Predicting Impact of Climate Change on Groundwater Dependent Ecosystems

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Abstract Groundwater plays a vital role in sustaining Groundwater Dependent Terrestrial Ecosystems (GWDTEs). As groundwater resources are controlled by long-term climate conditions, climate changes are potentially threatening these ecosystems. This paper presents a methodology to predict the potential impact of climate change on quantitative groundwater characteristics determining GWDTEs. The developed methodology includes coupling a distributed hydrological model with a transient groundwater flow model and is tested for the Kleine Nete basin, Belgium. Because the occurrence of phreatophytes is strongly determined by the dynamic properties of the groundwater system, a groundwater flow model with a high temporal and spatial distribution was developed using MODFLOW. The groundwater recharge and river heads are estimated with the WetSpa model using a daily timestep to incorporate the impact of changes in rainfall intensity. Potential future hydrological changes are calculated by comparing the hydrological state corresponding to 1960-1991 with future scenarios developed for 2070-2101. Since the uncertainty in the prediction of the future climate components such as potential evapotranspiration (PET) and precipitation is still high an ensemble of 28 climate scenarios were chosen from the PRUDENCE database. For each of these scenarios the recharge, river stage, groundwater head and groundwater flow are estimated for 32 years with half monthly timesteps. Comparison of the original measured PET with future PET shows that the PET during summer rises in all future scenarios with about 1 mm day^{-1}. For winter conditions the scenarios predict little change in PET. Future precipitation shows an increase in precipitation during winter and a decrease during summer. Future groundwater recharge decreases on average with 20 mm year^{-1}, the highest decreases are simulated from July until September. Average groundwater heads indicate an average decrease of 7 cm. Groundwater levels in interfluves generally show decreases up to 30 cm. The mean lowest groundwater level decreases on average with 6 cm, while the mean highest groundwater level decrease about 3 cm. On average the groundwater discharge reduces with 4%, from 5 to 4.8 m³ s^{-1}. GWDTEs that currently receive a low groundwater discharge, are likely to disappear due to future climate changes.

Keywords groundwater; groundwater dependent terrestrial ecosystems; climate change; Belgium; groundwater recharge

INTRODUCTION

Freshwater resources are vulnerable to climate changes (IPCC, 2007). Because groundwater is less visible and has a more complex relationship with the climate then surface water bodies it has been studied less up till now (Kundzewicz and Döll, 2009; Scibek et al., 2007). Nevertheless, groundwater is a major source of drinking water across the world and plays a vital role in maintaining the ecological value of many areas (IPCC, 2007; UN/WWAP, 2009). To ensure drinking water availability and protect Groundwater Dependent Terrestrial Ecosystems (GWDTEs) in the future it is important to assess the impact of expected climate changes on the groundwater resources.

Assessing the impact of climate changes on the groundwater resources requires methods to estimate the water flux in and out of the groundwater system. Previous studies show a variety of complexity to estimate groundwater recharge. For example Chen et al. (2002) and Serrat-Capdevila et al. (2007) apply a simple linear function including precipitation and temperature, while Woldeamlak et al. (2007), Jyrkama and Sykes (2007), van Roosmalen et al. (2009) amongst others apply a more complex approach to simulate the groundwater recharge. To estimate groundwater recharge under changing climatic conditions, Jyrkama and Sykes (2007) advice a physically based approach that accounts for temporal variation of the climatic variables and spatial variation of the surface and subsurface properties of the study basin.

The uncertainty on climate change forecasts is still very high. The total uncertainty is a combination of uncertainty caused by future world visions, and in this case in particular the resulting future greenhouse gas emissions, and the uncertainty of the General and Regional Circulation Models (GCMs and RCMs). To improve the assessment of future climate changes on the groundwater systems Hendricks Franssen (2009) emphasizes the importance of downscaling future precipitation from GCMs. Kundzewicz et al. (2008) suggest for example the use of joint analysis of ensembles of climate models to characterize uncertainties.

The majority of the current studies assessing the impact of climate change on the groundwater system estimate the impact on a yearly or seasonal average condition (e.g. Scibek et al., 2006; Scibek and Allen, 2006; Woldeamlak et al., 2007). A few recent studies have applied transient methods to estimate the impact of climate changes on the groundwater system (van Roosmalen et al., 2009; Goderniaux et al., 2009). However, both van Roosmalen et al. (2009) and Goderniaux et al. (2009) limit the analysis of the transient results to the predicted change in some observations wells. Nevertheless, the groundwater dynamics within a year is of major importance for groundwater dependent terrestrial ecosystems (Naumburg et al., 2005). The groundwater dependent vegetations along with riverine landscapes have on its turn an important ecological function (Naumburg et al., 2005) and should therefore be protected. Applying transient models also allows including more accurately precipitation intensity and number of dry and wet days projections due to climate change altering the soil moisture content and consequently influencing largely the groundwater recharge.

The objective of this study is to assess the impact of climate change on the groundwater system. We will focus on the intra-annual dynamics of the groundwater system and study differences in yearly extreme dry and wet periods. Hydrological results of this research could be applied by ecologists to assess the impact of future climate change on groundwater dependent terrestrial and riverine ecosystems.

STUDY AREA

The study area is the Kleine Nete basin, which is a sub-basin of the Scheldt basin. The Kleine Nete basin has an area of 581 km². The elevation ranges from 3 to 48 m, the average slope is about 0.4%. Interfluves are slightly elevated, the valleys broad and swampy. The dominant soil texture in the basin is sand, though in the valleys some loamy sand, sandy loam and sandy clay is present. The region has a temperate climate characterized by a warm summer and a cool winter with little snowfall. The average annual presentation during the period 1960-1991 was 828 mm with a standard deviation of 136 mm. Precipitation is distributed almost equal over the year. Over the same period 1960-1991 the measured potential evapotranspiration (PET) is 664 mm with a standard deviation of 47 mm. Sandy deposits of Miocene, Pliocene and

Pleistocene form a high productive aquifer with a depth of roughly 200 meter (Wouters and Vanderberghe, 1994). The land cover in the study basin consists mainly of agricultural fields including meadows (60%), coniferous and mixed forest (20%) and urban areas (10%). Groundwater is extensively used in the basin, in total there are 565 wells which extract a total of 54,291 m^3 day^{-1} of which about 30200 m^3 day^{-1} is extracted by a public drinking water company.

