Climate change impacts on groundwater resources: modelled deficits in a chalky aquifer, Geer basin, Belgium

Manuscript prepared for submission to Hydrogeology Journal

Serge Brouyère[1], Guy Carabin[2] and Alain Dassargues[3]

Hydrogeology Group, Department of Georesources, Geotechnologies and Building Materials, Building B52

University of Liège

4000 Sart Tilman

Belgium

Tel: +32-43662377 / Fax: +32-439198

Serge.Brouyere@ulg.ac.be

[1] **corresponding author**

[2] now at Numeca International, Avenue F. Roosvelt, Bruxelles

[3] also at Hydrogeology & Engineering Geology Group, Department of Geology-Geography, Katholieke Universiteit Leuven, Redingenstraat 16, B-3000 Leuven, Belgium.

Abstract

An integrated hydrological model (MOHISE) was developed in order to study the impact of climate change on the hydrological cycle in representative water basins in Belgium. This model considers most hydrological processes in a physically consistent way, more particularly groundwater flows that are modelled using a spatially distributed finite element approach. Thanks to this accurate numerical tool, after detailed calibration and validation, quantitative interpretations can be drawn from the groundwater model results. Considering IPCC climate change scenarios, the integrated approach was applied to evaluate the impact of climate change on the water cycle in the Geer basin in Belgium. The groundwater model is described in detail, and results are discussed in terms of climate change impact on the evolution of groundwater levels and groundwater reserves. From the modelling application on the Geer basin, it appears that, on a pluri-annual basis, most tested scenarios predict a decrease in groundwater levels and reserves in relation to variations in climatic conditions. However, for this aquifer, the tested scenarios show no enhancement of the seasonal changes in groundwater levels.

Introduction

Climate change is probably one of the most challenging pressures facing hydrological systems and water resources. Important research efforts have already been devoted to the evaluation of climate change impact on hydrological resources in general (e.g., Westmacott and Burn 1997; Gellens and Roulin 1998; Sun et al., 2000; Beeton, 2002; Menzel and Bürger 2002). However, as mentioned in a recent IPCC report (IPPC 2001), very little research has focused, until now, on the potential effects of climate change on groundwater resources. And yet the groundwater resource is of first importance because it is one of the best protected reserves of water for distribution. It constitutes also the only contribution of water to streams and rivers during the recession period, in the spring, summer and early autumn. Variations in temperature and precipitation during the year may have a direct impact on changes in groundwater levels, reserves and quality (Goldscheider, 2003). Indirectly, climate change may also have effects on land management practices, land use and agricultural practices such as irrigation with water extracted from aquifers, which could also alter hydrological systems (e.g. Eheart and Tornil 1999, Loaiciga et al. 2000).

In temperate areas, such as Belgium, direct percolation from rain water is considered as occurring mostly during the recharge period, from November until April, when soil and subsoil layers overlying the aquifer are filled up to field capacity. Deep percolation stops when soil moisture deficits appear during spring, summer and early autumn. In terms of climate change, an increase in winter rainfall is usually foreseen in such regions. However, at the same time, it is expected that a shorter recharge season could prevail, leading to uncertain trends for the total recharge of aquifers. Additionally, indirect recharge from surface water bodies and from overland flow will obviously be affected by changes in stream flow and in overland flow events. River-aquifer interactions may be largely influenced by climate conditions occurring in the headwaters of the basin, which may be several hundred kilometres upstream (Arnell 2002).

In each case, accurate and realistic hydrological models are needed to produce indicative results, taking the spatial heterogeneity of the basin characteristics into account and considering the transient behaviour of the whole hydrological system in the basin.

In this paper, results relating to the groundwater component of an integrated hydrological model, developed for the Geer basin in Belgium (Figure 1) are presented and used to illustrate and discuss the direct impact of climate change on groundwater resources. In this first step, water quality aspects or possible entropic pressure changes are not considered. First, the general structure of the integrated hydrological model MOHISE is presented. Second, the studied aquifer is described and the modelling concepts are presented. Third, climate change scenarios, tested with the model developed for the Geer basin, are presented and discussed in terms of impacts on groundwater flow conditions.

The groundwater model within the integrated hydrological model

Even if some authors consider that the greatest uncertainties affecting the simulated hydrological cycle arise from the uncertainty that affects climate change scenarios, it is not a reason for neglecting the physical description of the hydrological processes in the models. For example, the reliable estimation of groundwater levels, reserves and base-flow to the streams requires an accurate and physically consistent simulation of all the interactions existing between the different parts of the hydrological cycle, especially in drought conditions (Dassargues et al. 1999). Many integrated hydrological models use transfer functions or lumped models (linear reservoirs é) for simulation of the groundwater component. From a groundwater perspective, these approaches, that are oversimplified, should rather be qualified as ócalibratedô black-box models. Very often, the conclusion is drawn that the good agreement found between observed and modelled hydrographs demonstrates the ability of such models to simulate the overall pattern of the flow response across the whole range of flows. Actually, empirical models cannot be relied on when predictive computations are performed with aquifer stresses (i.e. recharge, pumping, boundary conditions) that will possibly lie out of the calibration range. Even if incremental changes induced by climate change do not seem very important on a year basis, they may lead, after a few years, to stress conditions out of the range of present conditions.

The integrated hydrological model MOHISE is a deterministic, spatially distributed, physically-based model, composed of three interacting sub-models: a soil model, a surface water model and a groundwater model, dynamically linked and operated by a ómeta-structureô that synchronizes the runs on a multi-node parallel IBM-SP2 workstation and organises exchanges between the different sub-models. The EPIC-GRID soil model (Sohier et al. 2000) is a semi-distributed model that computes, in each 1 km² cell of a regular grid, a water budget at the soil surface and in the unsaturated zone, calculating water fluxes related to evapotranspiration, surface and subsurface runoff and percolation. The unsaturated zone includes the root zone in relation to crop growth. Surface and subsurface runoff components computed by EPIC are routed to the river network based on the solution of a Manning equation coupled to a steepest descent algorithm implemented at the meta-structure level. The surface water model (Smitz et al. 1997; Everbecq et al. 2001) solves one-dimensional Saint-Venant equations to model water flows in the river network. Groundwater flows are computed using the finite element simulator SUFT3D (Carabin and Dassargues 1999; Brouyère 2001).

