Effects of climate change on the groundwater system in the Grote-Nete catchment, Belgium

S. T. Woldeamlak · O. Batelaan · F. De Smedt

Abstract The effects of climate change on the groundwater systems in the Grote-Nete catchment, Belgium, covering an area of 525 km^2, is modeled using wet (greenhouse), cold or NATCC (North Atlantic Thermohaline Circulation Change) and dry climate scenarios. Low, central and high estimates of temperature changes are adopted for wet scenarios. Seasonal and annual water balance components including groundwater recharge are simulated using the WetSpass model, while mean annual groundwater elevations and discharge are simulated with a steady-state MODFLOW groundwater model. WetSpass results for the wet scenarios show that wet winters and drier summers are expected relative to the present situation. MODFLOW results for wet high scenario show groundwater levels increase by as much as 79 cm, which could affect the distribution and species richness of meadows. Results obtained for cold scenarios depict drier winters and wetter summers relative to the present. The dry scenarios predict dry conditions for the whole year. There is no recharge during the summer, which is mainly attributed to high evapotranspiration rates by forests and low precipitation. Average annual groundwater levels drop by 0.5 m, with maximum of 3.1 m on the eastern part of the Campine Plateau. This could endanger aquatic ecosystem, shrubs, and crop production.

Résumé Les effets du changement climatique sur les systèmes aquifères du bassin versant de la Grote-Nete qui représente une aire de 525 km^2 en Belgique, sont modélisés suivant des scenarii de types climat humide (effet de serre), climat froid ou NATCC (modification de la circulation thermohaline dans l'Atlantique Nord) et climat sec. Des estimations basses, centrales et élevées des changements de la température sont adoptées pour les scénarii de type climat humide. Les composantes saisonnières et annuelles du bilan d'eau, dont la recharge des eaux souterraines, sont simulées par un modèle WetSpass, tandis que les niveaux moyens annuels des eaux souterraines et l'écoulement sont simulés avec un modèle hydrogéologique MODFLOW en régime permanent. Les résultats de WetSpass pour les scenarii climat humide montrent que des hivers humides et des étés plus secs sont à prévoir par rapport à la situation actuelle. Les résultats de MODFLOW pour un scenario climat humide élevé montrent une élévation du niveau des eaux souterraines allant jusqu'à 79 cm, ce qui pourrait perturber la distribution et la diversité des espèces des prairies. Les résultats obtenus pour les scenarii climat froid donnent des hivers plus secs et des étés plus humides qu'actuellement. Les scenarii climat sec conduisent à des conditions sèches pour toute l'année. Il n'y a pas de recharge pendant l'été, ce qui s'explique principalement par des taux d'évapotranspiration par les forêts élevés et des précipitations faibles. Les niveaux moyens annuels des eaux souterraines baissent de 0.5 m, avec un maximum de 3.1 m pour la partie Est du plateau de la Campine. Ceci pourrait menacer les écosystèmes aquatiques, les arbustes et la production agricole.

Resumen Se ha modelizado los efectos del cambio climático en los sistemas de agua subterránea en la cuenca Grote-Nete, Bélgica, que cubre un área de 525 km^2, usando escenarios húmedos (invernadero), fríos o NATCC (Cambio de Circulación Termohalino del Atlántico Norte) y clima seco. Se adoptan estimados clásicos, bajos, centrales y altos para cada escenario. Se simulan los componentes de balance hídrico estacional y anual incluyendo recarga de agua subterránea usando el modelo WetSpass, mientras que la descarga y elevaciones anuales de agua subterránea se han simulado en régimen permanente con el modelo de agua subterránea MODFLOW. Los resultados con WetSpass para los escenarios húmedos muestran que se esperan inviernos húmedos y veranos más secos en relación con la situación actual. Los resultados con MODFLOW para el escenario húmedo alto muestran que los niveles de agua subterránea incrementan hasta en 79 cm lo cual podría afectar la distribución y riqueza de especies de las praderas. Los resultados obtenidos para escenarios fríos predicen condiciones secas para todo el año. No existe recarga en verano los cual se atribuye principalmente a los altos ritmos de evapotranspiración del bosque y a la baja

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precipitación. Los niveles promedio anuales de agua subterránea bajan 0.5 m con un máximo de 3.1 m en la parte oriental de la Meseta Campine. Estos descensos en el nivel de agua subterránea pueden poner en peligro el ecosistema acuático, arbustos, y la producción de cultivos.

Keywords Groundwater systems · Groundwater recharge/water budget · Geographic information systems · Climate change · Belgium

Introduction

Water is indispensable for life, but its availability at a sustainable quality and quantity is threatened by many factors, of which climate plays a leading role (IPCC 1997). The Intergovernmental Panel on Climate Change (IPCC 2001a) defines climate as "the average weather in terms of the mean and its variability over a certain time-span and a certain area" and a statistically significant variation of the mean state of the climate or of its variability lasting for decades or longer, is referred to as climate change.

There has been scientific evidence that human activities may already be influencing the climate for several centuries as rapid changes have been recorded for the second half of the eighteenth century owing to the industrial revolution (Miller 1990; IPCC 1996). The main causes of climate change are the burning of fossil fuels and changes in land use and land cover that eventually increase the atmospheric concentrations of greenhouse gases, which tend to warm the atmosphere (Miller 1990; Bouraoui et al. 1999; Rosenberg et al. 1999). Because climate change is expected to bring about change in global temperature and precipitation, threat of floods, increase in global mean sea level, and associated damages, loom at large in conjunction with the high water demand and pollution levels associated with the ever-increasing world population (IPCC 1997). Hence, there are increasing concerns raised for the need to predict future climate conditions and their effects on water resources, so as to ensure constant water availability and mitigate foreseeable damages.