Within the Kleine Nete catchment several ecologically important areas are protected by the European Natura2000 network, set up for the protection of Europe's most vulnerable habitats. Several of these habitats depend largely on oligotrophic and mesotrophic site conditions. Typical habitats are Northern wet heaths, Shady woodland fringes, Atlantic Quercus robur – Betula woods, Alnus-Fraxinus woods, etc.

METHODOLOGY

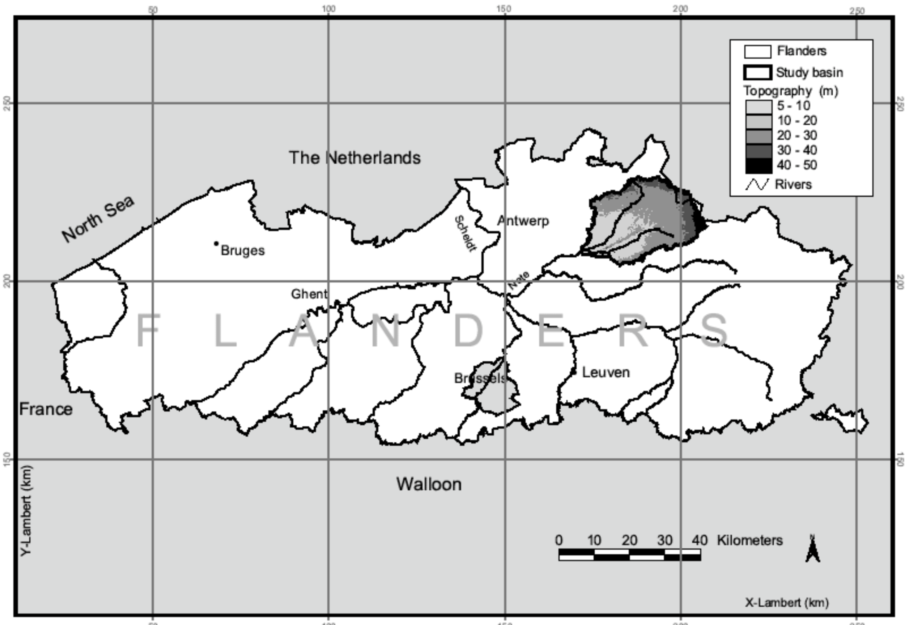

Fig. 1 *Location of the study area within the Flanders region (Belgium).*

This study compares the groundwater head and flux for the reference period (1960-1991) with future climate scenarios (2071-2100). Climate change scenarios are obtained from the PRUDENCE database and combine several General and Regional Circulation Models (Christensen and Christensen, 2007). All scenarios applied in this research are based on the A2 and B2 world views (Nakicenovic et al., 2000). In total 28 scenarios climate change scenarios were obtained (Table 1), for each of these scenarios daily future PET and precipitation series are simulated, based on the reference PET and precipitation series from measuring stations near the study area.

Table 1 Climate change scenarios applied is this study (Christensen and Christensen, 2007).

	SCENARIO	Institute	Model	SRES SCENARIO	Driving data
1	SMHI-MPI-A2	SMHI	RCAO	A2	ECHAM4/OPYC
2	SMHI-MPI-B2	SMHI	RCAO	B2	ECHAM4/OPYC
3	SMHI-HC-22	SMHI	RCAO	A2	HadAM3H
4	SMHI-A2	SMHI	RCAO	A2	HadAM3H
5	SMHI-B2	SMHI	RCAO	B2	HadAM3H
6	KNMI	KNMI	RACMO	A2	HadAM3H
7	METNO-A2	METNO	HIRHAM	A2	HadAM3H
8	METNO-B2	METNO	HIRHAM	B2	HadAM3H
9	DMI-S25	DMI	HIRHAM	A2	HadAM3H
10	DMI-ecsc-A2	DMI	HIRHAM	A2	ECHAM4/OPYC
11	DMI-ecsc-B2	DMI	HIRHAM	B2	ECHAM4/OPYC
12	DMI-HS1	DMI	HIRHAM	A2	HadAM3H
13	DMI-HS2	DMI	HIRHAM	A2	HadAM3H
14	DMI-HS3	DMI	HIRHAM	A2	HadAM3H
15	ETH	ETH	CHRM	A2	HadAM3H
16	HC-adhfa	HC	HadRM3P	A2	HadAM3P
17	HC-adhfe	HC	HadRM3P	A2	HadAM3P
18	HC-adhff	HC	HadRM3P	A2	HadAM3P
19	HC-adhfd-B2	HC	HadRM3P	B2	HadAM3P
20	MPI-3005	MPI	REMO	A2	HadAM3H
21	MPI-3006	MPI	REMO	A2	HadAM3H
22	CNRM-DC9	CNRM	ARPEGE	B2	ARPEGE
23	CNRM-DE5	CNRM	ARPEGE	B2	HadCM3
24	CNRM-DE6	CNRM	ARPEGE	A2	ARPEGE
25	CNRM-DE7	CNRM	ARPEGE	A2	ARPEGE
26	GKSS-SN	GKSS	CLM	A2	HadAM3H
27	UCM-A2	UCM	PROMES	A2	HadAM3H
28	UCM-B2	UCM	PROMES	B2	HadAM3H