The three sub-models exchange computed water flow rates at different locations and times. To handle these exchanges efficiently, spatial and temporal mapping procedures were developed between the sub-models. The interface between the soil and groundwater models is relatively straightforward. Recharge fluxes (percolation) computed by the soil model are applied at the top of the groundwater model as prescribed fluxes (second-type or Neumann boundary conditions). The interaction is unidirectional, from the soil model to the groundwater model. For an accurate simulation of possible water table rise, advantage is taken of the capacity of the SUFT3D code to model groundwater flows in the unsaturated zone. The unidirectional coupling of the soil ï groundwater interaction could be limiting in the case of shallow aquifers if, due to climate change, increase summer soil moisture stress might increase upward capillary rise of groundwater into the root zone, leading to another potential loss of groundwater. However, in the studied case (see next sections), the water table is located at depths ranging from 10 to 40 meters, which prevents any groundwater abstraction by capillary processes. In order to describe accurately the spatial heterogeneity of the aquifer, the spatial discretisation used in the groundwater model is not identical to the regular grid of the soil model. A spatial distribution algorithm was thus developed: the gravity centre of each upper boundary element of the groundwater model is computed. The recharge value computed in each cell of the soil model is attributed to elements for which the gravity centre falls in that cell.

Interactions between rivers and aquifers are expressed as mixed boundary conditions (third-type or Cauchy boundary conditions). The computed water flow rates depend on the difference existing between water levels in the aquifer and in the river respectively (Carabin and Dassargues 2000). The interface between the groundwater model and the river model is developed taking into account the one-dimensional succession of river nodes and the irregular mesh of nodes in the SUFT3D (Figure 2). A value transmitted to a node of the groundwater model is spatially interpolated from two successive nodes of the river model located upstream and downstream. On the contrary, a value transmitted to a node of the river model is the sum of all contributions associated to the groundwater model nodes located upstream.

Groundwater modelling of the Geer basin

Hydrogeological conditions

Groundwater resources located in the Geer basin provide about 60,000 m^3/day of drinking water for the city of Liège and its suburbs (Dassargues and Monjoie 1993). The Hesbaye plateau extends over about 350 km^2. Altitudes range from 206 m in the southwest to 80 m in the northeast part of the region. From top to bottom, the substratum is made up of (Figure 3):

- a Quaternary loess of variable thickness, up to 20 m,
- a maximum of 10 m of a flint conglomerate, highly heterogeneous geological formation made of dissolved chalk residues (flints, sand, clay and locally phosphate),
- locally, several meters of Tertiary sand deposits, mostly in the north of the Geer basin, where they take the place of the flint conglomerate,
- Cretaceous chalks forming the main reservoir of the Hesbaye aquifer, showing depths ranging from a few meters in the south, up to 100 m in the northeastern part of the basin; in most of the area, this layer is divided in two main units by a thin layer of hardened chalk called the ñHardgroundò, mostly continuous but with windows that locally enhance the hydraulic connectivity between the two main parts of the chalk aquifer,
- at the bottom, several meters of smectite clay of low hydraulic conductivity, considered as the aquifer base. This bottom layer slopes northwards with a gradient of 1 % to 1.5 %.

The mean hydraulic gradient in the aquifer is north-oriented, ranging from 0.01 in the south to 0.003 in the north, close to the Geer river (Dassargues and Monjoie 1993). The groundwater table is located at depths ranging from 10 m to more than 40 m below the land surface. Most of the aquifer is unconfined, except in the north, where semi-confined conditions prevail under the Geer alluvial deposits. Locally, confined conditions may prevail under Tertiary clayey sediments.

An important fault (the ôHorion-Hozémontô fault, Figure 1), associated with a zone of highly fractured chalk, crosses the domain from southwest to northeast, greatly influencing hydrogeological conditions. Fractured zones in the chalk also correspond to dry valleys visible in the surface morphology. Finally, dug in the lower part of the chalk, 40 km of galleries belonging to a local water company, play a key role in the shape of the piezometric surface. Groundwater is drained in most portions of the galleries but an important quantity of water is also recharged from the galleries into the aquifer in other zones, depending on local differences between water levels in the aquifer and in the galleries. Under low water level conditions, some sections of the galleries may become dry. Apart from the galleries, the aquifer is exploited by pumping wells owed by water companies, local industries and agricultural settlements.

In some locations, groundwater level fluctuations with time can reach more than 15 meters. The thickness of the unsaturated zone may reach 40 meters. In the south, the hydrogeological basin limit varies slightly because of fluctuations of groundwater levels. The Geer River is the main outflow of the chalk aquifer. However, on an annual basis, water balance in the Geer basin shows a water loss, estimated to range between 15 mm (Monjoie 1967) and 62 mm (Hallet 1999). The ôlostô groundwater flows under the Geer River to the groundwater basin located northward, due to sloping and deepening of chalk layers towards the north. This groundwater flow subtracted from the water balance in the basin varies with groundwater levels in the aquifer; it has been correlated with water levels and flow rates measured in the Geer River.

Discretisation choices

Horizontally, the limits of the modelled area correspond to the Geer hydrological basin. Variations of the hydrogeological basin in the south were neglected, this boundary being considered as impervious (groundwater divide). Horizontally, the three-dimensional finite element discretisation considers a mean element size of about 700 m and it is refined where important stresses are applied or important piezometric gradients expected (close to faults, galleries or pumping wells).

Vertically, the mesh is made up of seven layers of finite elements. From the bottom to the top, three layers are defined in the deep chalk, one layer for the óHard groundô, one layer for the upper fractured chalk, one layer for the flint conglomerate and finally one layer for the loess. Laterally, the layers may represent different geological units. Hence, the ñHardgroundò is not present everywhere and the conglomerate layer disappears toward the north where it is replaced by the Tertiary sands. Where groundwater levels fluctuate in the chalk, the seven layers of finite elements represent the chalk. Galleries are modelled using one-dimensional highly conductive finite elements (Sudicky et al. 1995; Therrien and Sudicky 2000; Brouyère 2001). Globally, the three-dimensional mesh is made up of 31,423 finite elements and 18,680 nodes.