As pointed out by Allen et al. (2004), there have been many studies relating the effect of climate changes on surface water bodies, e.g., Drogue et al. (2004), Gellens (1991), Meenzel and Bürger (2002), and Pfister et al. (2004). However, very little research exists on the potential effects of climate change on groundwater, although groundwater is the major source of drinking water across much of the world and plays a vital role in maintaining the ecological value of an area (Batelaan et al. 2003; IPCC 2001b). Available studies show that groundwater recharge and discharge conditions are a reflection of the precipitation regime, climatic variables, landscape characteristics and human impacts such as agricultural drainage and flow regulation (Allen et al. 2004; De Wit 2001). Hence, predicting the behavior of recharge and discharge conditions under future climatic and other changes is of great importance for integrated water management. For instance, substantial reductions in groundwater recharge near Grenoble, France, simulated by Bouraoui et al. (1999), was almost entirely attributed to increase in evapotranspiration during the recharge season under CO_2 doubling scenarios. A study by (Brouyère et al. 2004) for the Geer basin in Belgium shows mostly a decrease but also some slight increase of recharge for climate scenarios derived from several general circulation models (GCMs). According to Sandstrom (1995), a 15% reduction in rainfall, with no change in temperature, results in a 40–50% reduction in recharge, inferring that small changes in rainfall can lead to large changes in recharge and, hence, in groundwater resources. Sensitivity analysis conducted by Vaccaro (1992) based on historical and projected climate regimes on the Columbia Plateau, Washington, USA, showed a respective increase and decrease of recharges for predevelopment and present state land-uses ("present" state referring to 1980). Rosenberg et al. (1999) predict decrease in recharge under climate change scenarios projected by three GCMs for the High Plains aquifer in the United States. The study combines climate change scenarios from GCM outputs and the direct effect of CO_2 concentration on the growth and evapotranspiration of plants. York et al. (2002) used a coupled aquifer-land surface-atmosphere model on a decadal scale to study aquifer-atmosphere interactions. Their results show that 5–20% of groundwater-supported evapotranspiration is drawn from the aquifer annually. In addition, a long-term simulation of extended drought conditions will result in a decline of the water table by over 15 m.

The main objective of this study is to analyze the sensitivity of water balance components, especially recharge and groundwater discharge, in the Grote-Nete basin resulting from climate changes, using different climate scenario outputs at a regional scale. Size, rate, and volume of groundwater recharge and discharge are identified using a three-dimensional groundwater flow model, MODFLOW (Harbaugh and McDonald 1996), in conjunction with a physically based distributed water balance model, WetSpass (Batelaan and De Smedt 2001), integrated in a GIS environment.

Methodology and study area

The methodology consists of three steps. To begin with, climate scenarios are formulated for the years 2050 and 2100. This is done by assigning percentage or value changes of climatic variables on a seasonal and/or annual basis only for the years 2050 and 2100 relative to the present year (2000). Secondly, based on these scenarios and present situation, seasonal and annual recharge, evapotranspiration and runoff are simulated with the WetSpass model. Finally, the annual recharge outputs from WetSpass are used to simulate groundwater system conditions using steady-state MODFLOW model setups for the present condition and for the future years.

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Table 1 Description of climate scenarios (Können (2001)

Climate scenarios	Description	
Wet	Low	Wet, low estimate of temperature change, −5% wind-speed change
	Central	Wet, central estimate of temperature change, no wind-speed change
	High	Wet, high estimate of temperature change, +5% wind-speed change
Cold (NATCC)	Sudden changes in the North Atlantic circulation, no wind-speed change	
Dry	Dry scenario, high estimate of temperature change, −10% wind-speed change	

NATCC North Atlantic thermohaline circulation change

Although numerous scenarios for both 2050 and 2100 have been used, only selected scenarios for 2100 that represent the range of responses are discussed hereafter.

Climate scenarios

A climate scenario is defined as a plausible future climate that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change (IPCC 2001a). The climate scenarios used in this study were developed by the Royal Netherlands Meteorological Institute (KNMI), The Netherlands, and have been used in several water management studies, e.g. Kors et al. (2000) and Van Rossum et al. (2001). Nevertheless, not all scenarios are presented in this paper. Table 1 gives the climate scenarios as described by Können (2001). Temperature, precipitation, potential evapotranspiration, and wind-speed changes proposed by those scenarios are presented in Table 2. The climate scenarios are categorized in three general types, i.e. greenhouse, North Atlantic Thermohaline Circulation Change (NATCC), and dry scenarios, which are assumed to be realistic representations of the controversial views regarding the change in climate for the future. All scenarios are based on an incremental approach where particular climatic elements are changed by realistic but arbitrary amounts, commonly applied to study the sensitivity of an exposure unit to a wide range of variations in climate. In most studies, constant changes throughout the year have been adopted, as for instance Terjung et al. (1984) and Rosenzweig et al. (1996).