The impact of the climate change on the groundwater system is simulated by applying a coupled WetSpa – MODFLOW approach. WetSpa (Liu et al., 2003), a physically based distributed hydrological model, simulates with a daily time step the river discharge at the outlet of the basin and the groundwater recharge for each 50 by 50 m raster cell in the watershed. The WetSpa model was calibrated using the measured river discharges and estimated baseflow at the catchment outlet. The results of a hydraulic model for the main rivers in the basin are used to obtain river heads for every 50 m transect of those rivers, based on WetSpa simulated river discharge at the basin outlet. The obtained river heads and the groundwater recharge are averaged to a half monthly time step for the MODFLOW model. The groundwater flow model MODFLOW (Harbaugh and McDonald, 2000) simulates the effect of the climate induced changes in river head and groundwater recharge on the groundwater level and flux. The watershed boundaries of the model are set to no-flow boundaries. All rivers, canals and lakes are taken as internal boundary conditions and parameterized with the RIVER package. The drainage from ditches and small streams are simulated with the

DRAIN package. The MODFLOW model is calibrated using 10,226 head observation, measured between 1992 and 2001, from 113 observation wells more or less equally distributed over the basin.

The mean highest (MHGL), mean lowest (MLGL) and mean spring (MSGL) groundwater levels are calculated respectively as the three highest, the three lowest and the three groundwater level measurements around the 1st of April per year, based on two weekly measurements, and averaging these values over at least eight years (Sluijs and Gruijter, 1985). Wetland vegetation is sensitive to MHGL, MLGL and MSGL. These variables are therefore useful to determine if climate changes are expected to influence groundwater dependent terrestrial ecosystems. The groundwater discharge frequency is calculated as the percentage of time for which groundwater discharge is simulated in a 50 by 50 meter pixel of the MODFLOW model.

RESULTS

Model calibration and validation

The WetSpa model is calibrated and validated using daily discharge at the watershed outlet measured respectively between 1992-1996 and 1997-2001. Model efficiencies for the validation period are 73%, 62% and 72% for respectively the Nash-Sutcliffe coefficient, model efficiency for low flows and model efficiency for high flows (Hoffmann et al., 2004). These efficiencies show that the model is performing well both for high and low flow. The estimated baseflow from the WetSpa model was compared with the baseflow derived from an automated baseflow filter (Arnold et al., 1995; Arnold and Allen, 1999). Looking at the baseflow filters as observations, the baseflow estimated with WetSpa has a Nash-Sutcliffe efficiency of 87%.

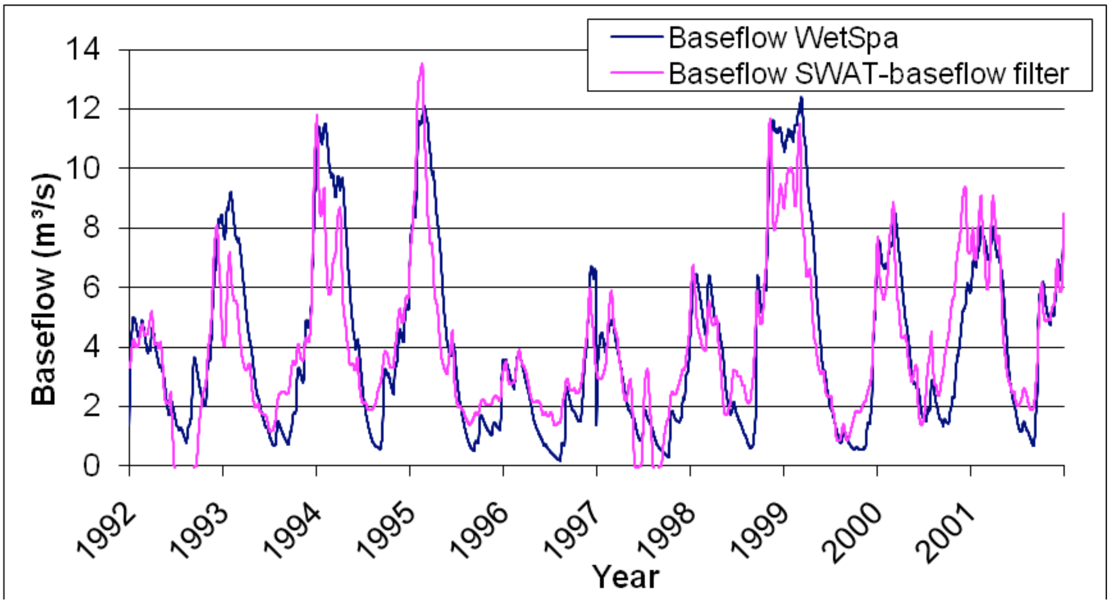

Fig. 2 *Comparing baseflow simulated with WetSpa and baseflow filtered by SWAT baseflow filter.*

The transient groundwater model resulted for the period of 1992-2001 in an average BIAS, between observed and simulated hydraulic heads, of -0.03 m, a mean average error of 0.59 m and a root mean square error of 0.81 m.

Climate scenarios

Evapotranspiration and precipitation are the major climatic factors influencing groundwater recharge. Figure 3 and 4 illustrate respectively intra-annual dynamics in potential evapotranspiration (PET) and precipitation of the 28 climate change scenarios. The graphs in Fig. 3 and 4 show respectively the half monthly PET and precipitation amounts (mm day^{-1}), averaged over the 32 considered years, simulated for the reference period (blue line), the scenarios (grey lines) and the average of all scenarios (black line). Orange bars show the standard deviation of the different scenarios.