The model development and data handling were performed taking advantage of a database developed for hydrogeological applications (Gogu 2000; Gogu et al. 2001).

Calibration and validation

The calibration of the groundwater model was performed in two steps. A first calibration was performed assuming steady state conditions for two contrasting piezometric situations: one corresponding to high groundwater levels (during the period 1983-84), the second to low groundwater levels (during the period 1991-1992). This approach, based on contrasted steady state conditions, was useful for assessing the vertical heterogeneity of the aquifer. For this calibration step, the groundwater model was run in stand-alone mode, assuming a constant and uniformly distributed recharge. Computed piezometric levels were compared to annually averaged groundwater levels. In a second step, the calibration was improved by running transient simulations with the integrated hydrological model. On the basis of available datasets, the simulation period was split into two parts. The first period was used for model calibration (1975-1988), the second for model validation (1989-1995). Observation wells are equally distributed in the domain, except in the north of the Geer River.

Steady state calibration

175 piezometric measurements were available for the period 1983-1984 corresponding to the last extensive campaign for piezometric measurements. For the second period (1991-1992), about forty measured piezometric levels could be used. In Figure 4, the general quality of the calibration is presented in a scatter plot diagram of observed versus computed groundwater levels.

Transient calibration and validation

As the study is aimed at evaluating the impact of climate change on the hydrological cycle, a transient calibration must be performed for an accurate simulation of groundwater level variations with time. This was performed for the period 1975-1988, based on water levels measured in 34 observation wells. To check the accuracy of this calibration, a validation was performed by the simulation of the period 1989-1995.

Data were not available for the whole calibration or validation period. However a minimum of 5 years was available for each observation well. As these simulations were conducted using the integrated model, the calibration and validation were also based on a comparison between measured and computed flow rates in the Geer basin, including the base flow from the aquifer. Measured hydrographs at several locations within the basin were used, particularly at the basin outlet, at Kanne (Figure 1).

As an example, the computed piezometric map corresponding to the beginning of September 1984 is presented in Figure 5, together with a scatter plot diagram of observed versus computed groundwater levels for the same period. In terms of groundwater level fluctuations, the quality of the calibration varies from one observation well to another. Figure 6 shows measured and computed groundwater level variations as a function of time, at selected wells. Figure 7 presents the different computed flow rates contributing to the total flow rate and the measured total flow rate at the outlet. Generally speaking, the adjustment is satisfactory. However, it is observed that computed piezometric fluctuations are not sufficiently smoothed. In some zones, this may be attributed to too short a delay for the computed recharge reaching the water table, or possibly to an inaccurate evaluation of the chalk storage capacity. Furthermore, it has to be noted that the EPIC-GRID soil module computes the effective recharge on 1 by 1 km grid cells. Such a discretisation induces spatial smoothing of both the topography and unsaturated zone thickness, leading to possible inaccuracy in the computed delay of effective recharge.

From the calibration results, it appears that the main fractures and dry valleys are characterized by higher hydraulic conductivity values, of the order of 1×10^{-3} m/s. In the chalk, the hydraulic conductivity value varies from 1×10^{-5} to 6×10^{-4} m/s. In the upper chalk layer, hydraulic conductivity values are from 2 to 10 times higher than in the lower chalk layer. This can be explained by alteration and constrains relaxation in chalk rocks lying at shallower depths. The ñHardgroundò is characterized by a low hydraulic conductivity value, of the order of 1×10^{-5} m/s. This layer enhances the vertical heterogeneity of the aquifer.

Impact of climate change on groundwater resources

Selection of climate change scenarios

The climatic scenarios were selected and prepared by the Royal Institute of Meteorology of Belgium (IRMB). They are based on experiments conducted with seven general circulation models (GCM), made available to the scientific community through the Intergovernmental Panel on Climate Change. They respond to criteria selected by the IPCC Task Group on Climate Scenarios for Impact Assessment. The main difficulty comes from the scale mismatch between the large (continental) scale of climate models and the ólocalô scale associated to hydrological models (Loaiciga et al. 1996), the latter requiring daily data, with higher resolution of a few square kilometres.

A subset of 3 GCMs was selected, giving preference to scenarios offering the highest resolution and the most contrasted changes: the ECHAM4 (German Climate Research Centre), the HadCM2 (UK Hadley Centre for Climate Prediction and Research) and the CGCM1 (Canadian Centre for Climate Modeling and Analysis) models. The climate change scenarios were prepared as follows. The period 1969-1995, for which detailed meteorological, hydrological and hydrogeological information were available, was chosen as a baseline. Using the IPCC climatic scenarios, monthly increments of precipitation and temperatures were computed for three modelled periods 2010-2039, 2040-2069, and 2070-2099. Using these increments, ólocalô climate change scenarios were constructed by combining the daily precipitation and temperature values of the baseline period (1969-1995) with the appropriate monthly change rates, in order to obtain realistic daily data for the climatic scenarios. Doing so does not change the pluri-annual distribution of ówetô and ódryô years, however, it allows considering in an efficient way the variations in intensity of precipitations and the incremental temperature changes (Yusoff et al., 2002). More details about the preparation of the climate change scenarios by IRMB can be found in De Wit et al. (2001). In the scenarios, the quantity of rain is increased during the winter time and decreased during the summer time, compared to present climatic conditions.

Simulation of climate change scenarios

A comparison between results computed for the scenarios and for the historical simulation provides a useful way to show the possible impact of climatic change on the hydrological cycle. In order to have computational results reflecting only the impact of climatic changes, other stresses (mostly extracted flow rates) were maintained constant for the climate change scenario simulations. Since historical extracted flow rates were actually not constant, a ñreference simulationò was run again, similar to the historical simulation, but with constant extracted flow rates. This does not exactly reflect the reality but it provides a useful reference for the further comparisons. In the Geer basin, extracted flow rates being nearly constant over time, the use of averaged values computed for the period 1985-1995 does not lead to important changes in the aquifer exploitation scenario. The impact of climate change is finally based on a comparison between the óreferenceô historical scenario and the climate change scenarios, rather than on a comparison between the actual historical scenario and the climatic scenarios.