Greenhouse scenarios

Greenhouse scenarios, as described by Können et al. (1997) and Kors et al. (2000), generally result in more precipitation and thereafter are referred to as wet scenarios. Their main feature is a global warming with three possible estimates of temperature change, namely low, central, and high. Model uncertainties are assumed to be covered by the range between the low and high estimates. Van Deursen et al. (2001) show that for Europe the range between low and high temperature estimates represents an 80% confidence interval of possible temperature changes. Empirical relations between observed mean temperature and precipitation show that precipitation changes are directly proportional to the temperature changes (Tank and Buishand 1995; Tank and Können 1997), but, unlike temperature changes, precipitation changes vary according to summer and winter seasons as shown in Table 2. Likewise, potential evapotranspiration will increase linearly with temperature but is assumed to be independent of the season (Haasnoot et al. 1999; Können 2001). The observed decadal variability for wind-speed in the past century has been in the range of ±5% and is therefore adopted for those scenarios Können (2001).

NATCC scenario

The North Atlantic thermohaline circulation change (NATCC) scenario is expected when the climate change is induced by a sudden change in the North Atlantic thermohaline circulation resulting in the cooling of ocean and cooling of the atmosphere affecting northwest Europe, thereafter referred to as cold scenario (Alcamo et al. 1994; Bryden et al. 2005). Assuming that the present conditions prevail and ignoring the effect of the wet scenario, the ocean is expected to cool by 4°C for the worst-case scenario, with an associated decrease of 2°C in the study area (Können 2001). For the cold scenario, it is assumed that temperature and precipitation/evapotranspiration changes remain coupled. Hence, a decrease in temperature will induce a decrease in precipitation/evapotranspiration by an amount inversely proportional to the wet scenarios.

Dry scenario

Dry scenario represents climate scenario where the temperature and precipitation changes are uncoupled, while the relationship between temperature and evapotranspiration is preserved. In addition, there is a lower

Table 2 Climate scenario changes for 2100 according to proposed climate scenarios

Climate scenario		Temperature change (°C)	Precipitation change (%)			PET change (%)	Wind-speed change (%)
			Annual	Summer	Winter		
Wet	Low	+1	+3	+1	+6	+4	−5
	Central	+2	+6	+2	+12	+8	0
	High	+4	+12	+4	+24	+16	+5
Cold		−2	−6	−2	−12	−8	0
Dry		+4	−10	−10	−10	+16	−10

PET potential evapotranspiration

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probability of having strong winds (Können 2001). These types of scenarios may occur if climatic change is dominated by circulation changes, rather than by physical effects like the Clausius-Clapeyron. This is consistent with some Intergovernmental Panel on Climate Change (IPPC) runs, where mid Europe exhibits a decrease in rainfall because of a more prominent influence of the Azore high pressure as described by Kors et al. (2000).

Recharge estimation

WetSpass is a quasi physically distributed seasonal-water-balance model, which takes into account detailed soil, land-use, slope, groundwater depth, and hydro-climatological distributed maps with associated parameter tables for estimating groundwater recharge. The model uses seasonal (summer and winter) geographical information systems (GIS) input grids of the mentioned inputs to estimate annual and seasonal groundwater recharge values:

$$R = P - S - \mathrm{ET} \tag{1}$$

where R is the groundwater recharge, P is the precipitation, S is surface runoff and ET is evapotranspiration, with all having (L T^{-1}) dimensions.

The surface runoff depends on the land-use, soil, slope and precipitation intensity in relation to infiltration capacity of the soil. It is calculated using the classical rational formula

$$S = C_{\mathrm{HOR}} C(P - I) \tag{2}$$

where C_{Hor} is a coefficient (-) that parameterizes the part of the seasonal precipitation that actually contributes to runoff, C is a runoff coefficient based on the rational formula (-) and I is the interception (L T^{-1}).

ET is calculated as a sum of evapotranspiration and interception. The transpiration component of the ET is calculated as

$$T = cE_o \; if \; (G_d - h_t) \leq R_d \tag{3}$$

$$T = f(\theta) cE_o \; if \; (G_d - h_t) > R_d \tag{4}$$

where T is the transpiration (L T^{-1}), c is the vegetation coefficient (-), E_{o} is the potential open-water evaporation (L T^{-1}), G_d is the groundwater depth (L), h_{t} is the tension saturated height (L), R_{d} is the root depth (L) and $f(\theta)$ is a function of water content. The model assumes that the plant available soil-moisture storage is filled up in the winter and can be used for transpiration in the summer.

Since one of the inputs required for WetSpass is the groundwater depth data, which is predicted with the MODFLOW model, an interface has been developed in an ArcView GIS platform to couple the two models, facilitating exchange of data between the two models (Kassa 2001). The coupled WetSpass-MODFLOW model is run for the present situation and for each of the climate change scenarios on an annual basis.

Groundwater modeling

The present situation groundwater system is simulated on a 50-m grid cell resolution, by applying the US Geological Survey (US Geol Surv) modular three-dimensional finite difference groundwater model (MODFLOW; Harbaugh and McDonald 1996). Batelaan et al. (2003) describe the present conditions of the study area and the groundwater model calibration on piezometric data. The aquifer system is generally composed of marine sediments of the Tertiary and Quaternary age, with a thickness of up to 90 m as described by Schiltz et al. (1993). Thus, only one layer was used with transmissivity ranging from about 500 m^2 day^{-1} on the western part to about 3,000 m^2 day^{-1} on the eastern part of the area (Batelaan et al. 2003).The base of the sandy aquifer system is formed by heavy clays of the Boom Formation. 166 wells extract a total of 67,296 m^3 day^{-1}. The groundwater model receives recharge estimated with the WetSpass model (Batelaan and De Smedt 2001). The eastern part of the study area corresponds with surface water catchment boundary and therefore is assigned a no-flow boundary. The north, south and west boundaries are assigned as constant heads taken from a regional supra-groundwater flow model developed for the entire Nete basin by Batelaan et al. (1996), as there are no natural boundaries or adequate piezometer measurements located at the boundary.