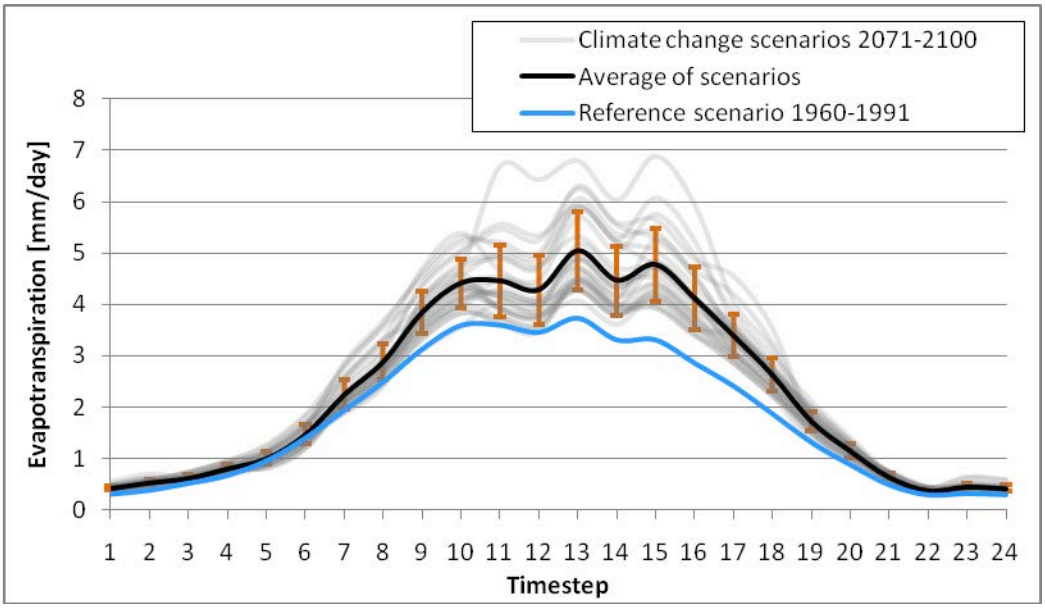

Fig. 3 *Average intra-annual variability of PET for the reference climate (1960-1991), climate scenarios (2071-2100) and the average of the climate scenarios.*

From Fig. 3 we read that during winter the PET is low and is not expected to change significantly for the future scenarios. During summer however, all scenarios project an increase in potential evapotranspiration with on average 1 mm day^{-1} and a standard deviation between the scenarios of 0.75 mm day^{-1}.

During the reference period (1960-1991) the average precipitation was 821 mm year^{-1}. The average future precipitation is predicted by the climate change scenarios as 767 mm year^{-1}, with a standard deviation of 36 mm year^{-1}. Generally an increase in precipitation is projected for the ‘winter’ months (roughly November – April) while a decrease is projected for the ‘summer’ months. On average the scenarios predict around 100 mm less precipitation during ‘summer’ and about 50 mm more for the ‘winter’. Although all simulated scenarios follow roughly the same trend, there is a relatively large spread in the predicted amount of future precipitation.

Groundwater recharge

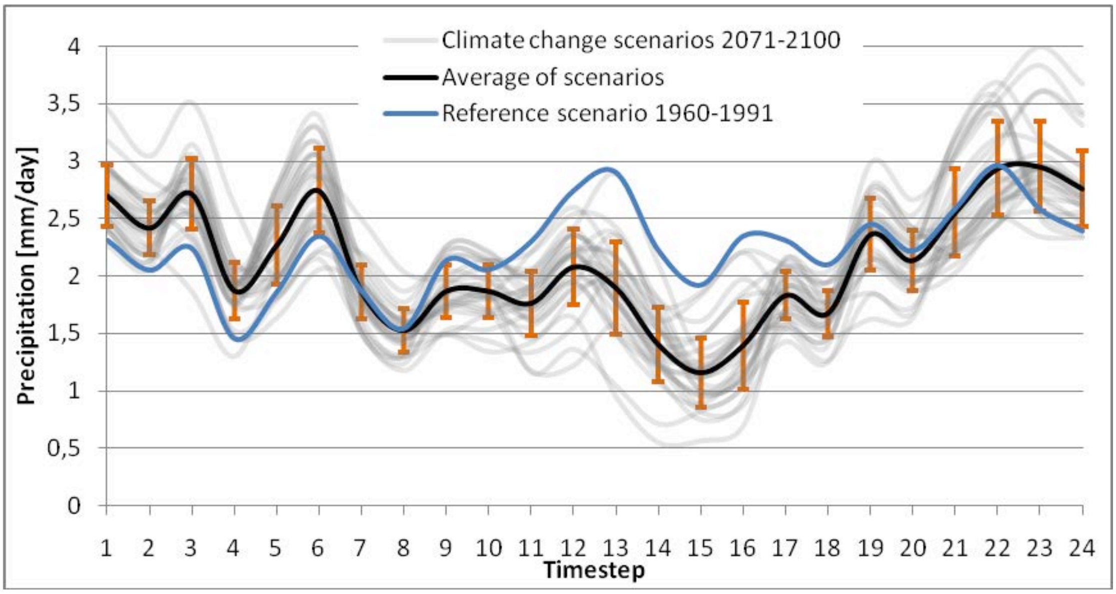

Fig. 4 *Average intra-annual variability of precipitation for the reference climate (1960-1991), climate scenarios (2071-2100) and the average of the climate scenarios.*

Figure 5 illustrates the intra-annual dynamics of groundwater recharge simulated for the reference (blue) and climate change scenarios (grey) estimated by WetSpa. Orange bars show the standard deviation from the different future climate scenarios.

Similar as for the precipitation, the groundwater recharge decreases from April to November and increases from December to March. During the period 1960-1991 the average simulated groundwater recharge is 291 mm year^{-1}. The average future groundwater recharge predicted by the WetSpa model is 271 mm year^{-1}.