Impact of climate change on groundwater levels in the Geer basin

In terms of groundwater reserves, the analysis is mainly based on the comparison between computed groundwater levels at selected observation wells in the studied basin. As an illustration, the comparison between evolutions of groundwater levels computed with the reference simulation and with the different climatic scenarios is presented for two wells: F06 in the northeastern and LAN002 in the western part of the basin. For these two wells, the evolutions of groundwater levels are presented in Figure 8a and 8b.

Climatic scenarios ECHAM4 and HADCM2 predict a clear decrease of groundwater levels, while scenario CGCM1 leads to the prediction that groundwater levels fluctuate more or less around reference groundwater levels or slightly higher. The maximum groundwater level decrease differs from one observation point to the other. At well LAN002, the highest decrease is about 7 m, while at well F06, the decrease is around 2.5 m.

On Figure 8b, sub-scenario ECHAM4_1039 (2010-2039) shows an anomalous increase of groundwater level from April 1994. This is a numerical artefact due to a local desaturation in the one-dimensional finite elements representing the southern gallery in the model. Actually, the axial hydraulic conductivity of the one-dimensional elements used to model the gallery is allowed to diminish in sections of the gallery where the groundwater level in the aquifer falls below the bottom level of the gallery. This was implemented in order to minimize pumping in desaturated sections of the galleries. However, if groundwater levels become very low, a large hydraulic gradient is artificially created in the model to compensate for the fact that the hydraulic conductivity in the gallery becomes very low as well. In any case, this confirms that climate change may have a major impact on groundwater in the Geer basin. Hence, the groundwater extraction policy will probably have to be reconsidered in that basin, with a decrease or a stop of water extraction in the southern gallery and a transfer of the water production to the northern gallery. Of course, this kind of analysis should also consider possible changes in water demand and land practice.

Groundwater levels computed using the different climatic scenarios do not show enhancement of the seasonal changes compared to the reference situation. This seems to indicate that climate change will rather have a pluri-annual impact on groundwater resources, leading globally to a ómonotonicô decrease with time of groundwater levels, rather than an impact on seasonal fluctuations of groundwater levels. However, it has to be noticed that, due to the existence of a thick unsaturated zone, seasonal changes in the percolation can be strongly smoothed, making it difficult to observe any clear variation in seasonal changes of groundwater levels between the reference and the climate change simulations.

Impact of climate change on the groundwater balance in the Geer basin

A simplified water balance analysis was performed, year-by-year, at the scale of the Geer basin. Taking the ódryô years 1977 and 1986 and the ówetô years 1983 and 1988 as examples, Table 1 summarizes the results obtained for the reference simulation and for the ECHAM4_1039 scenario that appears to be the ñdriestò in terms of computed groundwater flows. For this scenario, the simulated groundwater recharge seems globally to be the lowest, as a result of the complex combined actions of temperature increase and precipitation changes. At the first look, this can be considered as surprising as it appears that the next two periods are characterized by higher aquifer recharge. Actually, for the second and the third period of ECHAM4, the effect of temperature changes is over balanced by precipitation changes.

Under current conditions (reference scenario), if averaged values are considered for 1977, a mean flow rate of 2.55 m^3/s is computed at the outlet of the basin, with a mean base flow component of 0.89 m^3/s. Considering that about 2 m^3/s are extracted for water distribution or flowing out of the basin through non-impervious model boundaries, an average deficit of about 0.34 m^3/s can be estimated for groundwater reserves in 1977. As a comparison, considering a specific yield of 5%, this leads to a mean groundwater level decrease of 0.44 m over the whole aquifer. For 1983, an averaged value of 4.94 m^3/s is computed for the flow rate at the outlet with a base flow component of 1.97 m^3/s. This leads to an average gain for groundwater reserves of 0.97 m^3/s. This corresponds to a mean groundwater level rise of 1.26 m over the whole basin. The same reasoning can be applied for 1986 and 1988 to obtain respectively an average decrease of the piezometric head of 0.19 m (1986) and an average increase of 1.62 m (1988).

In the ECHAM4_1039 simulation, for the year referenced with regards to 1977, a mean decrease of 1.8 m of the water levels over the whole basin is estimated (instead of 0.44 m in the reference simulation). Similarly, for the year referenced to 1986 a mean decrease of 0.71 m is calculated (instead of 0.19 m in the reference simulation). For the years referenced to 1983 and 1988, the piezometric head rise is limited to 1.04 m instead of 1.26 m for 1983, and to 1.04 m instead of 1.62 m for 1988. These yearly average values indicate that, for relatively ódry yearsô, groundwater deficits are boosted; in the same time, for relatively ówet yearsô, groundwater excesses are attenuated.

The conclusion of this analysis is that, provided that the population distribution of ódryô and ówetô years does not change in the future (which is not considered in the present analysis), in the worst case scenario (ECHAM_1039), a generalised deficit of groundwater piezometric heads can be expected in the Geer basin. This effect could be minimised if an increase number of ówetô years will be observed in the future.

Conclusions

In this paper, results pertaining to the groundwater compartment are presented and discussed. From the hydrogeologist point of view, if reliable predictions are desired concerning the impact of climate change on the evolution of groundwater resources, it is very important that groundwater flows should be fully physically described and that the model should be able to deal with the heterogeneous nature of aquifer media. Equations that are solved are those accepted in the field of hydrogeology. The drawback is an integrated model that is probably more time consuming. However, this is the price to pay in order to get accurate results in terms of groundwater flows and groundwater levels.

From the modelling application on the Geer basin, it appears that the evaluation of the impact of climate change on groundwater reserves and on base flow is not straightforward. On a pluri-annual basis, most tested scenarios predict a decrease in groundwater levels and reserves in relation with variations in climatic conditions. At the same time, the tested scenarios do not show enhancement of the seasonal variations in groundwater levels. This is explained by the fact that, whatever the mean characteristics of weather conditions (ówetô or ódryô years), the percolation to the aquifer will be reduced compared to present recharge conditions.