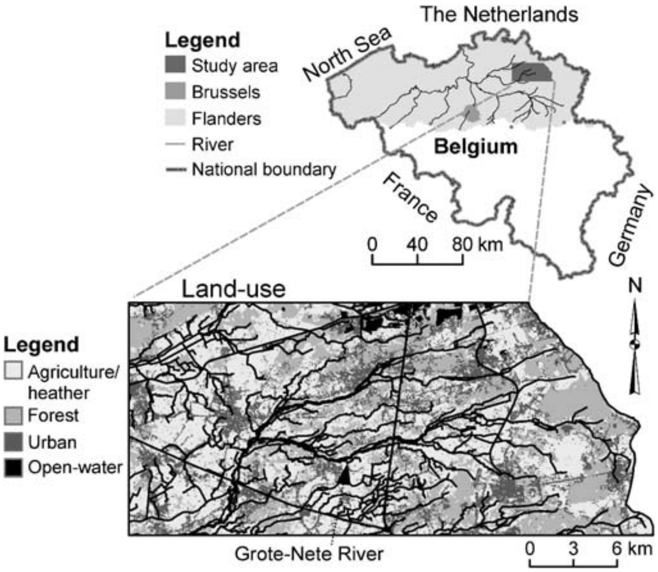

Fig. 1 Simplified land-use map and location of Grote-Nete study area in the Flanders region of Belgium

Table 3 Mean values of WetSpass calculated water balance components

	Precipitation (mm)	Evapotranspiration (mm)	Recharge (mm)	Runoff (mm)
Annual	764	447	277	44
Winter	372	111	239	22
Summer	392	336	38	22

Groundwater discharge was estimated by the DRAIN Package (Harbaugh and McDonald 1996) and is described by the equation pair:

$$D = C(h - h_D)\,for\,h > h_D \qquad (5)$$

$$D = 0\,for\,h \leq h_D \qquad (6)$$

Where, C is the conductance ($L^2\ T^{-1}$), h is the groundwater head (L) and h_D is the drainage level.

Drainage level for the study area was taken as 0.5 m below the ground surface, calibrated in the works of De Smedt and Batelaan (2001) and Asefa et al. (2000), in order to account for local depressions and actual surface water levels as they occur in ditches and ponds. An average conductance of 40 m^2 day^{-1} was used for the drains as obtained from the supra-regional model of Batelaan et al. (2000). For the modeling of the future groundwater conditions, the groundwater model set-up and parameters are kept the same as in the present situation, with the exception of recharge, which varies with the climate scenarios.

Study area

The study area is located about 60 km northeast of Brussels and covers about 525 km^2 as shown in Fig. 1. It is part of the Central Campine region including most parts of the Grote-Nete basin. It is characterized by a moderate rolling landscape cut by the Grote-Nete River and its tributaries, resulting in long stretched hills, very slightly elevated interfluves and broad swampy valleys (Wouters and Vandenberghe 1994).

The elevation ranges from 13 to 73 m, with an average of 32 m above sea level, while the mean slope is 0.24%. The soil type is dominated by sandy and loamy sand covering 91% of the basin, while loamy sand, silty loam and clay loam are also found in the valleys. The land-use comprises 28% arable land, 19% of built-up area, 18% deciduous forest, 15% grass lands, 10% coniferous forest, 5% heather, 3% mixed forest, and about 2% open-water bodies. A simplified map of land-use types is shown in Fig. 1. The long-term mean annual precipitation ranges from 743 to 801 mm with an average of 764 mm, while the average summer and winter precipitation are respectively 392 and 372 mm. In this study, winter months refer to October until March while summer months are April until September. The average annual potential evapotranspiration is 670 mm. The area has moderate average winter and summer temperatures of 5 and 14°C respectively.

Application and discussion

Groundwater model calibration and hydrological situation

The groundwater model for the present condition is calibrated using the mean annual groundwater levels from 38 piezometers for years between 1976 and 1996. Annual