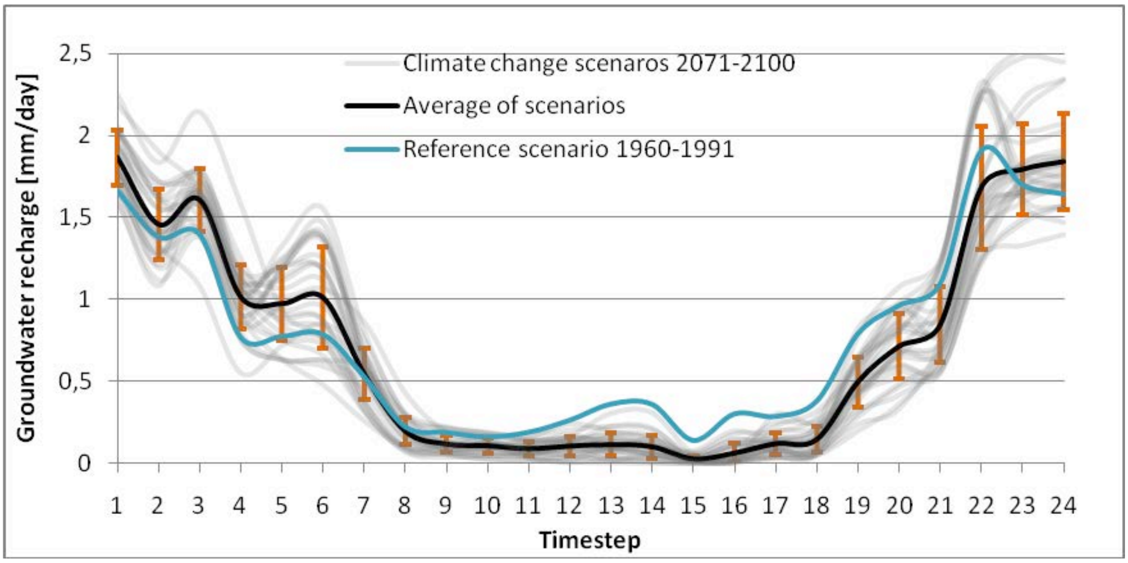

Fig. 5 *Average intra-annual variability of groundwater recharge for the reference climate (1960-1991), climate scenarios (2071-2100) and the average of the climate scenarios.*

Figure 6 illustrates the position of each scenario on the probability distribution of the average change in groundwater recharge obtained from all scenarios, assuming a normal probability distribution. On average the yearly groundwater recharge will decrease with 20 mm year^{-1} with a standard deviation of also 20 mm year^{-1}. Assuming the climate change scenarios are normally distributed, the probability of an average decrease in groundwater recharge is about 84%.

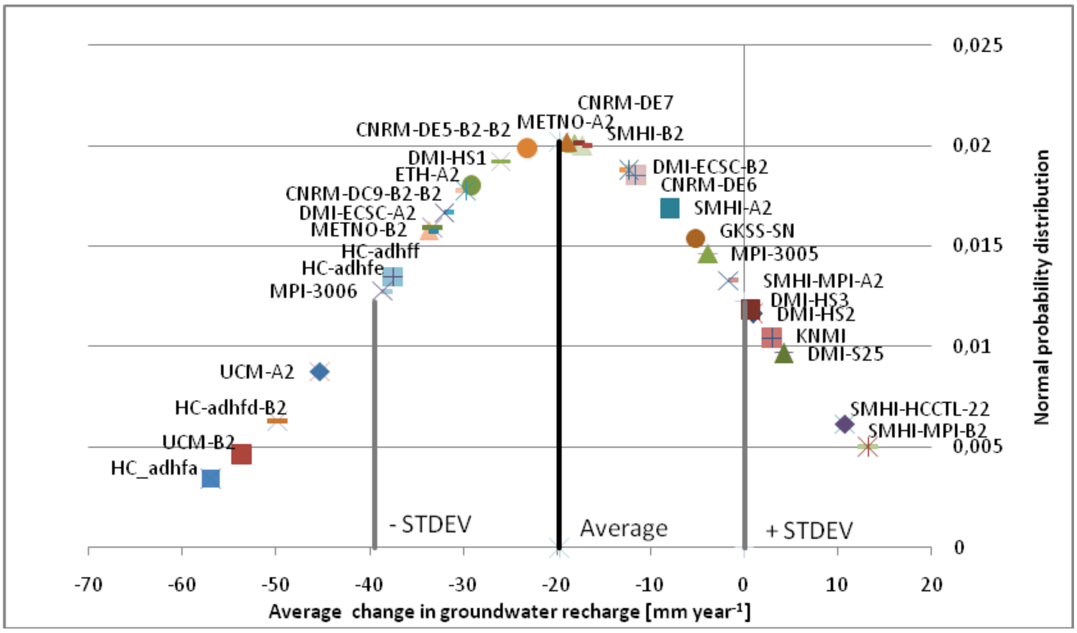

Fig. 6 *Distribution of average groundwater recharge change between the different climate change scenarios.*

Groundwater system

Figure 7a shows the difference between the average groundwater heads of all future scenarios and the current average groundwater level. Due to a convergence problem of the MODFLOW model with scenario CNRM-DE6, this scenario was excluded in all further analyses. From Fig. 7a it is clear that the lowest change in average groundwater head occurs in the valleys. The largest changes occur near the ridge and near the borders of the catchment where the groundwater head drops up to 0.3 m. On average the groundwater head declines with 7 cm, from 2.07 m to 2.14 m below topography with a standard deviation between the different pixels of 4 cm and between the different scenarios of 5 cm.

