0,10
1,5 0,75 0 1,5 3 4,5 6
Kilometers
Kadaster, Esri, HERE, Garmin, METI/NASA, USGS

Appendix D – Model simplifications

As the model is a simplification of reality there is a certain level of uncertainty in the resulting groundwater levels due to imperfections, assumptions, and simplifications. The model used in this study is the MIPWA 3.0 groundwater model which has been adapted for the Wieden by Arcadis. In this model a set of assumptions have been implemented to provide the same conditions for the reference situation and the future scenarios. Due to these assumptions the model no longer represents the reference situation and cannot be compared to measured field data to validate the accuracy of the model.

From another project carried out by Arcadis the same model was used in an area called 'de Weerribben' which has similar area characteristics as De Wieden and is located directly north of De Wieden. In this project the model was validated based on a set of measurement points spread throughout the area in which the measured AHG and ALG are compared to the simulated AHG and ALG. From this assessment it became clear that the model has a mean absolute deviation[3] (MAD) of 0.23 m for AHG and 0.24 m for ALG (Dotinga & Bodde, 2018a). This results in the model being, on average, too wet (average deviation of -0.17 m).

To provide an estimation of the uncertainty range for the model used in this study, the model choices are evaluated based on system knowledge and the validation results for de Weerribben. Two important model changes have been made compared to the model from the Weerribben: different meteorological input data and different cell size. The meteorological input data (precipitation and evaporation) from the Weerribben has a different source than the data used in this study. Both datasets have the same spatial resolution (1km cell size) but the daily values are different. The overlapping timeseries (2000-2010) are compared using a paired t-test with a 95% confidence interval applying the hypothesis that the mean difference is zero to determine if the data set from the Wieden can influence the uncertainty in the model. From the result the hypothesis could not be rejected ($t\ 0.42 < 1.960$ & $t\ 0.38 < 1.960$) meaning the input data can be considered equal and thus has no influence on the uncertainty in the model.

The cell size in this study is set to 50m instead of 25m for de Weerribben due to computational reasons. Within De Wieden the subsurface is strongly heterogenous which makes it difficult to capture local differences in the model. This could result in an overestimation in a location and an underestimation 5m away. This makes the local deviation less important as long as there is no systematic deviation present. This allows for global effect calculations which can locally deviate due to e.g., sand pop ups.

Increasing the cell size reduces the accuracy of the schematization of the subsurface layers resulting in local features being less pronounced in the model. A test run simulating 1981 with a grid size of 50m and grid size of 25m is carried out and compared using the mean absolute deviation (Figure 22). The mean absolute deviation (0.014 m) shows that the reduced grid size only has a small influence on the daily average groundwater level. This results in the model being, on average, similar to the 25m model (average deviation of -0.008 m).

[3] The mean absolute deviation (MAD) is the average distance between each data value and the mean of the data set. It describes the variation in a dataset.