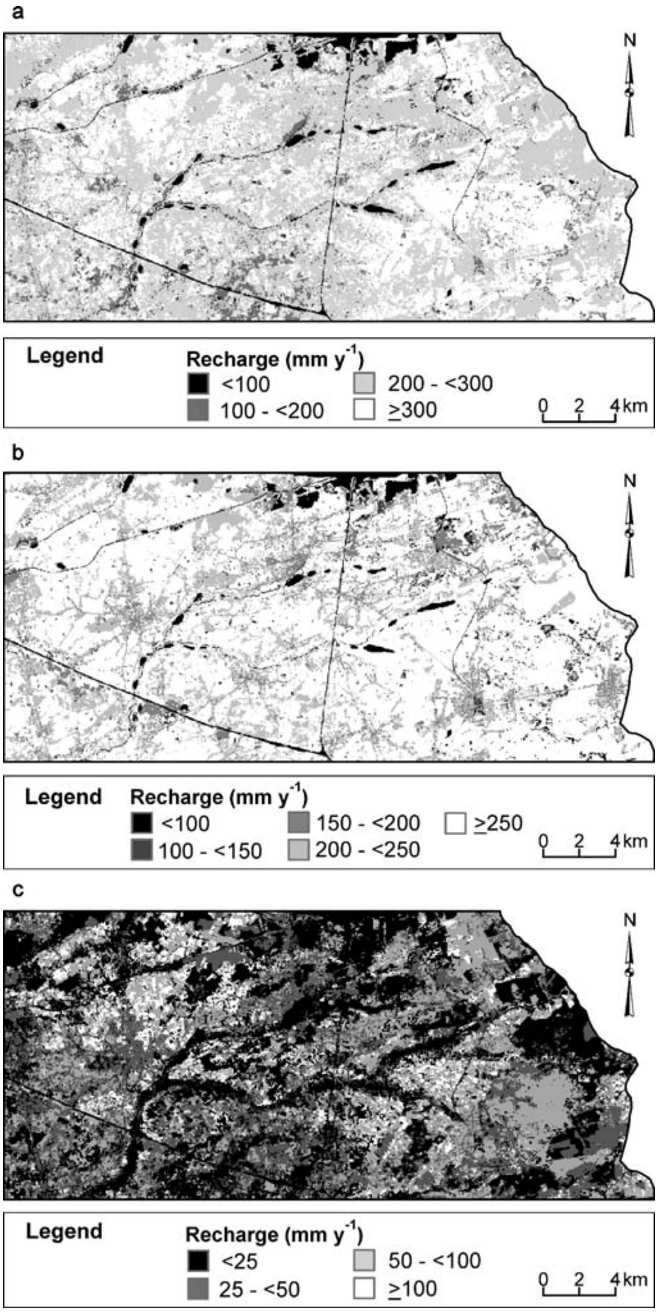

Fig. 2 WetSpass calculated recharge for present situation: **a** annual, **b** winter and **c** summer

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and inter-annual water level ranges vary between about 0.5–2 m, with most piezometers showing a fluctuation of about 1 m between the driest and the wettest periods. There is good agreement between simulated and observed groundwater heads with a correlation of 0.99. The mean absolute error is 0.43 m, the root mean square error is 0.61 m, and the Nash-Sutcliffe model efficiency is 0.98, which shows that the model is performing well. Also, observed and simulated heads are proportionally scattered around the mean of observations, which indicates that there is no systematic bias.

The results of the WetSpass model for the present hydrological situation yield annual, summer, and winter distributed evapotranspiration, recharge and runoff maps. Table 3 gives the mean values of the water balance components. The results show that runoff remains constant throughout the year, whereas recharge and evapotranspiration show high variability between the seasons. As a result, 86% of the recharge takes place during the winter, as compared to 14% during the summer.

WetSpass simulated distributed seasonal and annual recharge maps are presented in Fig. 2. The recharge rate ranges from zero to a maximum of about 408 mm y^{-1}, with an average of 277 mm y^{-1}, which is about 36% of the annual precipitation. Null or negligibly small values occur in valley areas due to shallow groundwater depth and extensive evapotranspiration by phreatophytes. Table 4 gives annual recharge values for different land-use-soil combinations. Above-average recharge values are obtained mostly for grass or forest land-uses dominated by coarse texture soils, while urban areas as well as areas dominated by fine textured soils yield below average recharge values. Similar findings were reported by De Smedt and Batelaan (2001).

Groundwater discharge areas and associated seepage rate obtained from the groundwater model are presented in Fig. 3. The discharge areas cover 19% of the total area with an average of 265 mm y^{-1}. While a large part of the discharge area corresponds to the depressions and valleys with an average rate of 4 mm day^{-1}, rates greater than 5 mm day^{-1} are mostly restricted to the river networks. Similar findings are reported by Batelaan et al. (2003).

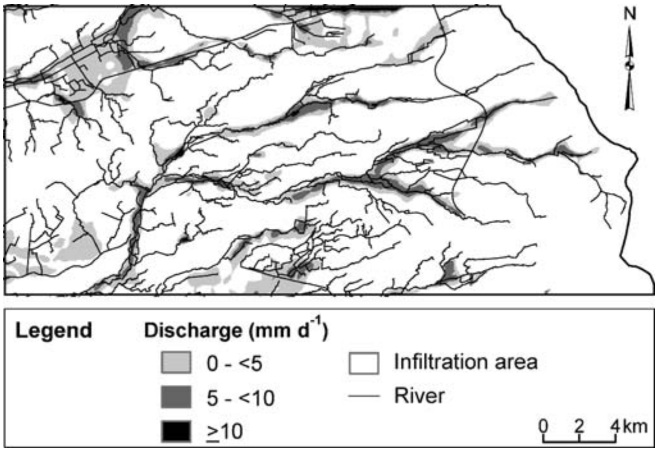

Fig. 3 MODFLOW calculated annual discharge values for present situation

Climate scenario analysis

WetSpass results of average annual and seasonal precipitation, evapotranspiration, groundwater recharge, and surface runoff changes of the climate scenarios relative to the present are presented in Table 5, while Table 6 presents MODFLOW-simulated annual changes in groundwater head, groundwater discharge rates, and areas; changes in groundwater-discharge rates and areas relative to the present situation.