Figure 7b shows the difference between the average of the MHGL maps from the future scenarios and the current MHGL map. The maps clearly illustrate that the MHGL decreases significantly especially at the more elevated areas and near the borders of the catchment. The basin average calculated decrease, using the average MHGL of the different scenarios, is 3 cm (from 1.63 to 1.66 m below the topography) with a standard deviation between the different pixels of 3 cm and between the different scenarios of 5 cm. Figure 7c indicates the difference between the average of the MLGL maps from the future scenarios and the current (1960-1991) MLGL map. The basin average calculated decrease, using the average MLGL of the different scenarios, is 6 cm (from 2.45 to 2.51 m below the topography) with a standard deviation between the different pixels in the basin of 3 cm and between the different scenarios of also 3 cm. The decrease in MSGL is less pronounced, in the valleys we even notice a small increase in head, on the interfluves there is generally still a groundwater head decrease around the start of spring (Fig 7d).

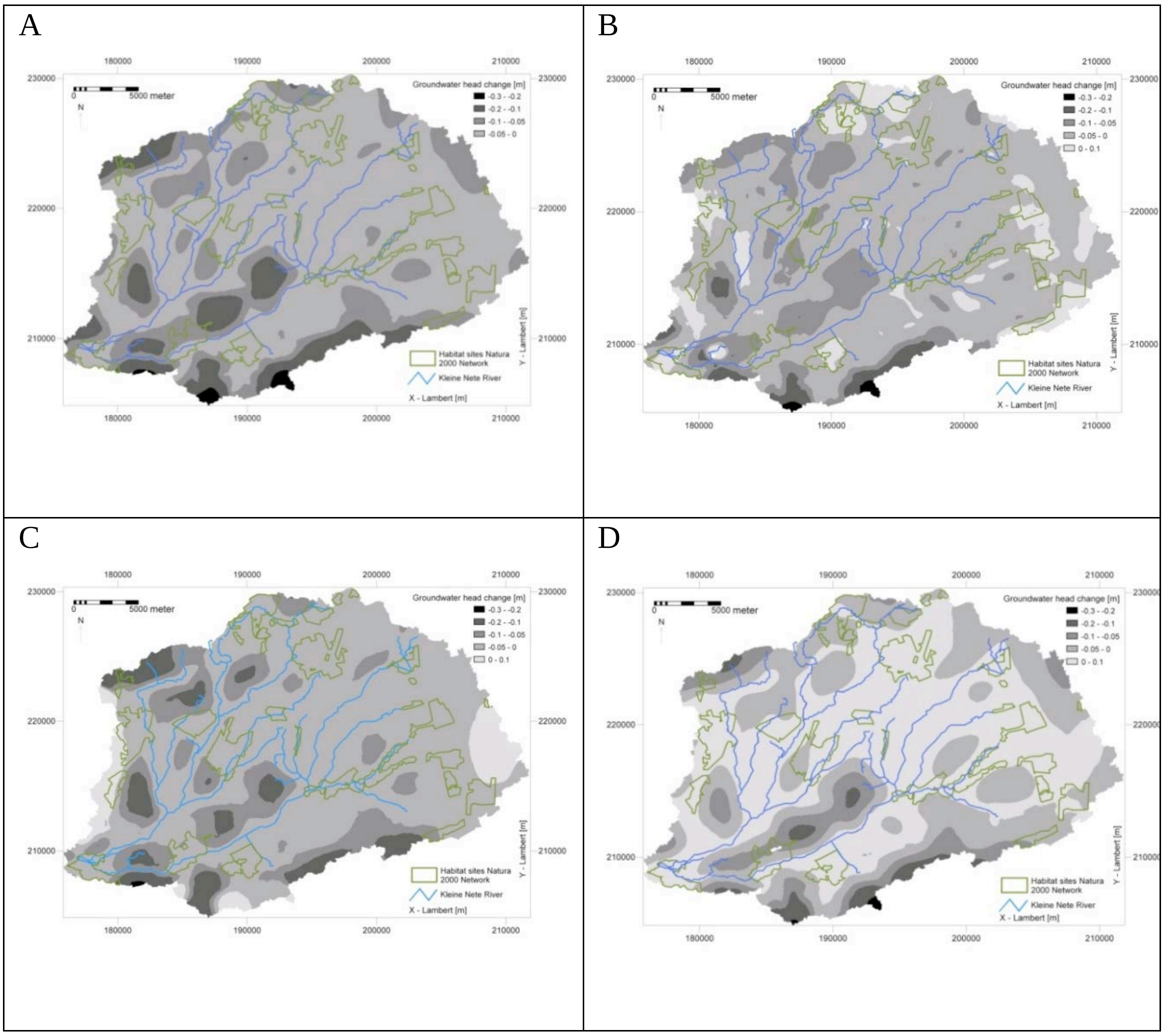

Fig. 7 *Change in average groundwater head (a), MHGL (b), MLGL (c) and MSGL (d) between the reference condition (1960-1991) and the average of the twenty-eight scenarios (2071-2100).*

Figure 8a shows the average ‘current’ frequency that drainage via the DRAIN conditions, further called groundwater discharge, occurs. The frequency is calculated over half-monthly time steps during the period 1960-1991. Areas having a high groundwater discharge frequency receive groundwater discharge during almost the whole year, areas with a lower frequency generally have groundwater discharge only during winter. From Fig. 8 we observe that open waters, along with some wetlands areas have a higher frequency in groundwater discharge. In the vicinity of these wetlands there are often areas with a lower groundwater discharge frequency, these areas often still have a high ecological value.

Figure 8b illustrates the change in groundwater discharge frequency comparing the average frequency of the different climate change scenarios with the current condition. The change is indicated absolute to the groundwater frequency presented in Fig. 8a. It is concluded that especially areas with a lower current groundwater discharge frequency (Fig. 8a), have a high chance to disappear due to climate changes.