These conclusions are in accordance with other works published recently that deal in a physical way with the modelling of groundwater resources. For example, Loaiciga et al. (2000) studied the impact of climate change on groundwater resources of the Edward BFZ regional karst aquifer in Texas. They draw the conclusion that, even if the pumping regime is not increased compared to present conditions, the groundwater resource in this aquifer could be strongly impacted under a warmer climate. Yusoff et al. (2002) studied the impact of climate change on a chalk aquifer in eastern England and also draw similar conclusions. De Wit et al. (2001) studied the impact of climate change on the hydrology of the river Meuse. Their general conclusion is that catchments with dominance of the fast runoff component over groundwater base flow are more sensitive to climate change than others. This is not the case of the Geer basin where the groundwater component is strongly dominant. Results, thus, seem here contradictory; however, it has to be noticed that, except the SIMGRO model (Veldhuizen et al. 1998), most modelling approaches (SCHEME, Roulin et al. 2000, MEUSEFLOW, van Deursen 2000) used in that research represent the groundwater component by linear reservoirs or multiple reservoirs. Furthermore, they applied those models on several sub-catchments of the Meuse catchment where groundwater resources are less important than in the Geer basin (e.g., the upper Ourthe catchment, the Mehaigne catchment é).

The analysis presented here focuses the direct impact of climate change on groundwater resources. In addition, soil degradation and changes in water demand, irrigation practices or land use can also be expected, enhancing the demand for groundwater exploitation (e.g., Eheart and Tornil 1999, Feddema and Freire 2001) or even groundwater quality (e.g., Arnell 1998). It thus seems realistic to claim that climate change is likely to have a dramatic impact on groundwater resources, due to the combined effect of direct and indirect factors. Despite all efforts that can contribute to a reduction of climate change, specific measures should be foreseen in order to minimize the effect of climate change on groundwater resources, e.g. the development of techniques for artificial recharge of aquifers.

Further steps in the examination of climate change impact on groundwater resources relate to the consideration in the modelling approach of indirect effects, like changes in land-use, irrigation, groundwater exploitation optimisation. Improvements could also be expected, should more accurate climate change scenarios become available and improved downscaling techniques developed. It could also be very interesting to evaluate the impact of climate change in other hydrological and hydrogeological contexts. First results were obtained for other basins in Belgium, showing a similar trend, but more data and results are needed in order to draw more general conclusions.

Acknowledgement

This study corresponds to a groundwater part of the project ñINTEGRATED MODELLING OF THE HYDROLOGICAL CYCLE IN RELATION TO GLOBAL CLIMATE CHANGEò (CG/DD/08) supported by Prime Ministerôs Office ï Federal Office for Scientific, Technical and Cultural Affairs of Belgium in the scope of the general program óGlobal Change Sustainable Developmentô. The authors would also like to thank the other teams involved in the project for their fruitful cooperation, Jean Houard who helped to improve the quality of the English of the manuscript, Perry Olcott, Ian Holman and an anonymous reviewer whose comments helped to improve the quality and the content of the manuscript.

References

Arnell, N., 1998, Climate change and water resources in Britain, Climatic Change, 39(1), 83-110.

Arnell, N., 2002, Hydrology and Global Environmental Change, Prentice Hall, 346 p.

Beeton, A. M., 2002, Large freshwater lakes: present state, trends,, and future. Environ. Cons., 29(1), 21-38.

Brouyère, S., 2001, Etude et modélisation du transport et du piégeage des solutes en milieu variablement saturé (Study and Modelling of transport and retardation of solutes in variably saturated media), in French, PhD Thesis, University of Liège, Faculty of Applied Sciences, 572p.

Carabin, G., Dassargues A., 1999, Modeling groundwater with ocean and river interaction, *Water Resour. Res*., 35(8), 2347-2358.

Carabin, G., Dassargues A., 2000, Coupling of parallel river and groundwater models to simulate dynamic groundwater boundary conditions (Proc. of Computational Methods in Water Resources 2000), Bentley L.R., Sykes J.F., Brebbia C.A., Gray W.G. & Pinder G.F., vol.2, 1107-1113, Balkema.

Dassargues, A., Monjoie, A., 1993, The Chalk in Belgium, in: The Hydrogeology of the Chalk of North-West Europe, Ed. Downing, Price, Jones, Oxford Science Publ., Clarendon Press, Oxford, UK, 153-269.

Dassargues A., Maréchal J.C., Carabin G. and Sels O., 1999, On the necessity to use three-dimensional groundwater models for describing impact of drought conditions on streamflow regimes, in Hydrological Extremes : Understanding, Predicting, Mitigating (Proc. of IUGG 99 Symposium HS1, Birmingham, July 1999), IAHS Publication n°255, 165-170.

De Wit, M.J.M., Warmerdam, P.M.M., Torfs, P.J.J.F., Uijlenhoet, R., Roulin, E., Cheymol, A., van Deursen, W.P.A., van Walsum, P.E.V., Ververs, M., Kwadijk, J.C.J., Buiteveld, H., 2001, Effect of climate change on the hydrology of the river Meuse, Wageningen University, Environmental Sciences, Water Resources, Report 108, 134 p.

Eheart, J.W., Tornil, D.W., 1999, Low-flow frequency exarcerbation by irrigation withdrawal in the agricultural Midwest under various climate change scenarios, *Water Resour. Res., 35*(7), 2237-2246.

Everbecq, E., Gosselain, V., Viroux, L. & Descy, J.- P., 2001, POTAMON: a dynamic model for predicting phytoplankton composition and biomass in lowland rivers. *Water Research*, 35(4), 901-912.

Feddema, J.J., Freire, S., 2001, Soil degradation, global warming and climate impacts, Climate Research, 17(2), 209-216.

Gellens, D., Roulin, E., 1998, Streamflow response of Belgian catchments to IPCC climate change scenarios, *J. Hydrol., 210*, 242-258.

Gogu, R.C., 2000, Advances in groundwater protection strategy using vulnerability mapping and hydrogeological GIS databases. Ph.D. Thesis, Applied Sciences Faculty of the University of Liege, Belgium, 152p.

Gogu, R., Carabin, G., Hallet, V., Peters, V., Dassargues, A., 2001, GIS-based hydrogeological databases and groundwater modelling, *Hydrogeology Journal*, 9, 555-569.

Goldscheider, N., 2003, Hydrogeology and Climate change, submitted to *Hydrogeology Journal*.