Wet scenarios

For the wet scenarios, an increase in the average runoff, groundwater recharge, and evapotranspiration is observed for all seasons and annual totals, except for the summer groundwater recharge. Although the percentage increase in runoff is higher than for the other water-balance components, most of the additional rainfall is either

Table 4 WetSpass simulated-mean-annual groundwater recharge (present situation) for different land-use-soil combinations; difference in mean-annual recharge (for climate scenarios relative to the present) for different land-use-soil combinations

	Recharge Present situation (2000)	Δ Recharge			
		Wet high scenario		Dry scenario	
	(mm)	(mm)	(%)	(mm)	(%)
Soil-Land-use					
Sand-agriculture	331	48	(14)	−103	(−31)
Sandy loam-Agriculture	298	37	(12)	−112	(−37)
Sand-forest	291	35	(12)	−140	(−48)
Loamy sand-forest	285	25	(9)	−162	(−57)
Loamy sand-agriculture	278	35	(12)	−118	(−42)
Sandy loam-forest	275	22	(8)	−147	(−53)
Silty loam-forest	228	9	(4)	−133	(−58)
Sand-urban	227	47	(21)	−72	(−32)
Silty loam-agriculture	219	17	(8)	−120	(−55)
Sandy loam-urban	218	44	(20)	−80	(−37)
Clayloam-forest	179	9	(5)	−147	(−82)
Loamy sand-urban	178	34	(19)	−66	(−37)
Silty loam-urban	138	36	(26)	−59	(−43)
Clay loam-agriculture	116	29	(24)	−74	(−63)
Clay loam-urban	110	42	(38)	−38	(−34)

Table 5 Changes in water balance components for the climate scenarios relative to the present

		Δ Precipitation		Δ Evapotranspiration		Δ Recharge		Δ Runoff	
		(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)
Climate scenario									
Annual	Wet low	26	(4)	20	(4)	5	(2)	2	(5)
	Wet central	52	(7)	31	(7)	17	(6)	5	(11)
	Wet high	105	(14)	59	(13)	38	(14)	10	(24)
	Cold	−52	(−7)	−31	(−7)	−18	(−6)	−5	(−11)
	Dry	−77	(−10)	45	(10)	−111	(−40)	−7	(−17)
Winter	Wet low	22	(6)	5	(5)	16	(7)	2	(7)
	Wet central	45	(12)	10	(9)	32	(13)	3	(14)
	Wet high	89	(24)	19	(17)	64	(27)	6	(29)
	Cold	−45	(−12)	−10	(−9)	−32	(−13)	−3	(−14)
	Dry	−37	(−10)	14	(13)	−47	(−20)	−4	(−19)
Summer	Wet low	4	(1)	15	(4)	−11	(−29)	1	(4)
	Wet central	8	(2)	22	(6)	−15	(−38)	2	(9)
	Wet high	16	(4)	40	(12)	−27	(−69)	4	(19)
	Cold	−8	(−2)	−21	(−6)	15	(38)	−2	(−9)
	Dry	−39	(−10)	30	(9)	−64	(−166)[a]	−3	(−15)

[a] Includes soil storage depletion from winter recharge

evapotranspired or recharged to the aquifer. In winter, most of the additional water from precipitation is recharged to the aquifer. High evapotranspiration during the summer is mainly attributed to forests. With deeper roots and higher leaf area index (LAI), they can utilize most of the soil moisture storage that comes from the winter recharge. As a result, the annual recharge increase for forests is less than that of agricultural land and even of urban areas. This is illustrated by Fig. 4a, where the annual recharge increase for the wet high scenario relative to the present is shown.

From the results, it becomes clear that the effect of a temperature increase outweighs the effect of a smaller increase in precipitation in the summer. Therefore, as in the present, most of the groundwater recharge takes place during the winter, but its proportion increases to 98% for the wet high scenario in 2100 as compared to the 86% of the present situation.

The overall increase in annual recharge leads to an increase in the groundwater level of the basin by an average of 16 cm for wet high scenario. Fig. 5a shows the increase in groundwater level for wet high scenario relative to the present. The highest increase, of about 79 cm, is obtained for the eastern part of the Campine Plateau. This is most likely to have an affect on the distribution and species richness of meadows, since they are substantially influenced by fine-scale variations in water-table depth, as shown by Araya (2005). The study shows that there is a marked difference in the distribution and species richness of meadows growing on fields with water-table depths ranging from 20 to 80 cm.

The rise in groundwater level is associated with an increase in groundwater discharge areas and rates as shown in Table 4; Fig. 6 shows an increase in groundwater discharge area for wet high scenario and a decrease in discharge area for dry scenario relative the present. Almost all of the additional discharge areas are located on the vicinities of rivers and wetlands, although some new wetlands are also created. These areas also correspond with areas of saturation where the groundwater fully or partially saturates the root zone. With the simultaneous increase in volume and rate of groundwater discharge, the type of phreatophytes that can grow in the area are likely to be affected (Batelaan et al. 2003; Hill et al. 1999; Ellenberg 1992).