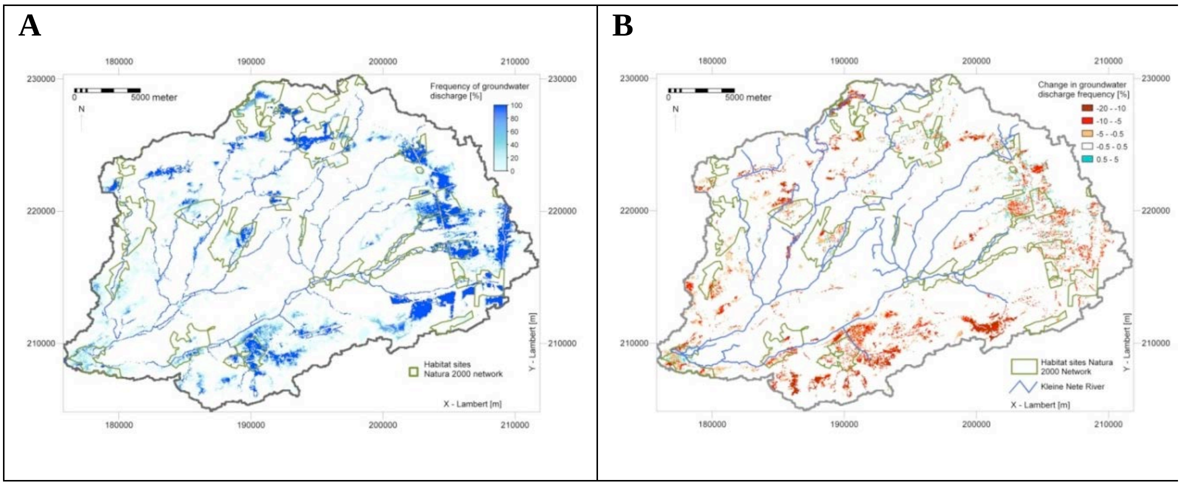

Fig. 8 *Reference frequency of groundwater discharge (a) and change in groundwater discharge frequency between reference period and the average of the future scenarios (b).*

Figure 9a visualizes the reference average daily groundwater discharge within the basin. Open waters, especially rivers are clearly recognizable due to their higher groundwater discharge, usually above 8 mm day^{-1}. Groundwater discharge areas beside open water generally have a flux lower than 4 mm day^{-1}. The average simulated groundwater discharge within the Kleine Nete basin is 5 $m^3 s^{-1}$. The average discharge at the basin outlet measured in Grobbendonk is 7 $m^3 s^{-1}$.

Figure 9b illustrates the change in groundwater discharge. Green pixels indicate an increase in groundwater discharge, orange to dark red pixels indicate a groundwater discharge decrease. Most pixels show a decrease in groundwater discharge, however there is also a considerable area where the groundwater discharge increases. The average groundwater discharge in the basin drops with 4.1% from 5 $m^3 s^{-1}$ to 4.8 $m^3 s^{-1}$.

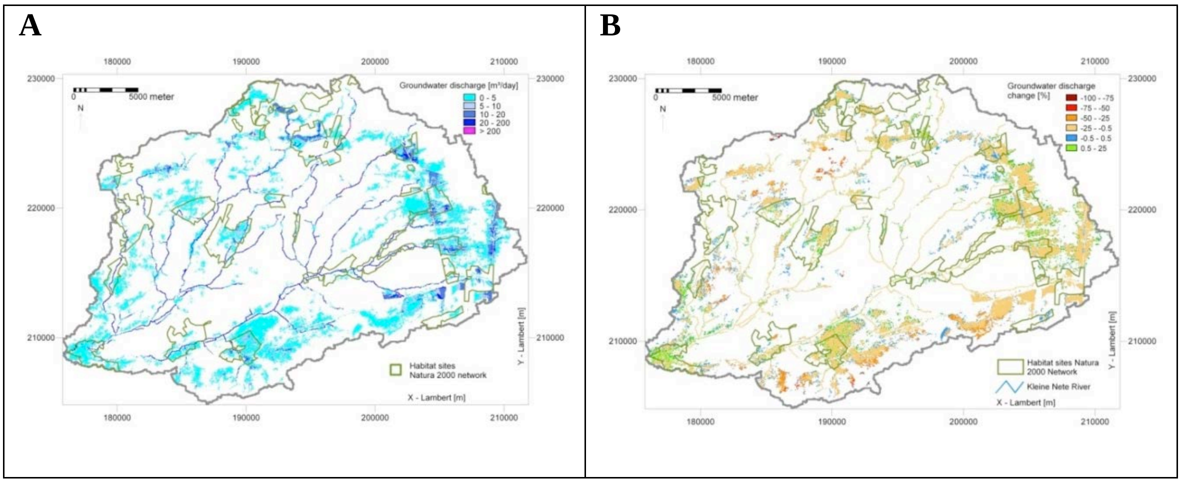

Fig. 9 *Reference groundwater discharge (a) and change in groundwater discharge between the reference period and the average of the future scenarios (b).*

DISCUSSION

Methodology

The applied methodology couples the distributed water balance model WetSpa with a MODFLOW groundwater model. The WetSpa model is applied to simulate the effects of climate changes on the groundwater recharge and on river discharges, which are converted to river heads. However, the groundwater component of the WetSpa model is highly simplified and does not include the calculation of distributed groundwater levels and fluxes. The advantage of simplifying the groundwater system in the WetSpa model is that the calculation time is relatively low. To assess the impact of the climate change scenarios on the groundwater system, including groundwater levels and fluxes, we apply the output of the WetSpa model in a transient MODFLOW model.

Similar to van Roosmalen et al. (2009) it is observed that our groundwater model captures the dynamics over time quite well, even though the mean simulated and observed values may differ considerably. However, in the context of this paper we mainly compared the results of the reference scenario with future climate change scenarios, in that sense is capturing appropriately the dynamics of the groundwater more important than obtaining the exact groundwater depth.