Hallet, V., 1999, Etude de la contamination de la nappe aquifère de Hesbaye par les nitrates: hydrogéologie, hydrochimie et modélisation mathématique des écoulements et du transport en milieu saturé (nitrate contamination of Hesbaye chalky aquifer in Belgium: hydrogeology, hydrochemistry and transport modelling), in French, PhD Thesis, University of Liège, Faculty of Sciences, 361p.

IPCC Third Report, 2001, Impacts, Adaptation and Vulnerability, Contribution of the working group II to the third assessment report of the Intergovernmental Panel on Climate

Change (IPCC), McCarthy J.J., Canziani, O.F., Leary, N. A., Dokken, D.J., White, K.S. (Eds.), Cambridge Univ. Press, UK, 1000p.

Loaiciga, H.A., Valdes, J.B., Vogel, R., Garvey, J., Schwarz, H., 1996, Global warming and the hydrological cycle, *J. Hydrol.*, 174, 83-127.

Loaiciga, H.A., Maidment, D.R., Valdes, J.B., 2000, Climate-change impacts in a regional karst aquifer, Texas, USA, *J. Hydrol., 227*, 173-194.

Menzel, L., Bürger, G., 2002, Climate change scenarios and runoff response in the Mulde catchment (Southern Elbe, Germany), *J. Hydrol., 267,* 53-64.

Monjoie, A., 1967, Observations nouvelles sur la nappe aquifère de la craie en Hesbaye (Belgique) (New observations about the chalky Hesbaye aquifer in Belgium). *Mémoires de lôAssociation Internationale des Hydrogéologues* (AIH-IAH), Istanbul.

Roulin, E., Cheymol, A., Gellens, D., 2000, Impact of climate changes on the water resources in the river Meuse basin, in: Proceedings of the International Conference on Integrated Water Resources Management for Sustainable Development, 19-21 December 2000, New Delhi, India, Mehrota, R., Soni, B. and Bhatia, K.K.S. (eds), National Institute of Hydrology, Roorkee, India, 1045-1054.

Smitz, J., Everbecq, E., Deliège, J.-F., Descy, J.-P., Wollast, R. and Vanderborght. J.-P., 1997, PEGASE, une méthodologie et un outil de simulation prévisionnelle pour la gestion de la qualité des eaux de surface (PEGASE : a methodology and a forecasting simulation tool for surface water quality management). *Tribune de l'Eau*. 588, 73-82.

Sohier C., Moeremans B., Deglin D. and Dautrebande S., 2000, Validation of the new catchment hydrological model EPIC-GRID for soil moisture evaluation and discharges simulation. Workshop ñThe future of distributed hydrological modellingò, Leuven, Belgium, 12 to 15 April 2000, Hydrological processes, special issue (in press).

Sudicky, E. A., Unger, A. J. A., Lacombe, S. , 1995, A noniterative technique for the direct implementation of well bore boundary conditions in three-dimensional heterogeneous formations, Water Resour. Res., 31(2), 411-415.

Sun, G., Amatya, D.M., McNulty, S.G., Skaggs, R.W., Hughes, J.H., 2000, Climate change impacts on the hydrology and productivity of a pine plantation. *J. Am. Water Resour. Ass.*, *36*(2), 367-374.

Therrien R., Sudicky E. A., 2000, Well bore boundary conditions for variably saturated flow modeling, *Adv. Water Resour.*, 24(2), 195-201.

Van Deursen, W.P.A., 2000, MEUSEFLOW 2.1, Laagwaterstudies Maasstroomgebied, RIZA project RI-2988A. RIZA, Arnhem, The Netherlands.

Veldhuizen, A.A., Poelman, A., Stuyt, L.C.P.M., Querner, E.P., 1998, Software documentation for SIMGRO v.3.0, Regional Water Management Simulator, Wageningen, DLO-Staring Centrum, Report 104-def.doc, 289 p.

Westmacott, J. R., Burn, D. H., 1997, Climate change effects on the hydrological regime within the Churchill-Nelson River Basin, *J. Hydrol., 202*, 263-279.

Yusoff, I., Hiscock, K.M., Conway, D., 2002, Simulation of the impacts of climate change on groundwater resources in eastern England, in: Hiscock, K.M., Rivett, M.O., Davison, R.M. (eds) Sustainable Groundwater Development, Geological Survey, London, *Special publication, 193*, 325-344.

Figure captions

Figure 1. Location map of the Geer basin

Figure 2. Mapping procedure between river and groundwater model nodes

Figure 3. Representative geological cross-section in the Geer basin (see Figure 1 for location of the cross-section in the Geer basin)

Figure 4. Scatter plots between observed and computed water levels in observation wells for the two simulations performed under steady state conditions

Figure 5. Computed piezometric map and scatter plot diagram comparing computed and measured groundwater heads for September 1984 (on the map, the circles correspond to observion wells for the piezometric campaign of September 1984)

Figure 6. Comparison between measured and computed groundwater level fluctuations at several selected observation wells for both validation and calibration periods; the dots represent measured groundwater levels; the continuous lines represent the computed evolution of groundwater levels at the well

Figure 7. Observed and computed flow rates at the outlet of the Geer basin at Kanne

Figure 8. Evolution of water levels at (a) well FO6 and (b) well LAN002 located in the Geer basin (climatic scenarios).

Table 1. Comparison between water balance variations for four reference years (1977, 1983, 1986 and 1988) for the reference simulation and the climatic scenario ECHAM4_1039.