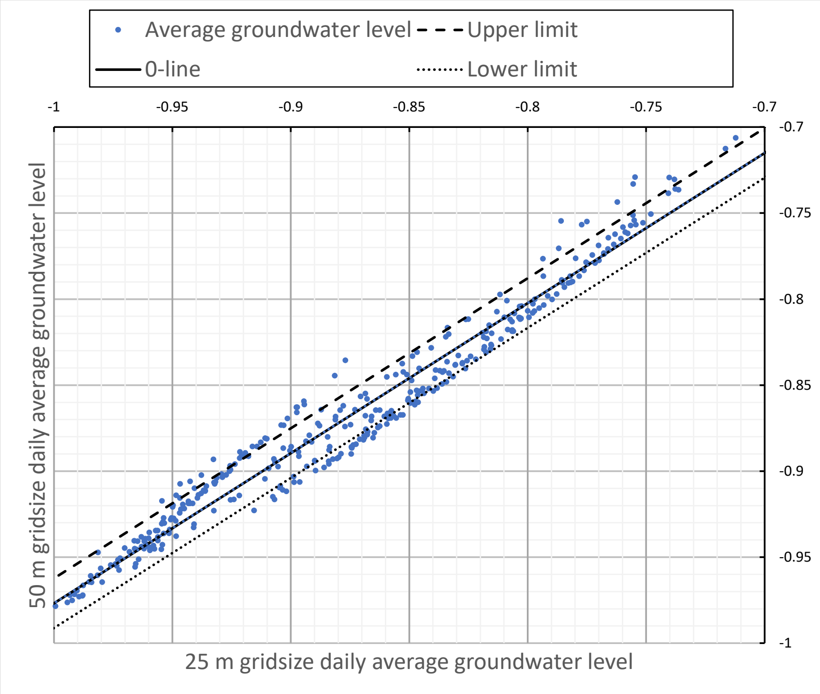
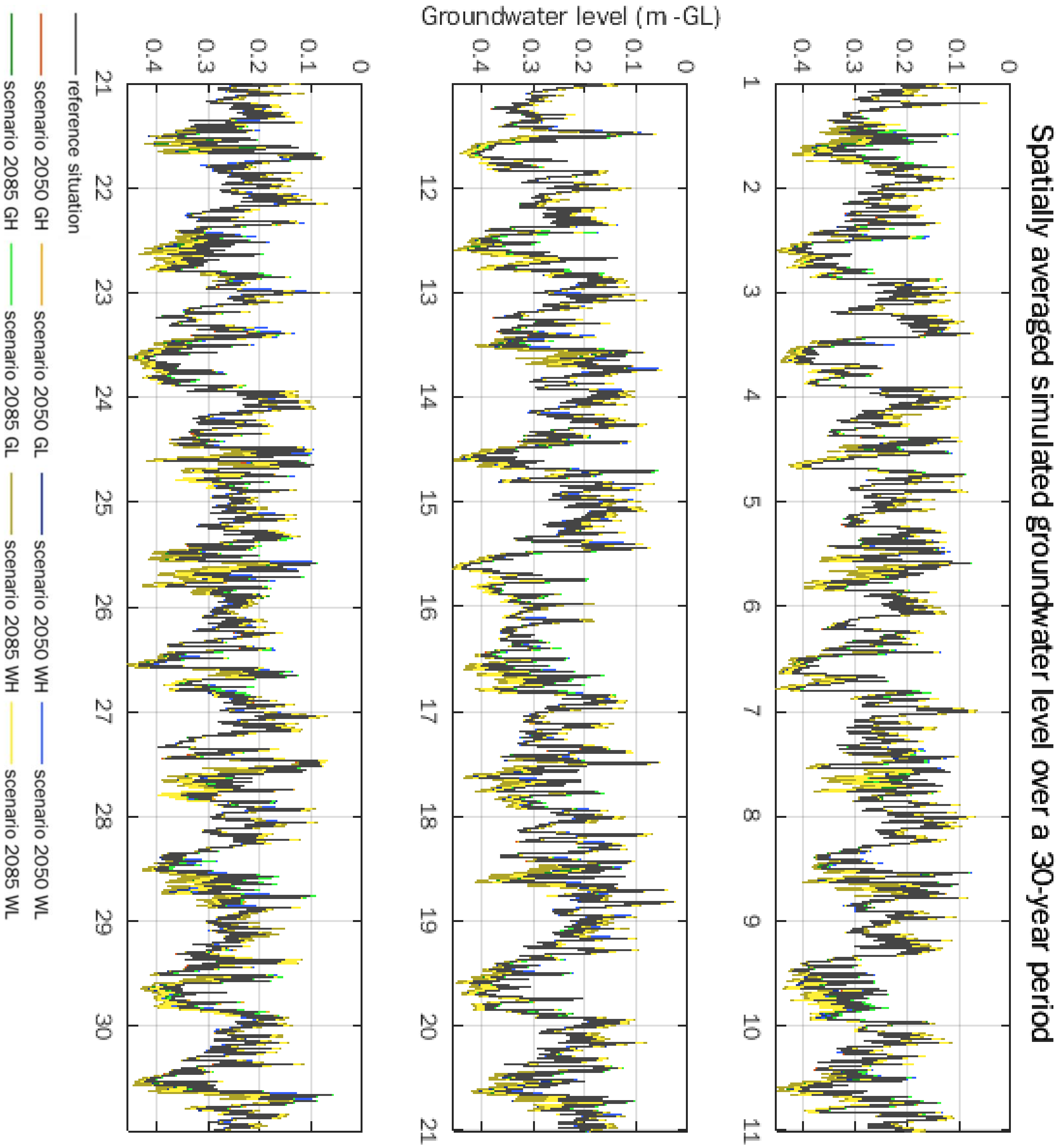


Figure 22: Comparison 25 m and 50 m grid size

From the assessment it becomes clear that the changes in the model have a very small influence on the model uncertainty, this means there is no reason to assume the model uncertainty is different to the model used for the Weerribben resulting in an uncertainty in the results of +/- 0.24 m. The focus of this study is the comparison between the reference situation and future scenarios, as all model runs use the exact same conditions the comparison between the scenarios and the reference situation is not limited by the uncertainty. This means that, as long as the water system is accurately implemented in the model and not altered in a scenario, any under- or overestimation will be the same for each scenario. This allows for the comparison between the different scenarios on a more detailed level.

Appendix E – Spatially averaged groundwater level for the reference situation and scenarios



Appendix F – Precipitation and evaporation distribution

Evaporation distribution during the reference situation and change for each KNMI'14 scenario