Cold scenario

Results for the cold scenario show that changes of water balance components will have the same magnitude as for the wet scenario's central estimate but reversed sign. This is obvious since the input parameters of the cold scenario is the opposite of the wet central scenario. Forested areas show minimum decrease because of reduction in evapotranspiration during the summer, triggering an increase in recharge in the summer that accounts for about 20% of the

Table 6 MODFLOW-simulated annual changes in groundwater head, groundwater discharge rates, and areas; changes in groundwater-discharge rates and areas relative to the present situation

	Δ Groundwater head	Discharge area		Δ Discharge area		Discharge rate	Δ Discharge rate	
	(cm)	(km^2)	(%)	(km^2)	(%)	(mm)	(mm)	(%)
Climate scenario								
Wet low	3	96.4	18.8	1.3	1	272	7	3
Wet central	8	99.4	19.4	4.3	5	279	14	5
Wet high	16	104.5	20.4	9.4	10	295	30	11
Cold	−8	90.7	17.7	−4.4	−5	251	−14	−5
Dry	−52	68.3	13.3	−26.8	−28	197	−68	−26

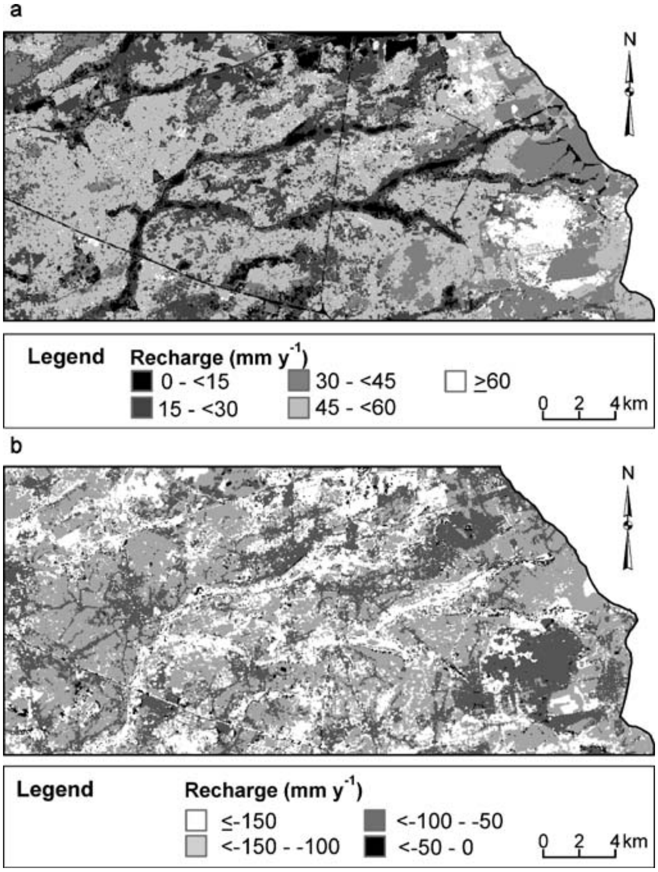

Fig. 4 WetSpass calculated annual recharge changes relative to the present for: **a** wet high scenario and **b** dry scenario

annual recharge. The decline on the average annual groundwater level is only about 8 cm.

Dry scenario

For dry scenarios, the situation is more dramatic and the changes in hydrological parameters are more pronounced. Only evapotranspiration shows an increase, while both groundwater recharge and surface runoff show a decrease for all seasons. Figure 4b shows the decrease in recharge for the dry scenario with respect to the present. The results of the dry scenario show a 40% decrease in average annual recharge relative to the present. Even though the winter recharge also decreases by about 20%, it remains the only source of the annual recharge. In fact, about 10% of the winter recharge that is stored in the soil is used in the summer to support high demand of evapotranspiration rate especially by forests.

Groundwater levels are expected to decrease by an average of 52 cm for the dry scenario, as shown in Fig. 5b, reaching as much as 3.1 m in the eastern part of the Campine Plateau, which is dominated by heather and forests on sandy soil. It can be seen that the areas with the greatest groundwater level reduction are located further away from the rivers and wetlands. This poses more risk not only to meadows and crops, but also to shrubs and short rooted trees. Crop production might be affected depending on the growing season and irrigation requirements.

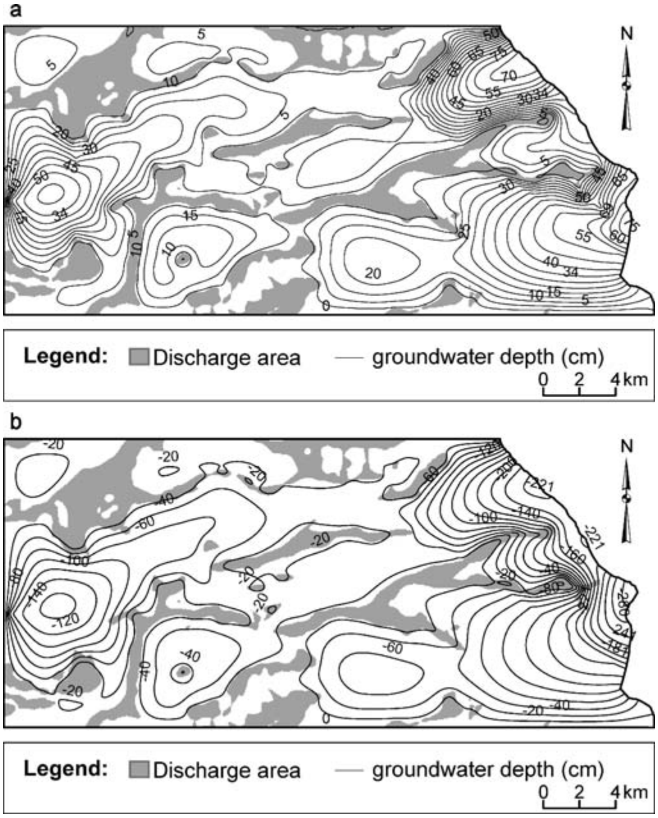

Fig. 5 Annual groundwater depth changes for: **a** wet high scenario and **b** dry scenario

With respect to groundwater discharge, dry scenarios depict an opposite picture from the wet scenarios. The groundwater discharge areas will decrease by an alarming 28% (as shown in Fig. 6), leading to partial or complete disappearance of some wetlands. There will also be a substantial decrease in groundwater discharge rate that could be detrimental for wetland and river ecosystems.