			I_{eff} (m^3/s)	BF (m^3/s)	Diff (m^3/s)	P + Ex (m^3/s)	ΔS_G (m^3/s)	ΔH_G (mm)	ΔH_{chalk} (m)
Reference simulation	ódryô years	1977	2.55	0.89	1.66	2	-0.34	-22	-0.44
		1986	3.49	1.64	1.85	2	-0.15	-10	-0.19
	ówetô years	1983	4.94	1.97	2.97	2	0.97	63	1.26
		1988	5.32	2.07	3.25	2	1.25	81	1.62
ECHAM4 30 years	ódryô years	1977	0.99	0.38	0.61	2	-1.39	-90	-1.80
		1986	2.36	0.91	1.45	2	-0.55	-35	-0.71
	ówetô years	1983	3.99	1.19	2.80	2	0.8	52	1.04
		1988	4.09	1.29	2.80	2	0.80	52	1.04

Ieff : effective infiltration, BF : Base flow, Diff = Ieff ï BF, P+Ex : Pumping + Exchanges, ΔS_G = Diff ï (P + Ex) : variation in groundwater stock (in m^3/s) , ΔH_G = Variation in groundwater stock (in mm), ΔH_{chalk} : variation in groundwater level assuming a mean specific yield of 0.05 for the chalk