Evaporation distribution [mm]		*Reference situation*	*2050*				*2085*			
Lower limit	Upper limit		GH	GL	WH	WL	GH	GL	WH	WL
0.0	0.2	1131	-45	-43	-48	-60	-61	-48	-66	-55
0.2	0.4	1535	-11	-12	-20	-43	-5	-25	-49	-39
0.4	0.6	939	-7	+0	+5	+8	+3	+17	-4	-1
0.6	0.8	685	-29	-21	-40	-20	-23	-26	-33	-31
0.8	1.0	618	-7	+2	-10	-9	+3	+7	-21	-16
1.0	1.2	538	-27	-24	-53	-30	-36	-24	-57	-47
1.2	1.4	489	+6	+19	-7	+14	+5	+10	-23	+0
1.4	1.6	497	-17	-17	-27	-12	-29	-18	-47	-23
1.6	1.8	463	-42	-11	-42	-18	-34	-11	-52	-32
1.8	2.0	414	-14	-5	-10	+12	-24	+2	-12	+11
2.0	2.2	384	-19	-23	-27	-15	-16	-2	-46	-20
2.2	2.4	376	+3	+2	-27	-4	-7	-12	-34	-14
2.4	2.6	363	-39	-18	-38	-14	-38	+0	-32	-29
2.6	2.8	342	+14	+13	-5	+28	+5	+10	-27	+19
2.8	3.0	304	-12	+6	+8	-3	-5	-4	-4	-3
3.0	3.2	307	-12	-22	-29	-4	-21	-8	-28	-13
3.2	3.4	290	-11	+1	-12	+20	-7	+13	-27	+0
3.4	3.6	224	+28	+23	+46	+8	+24	+14	+40	+40
3.6	3.8	216	+0	+0	+2	+9	+1	+12	+22	+4
3.8	4.0	170	+42	+23	+36	+26	+41	+18	+44	+41
4.0	4.2	161	+15	-1	+34	+10	+22	-2	+32	+21
4.2	4.4	143	+4	+10	+24	+8	+4	+10	+49	+5
4.4	4.6	109	+29	+24	+20	+16	+25	+16	+41	+35
4.6	4.8	99	+32	+14	+38	+13	+30	+7	+31	+27
4.8	5.0	79	+18	+6	+29	+18	+24	+12	+55	+7
5.0	5.2	36	+45	+33	+50	+31	+41	+21	+77	+57
5.2	5.4	29	+16	+0	+47	-7	+33	-7	+54	+20
5.4	5.6	4	+25	+18	+31	+14	+27	+16	+58	+24
5.6	5.8	5	+14	+2	+14	+4	+16	+2	+37	+9
5.8	6.0	0	+1	+1	+11	+0	+2	+0	+19	+3
>6.0		0	+0	+0	+0	+0	+0	+0	+3	+0

Precipitation distribution during the reference situation and change for each KNMI'14 scenario

Precipitation distribution [mm]		*Reference situation*	*2050*				*2085*			
Lower limit	Upper limit		GH	GL	WH	WL	GH	GL	WH	WL
0	1.0	6070	-90	-96	-80	-91	-100	-156	-51	-11
1.0	2.0	1154	+69	+25	+59	+35	+46	+67	+51	-3
2.0	3.0	800	-3	+8	+0	+17	-6	+17	+4	-21
3.0	4.0	636	-13	-8	-39	-53	-11	-12	-44	-41
4.0	5.0	531	+4	-7	+6	+11	+4	-1	-40	-5
5.0	6.0	375	+1	+16	-7	-4	-1	+6	+2	-29
6.0	7.0	302	-15	-20	-16	-5	-4	-8	-44	-11
7.0	8.0	222	+3	+15	+5	+8	-4	+16	+5	+6
8.0	9.0	193	-9	-5	-24	-11	-10	-11	-14	-19
9.0	10.0	162	+6	+11	+14	+11	+14	+9	-14	+6
10.0	11.0	112	+8	+12	+16	+9	+14	+13	+29	+16
11.0	12.0	72	+20	+17	+19	+23	+23	+13	+28	+28
12.0	13.0	60	-11	+2	+6	+4	+3	+8	+21	+18
13.0	14.0	60	-1	-13	-4	-13	-8	-10	-1	-17
14.0	15.0	38	+12	+21	+7	+15	+10	+13	-1	+8
15.0	16.0	38	-7	-2	-4	+0	-2	+3	+4	+5
16.0	17.0	23	+11	+7	+4	+8	+8	+4	+3	+11
17.0	18.0	24	-6	-4	+1	+1	-5	-2	+3	+5
18.0	19.0	15	+8	+8	+6	+3	+7	+12	+11	+4
19.0	20.0	14	-2	-4	+5	+5	+1	-1	-1	+9
20.0	21.0	9	+7	+7	+3	+2	+6	+6	+10	+3
21.0	22.0	5	+4	+6	+7	+11	+9	+4	+10	+6
22.0	23.0	11	-5	-7	+3	-3	-6	-2	-1	+5
23.0	24.0	9	-4	+0	-5	-1	-4	-4	+6	+0
24.0	25.0	4	+9	+6	+1	+0	+6	+7	+1	+2
25.0	26.0	0	+2	+4	+11	+11	+7	+6	+5	+6
26.0	27.0	2	+0	-1	+1	+3	+1	+1	+1	+4
27.0	28.0	1	-1	+0	+1	+1	-1	-1	+7	+6
28.0	29.0	2	+0	-1	-1	-2	-1	-1	+2	+2
29.0	30.0	5	-4	-4	-3	-4	-4	-4	-2	-4
>30.0		1	+7	+7	+8	+9	+8	+8	+10	+11