Overall, the sensitivity of recharge depends on how precipitation and temperature are related. When the relationship is directly proportional, as in the case of

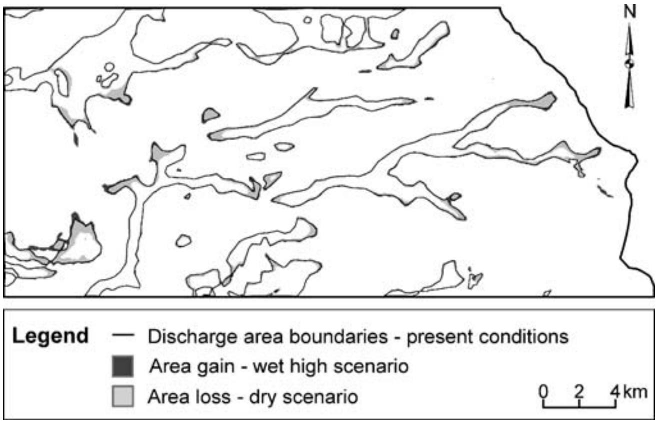

Fig. 6 Changes in discharge areas for future scenarios. Area gain for the wet high scenario and the area loss for the dry scenario

wet, cold, and combined wet and cold scenarios, their effects cancel out, resulting in moderate changes of the water balance components. However, when the relationship is inverse, as in the case of dry scenarios, their effects are compounded and become more severe. In both cases, forests play a very important role, either by reducing increases in the recharge, or aggravating the situation by contributing to the loss of recharge. However, as these opposing relationships between temperature and precipitation are mutually exclusive, mitigation plans will depend on the likelihood of their occurrence.

The average change in annual groundwater level, which ranges between an increase of a few centimeters for wet scenarios to a half meter decrease for dry scenarios, is more likely to affect meadows and crops. Moreover, for the dry scenarios, further decline of groundwater level on the eastern part of the Campine Plateau is expected to have an effect on shrubs and trees with short roots. In addition, aquifer recharge taking place only in winter with complete dryness in the summer may lead to significant groundwater fluctuation between the two seasons.

Although the absolute change in runoff is not as high as the change in recharge or evapotranspiration, it is the most sensitive parameter for wet scenarios. This, in addition to the increase in groundwater discharge areas and possible expanding of urban areas, may increase the likelihood of flooding depending on the duration and/or extreme events of precipitation.

Conclusions

In this study, the effects of climate change on the water balance and groundwater system of a sandy aquifer under temperate conditions are modeled using a physically distributed water balance model and a finite difference groundwater model. The climate scenarios considered are wet, cold and dry, as they are assumed to represent all controversial but realistic predictions of climate change.

Among the proposed scenarios, the ones which are likely to have a significant effect on the water-balance components and groundwater system are either the wet or dry scenarios. Further studies pertaining to climate change impacts for the study region should concentrate mainly on these scenarios. However, planning appropriate mitigation strategies will depend on the likelihood of occurrence of such climate change. In this sense constant observation for the coming years may reveal which scenario is more likely to occur. In addition, in order to study seasonal variation of the groundwater components and the effect of extreme events, studies based on a transient modeling approach should be conducted. Climate change impact studies based on steady-state groundwater simulations have limitations in representing boundary conditions and can only be used for assessing sensitivities before implementing more rigorous and data-intensive transient modeling.

For the wet scenarios, runoff was the most sensitive component showing the highest percent increase. This, combined with the increase in groundwater discharge areas, groundwater level and winter precipitation, might pose more risk of flooding, given the shallow groundwater depth of the area. On the other hand, a greater difference between summer and winter recharge, which implies greater seasonal fluctuation of the groundwater levels, may influence the distribution and species richness of wet meadows, as they are sensitive to fine-scale variations of the water-table depth. Furthermore, the decrease in summer groundwater recharge is mainly attributed to high evapotranspiration rates from forests.

In the case of dry scenarios, recharge is the most sensitive parameter and decreases for all seasons. More water is lost than can be replenished due to low precipitation and high evapotranspiration, especially by forests, throughout the year. This will result in a decrease of the annual groundwater levels by as much as 3 m. The consequences could be drastic, as this could reduce the water availability to crucially low levels for both aquatic life in wetlands and riverine ecosystems, especially in summer when the decline in water level is expected to be greater than the average annual decline. Prolonged dryness can eventually result in complete alteration/disappearance of short-rooted plant populations. Irrigation requirements for crop production might need to be adjusted to counteract the effects of summer dryness. This would lead to more pumping from the groundwater, which can further lower the groundwater levels. Thus, adding pumping scenarios that consider irrigation requirement and water-supply demands have to be considered in order to appreciate the full extent of the effects of dry scenarios.

It has also been shown that land-use plays an important role on the effects of climate change. Therefore, integrated water-management strategies can only feasibly be designed when climate scenario analyses are complimented with land-use scenarios. The results of such work could yield a range of options for making decisions for appropriate land-use development planning to safeguard the water resources in the catchment. In addition, as groundwater and surface water are inseparable components of the hydrologic cycle, concrete conclusions can only be made if their interaction is included in climate-change impact studies.

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