Further research should examine how models could be improved for assessing the impact of climate changes on the groundwater system, e.g. including vegetation growth, physically based ET calculation, hourly time discretization, further coupling of surface-subsurface processes without increasing the data requirements and computation time too extensively.

Uncertainties

Although climate models are continually improved, uncertainties on predicting the future climate remain high, especially for precipitation, which is the main driver in hydrology (IPCC, 2007). In order to cope to a certain extend with this uncertainty an ensemble of 28 climate change scenarios, taken from the PRUDENCE database, is used. It should however be mentioned that the PRUDENCE project examined only A2 and B2 scenarios, limiting the spread in future greenhouse gas concentrations projected by the SRES scenarios (Déqué et al., 2007). This study is one of the first to incorporate an ensemble of climate changes scenarios to study the impact on the groundwater system. Additionally, the model improves the spatial and temporal resolution of previous studies which makes the model more suited to simulate hydrological extremes.

Next to the input data uncertainty also the WetSpa and MODFLOW model have a significant uncertainty. The WetSpa model has been calibrated with river discharge measurements, the MODFLOW model with groundwater head observations, resulting in a Nash-Sutcliffe model efficiency of 73% for the river discharge and 87% for the baseflow, and a root mean square of 0.81 m for the MODFLOW model. Both model efficiencies are considered reasonable but should be kept in mind when analyzing the obtained results.

Results

All climate scenarios applied in this study project the PET to stay almost constant in winter but to rise significantly during summer. The scenarios are less consentient for precipitation, nevertheless on average the scenarios predict the precipitation to increase in winter but to decrease in summer. The simulated groundwater recharge change can roughly be explained by the predicted changes in PET and precipitation. From December to March there is an increase in groundwater recharge, while from April to November there is a decrease.

Simulated changes in groundwater head are spread widely throughout the basin, ranging from low changes generally in the valleys to high changes at the interfluves and near the edges of the basin. The average intra-annual groundwater head generally decreases, the highest groundwater heads shift from December – January to February – March – April, the lowest groundwater heads shift from September to October. Groundwater discharge frequency and flux seem quite sensitive to climate changes. Especially groundwater discharge areas next to open waters appear vulnerable for climate changes. Several protected habitats could receive less groundwater discharge due to the projected climate changes, which would lead to a decay of biodiversity.

We notice a significant spread in future groundwater recharge, groundwater head and groundwater flux calculated from the different scenarios. Previous studies by Kirshen (2002), Croley and Luukkonen (2003), Woldeamlak et al. (2007) and Serrat-Capdevila et al. (2007) also obtained a high variability in future groundwater trends for different scenarios. The general trend noticed from this study clearly indicates a decrease in groundwater recharge, resulting in lower groundwater levels and less groundwater discharge. It should be mentioned that the applied scenarios in this study do not cover the full climate change uncertainty. The higher the number of scenarios used in the ensemble the more information can be derived from the uncertainty of the climate change predictions. In future studies on the impact of climate change on hydrology, the use of stochastic rainfall models should be considered (Burton et al., 2009). These stochastic rainfall models could provide a very high number of projected precipitation series, which would increase the uncertainty bounds on the projected hydrological changes.

Jyrkama and Sykes (2007) emphasized the importance of distributed groundwater recharge simulations. The result of this study confirms their conclusion that the impact of the climate change on groundwater recharge, depth and flow is highly variable in space.

Apart from climate change also other anthropogenic induced changes are likely to have in impact on the future groundwater quantity. Dams et al. (2008) studied the impact of projected land-use changes on the average groundwater head. The results showed that the average decrease in groundwater head was rather small but the decreases were concentrated around the urban areas. To approximate the future state of our groundwater resources the combined effect of different factors such as: climate change, land-use change, groundwater exploitation should be taken into account.

CONCLUSIONS

GWDTEs are sensitive to changes in the groundwater system. As freshwater resources such as groundwater are sensitive to climate change, these climate changes threaten the ecologically important groundwater dependent ecosystems. Therefore this study aimed to assess the impact of climate changes on groundwater head and flux.

Because the uncertainty of the future precipitation and PET is high, we chose to use an ensemble of 28 different climate change scenarios. The scenarios were obtained from the PRUDENCE database. From the results we learn that the general trend is similar for all these scenarios, the quantity of the predicted changes on the other hand seems quite uncertain. It is important to be aware of this uncertainty and look at the results as projected trends rather than exact changes.

In the Kleine Nete basin, climate changes seem to result in a significant decrease in groundwater recharge, reducing the average groundwater level and groundwater discharge. Closer analysis of the intra-annual groundwater depth trend shows that especially the yearly lowest groundwater levels are decreasing. The mean spring groundwater depth shows the lowest decrease due to climate change. Model simulations show that also groundwater discharge flux and frequency will decrease due to climate changes, especially in areas currently receiving relatively little groundwater discharge. Because groundwater discharge is a controlling factor for some protected natural habitats in the study basin, the predicted decrease could result in a loss of valuable vegetation types in the study area.

From the results of the study we can conclude that predicted changes in the groundwater system vary largely in space and time. In future climate change impact assessments of the groundwater system, the time and space discretisation should therefore be carefully selected. To receive more insight knowledge on the impact of climate change on the groundwater system, similar studies should be applied on different catchments to incorporate both the spatial variability of the climate changes and the effect of the basin characteristics.

Considering the results of this study, we advice authorities to closely monitor groundwater levels, especially at the end of the summer, both in groundwater recharge and discharge zones in order to prevent loss of protected habitats. Adaptive measures such as increasing groundwater recharge could counteract the projected effects of climate changes on the groundwater system.

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