Table 1

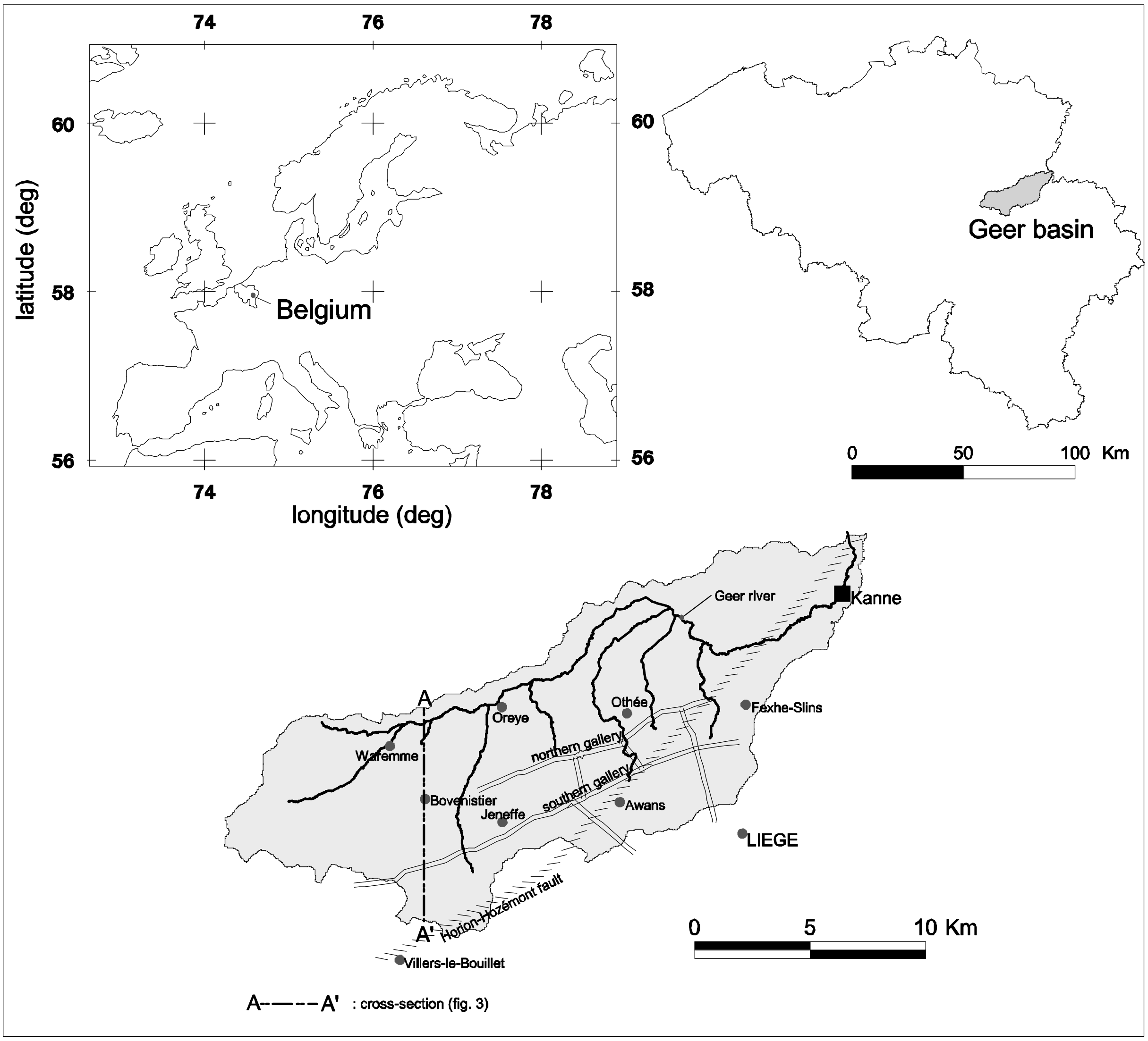

Figure 1. Location map of the Geer basin

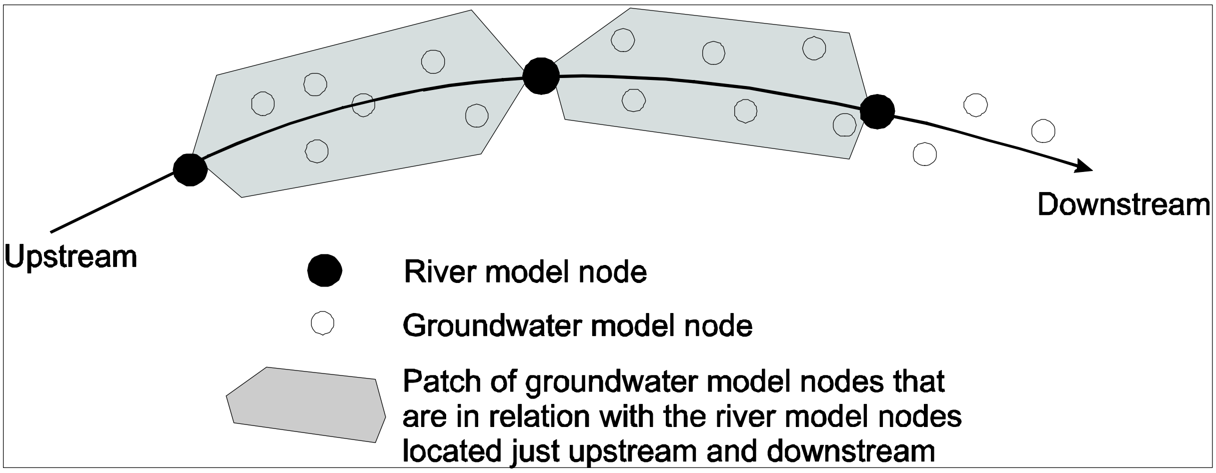

Figure 2. Mapping procedure between river and groundwater model nodes

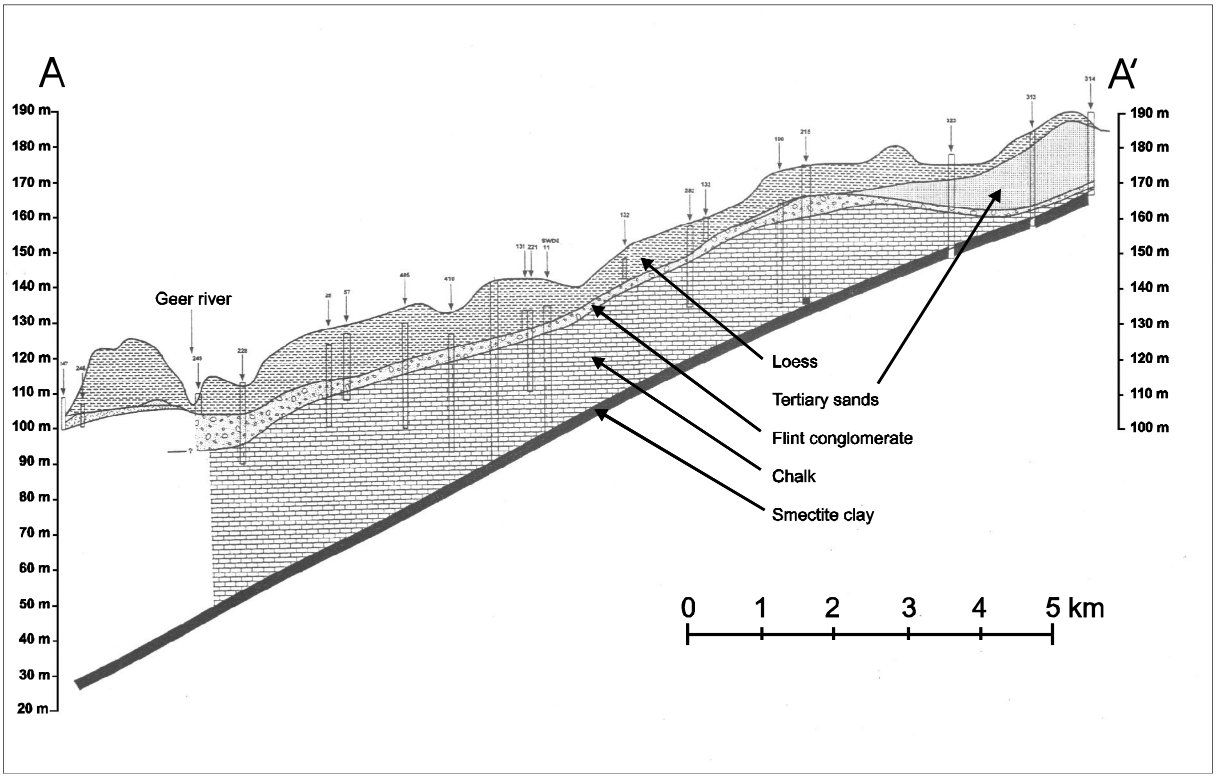

Figure 3. Representative geological cross-section in the Geer basin (see Figure 1 for location of the cross-section in the Geer basin)

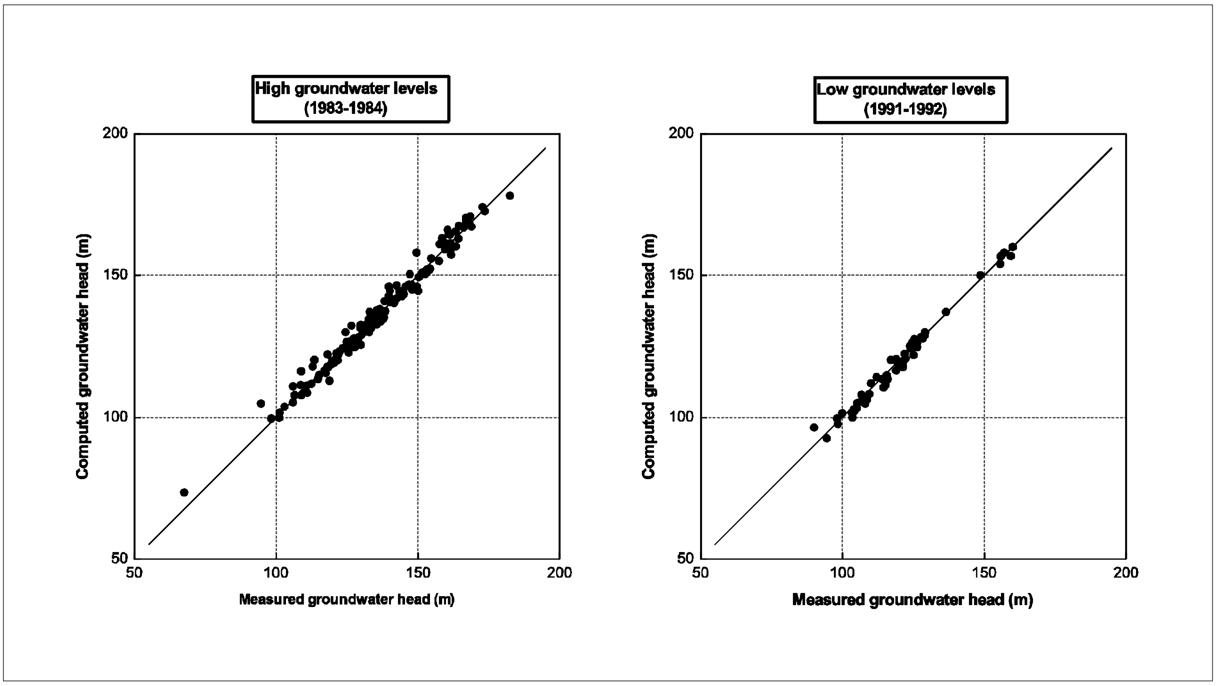

Figure 4. Scatter plots between observed and computed water levels in observation wells for the two simulations performed under steady state conditions

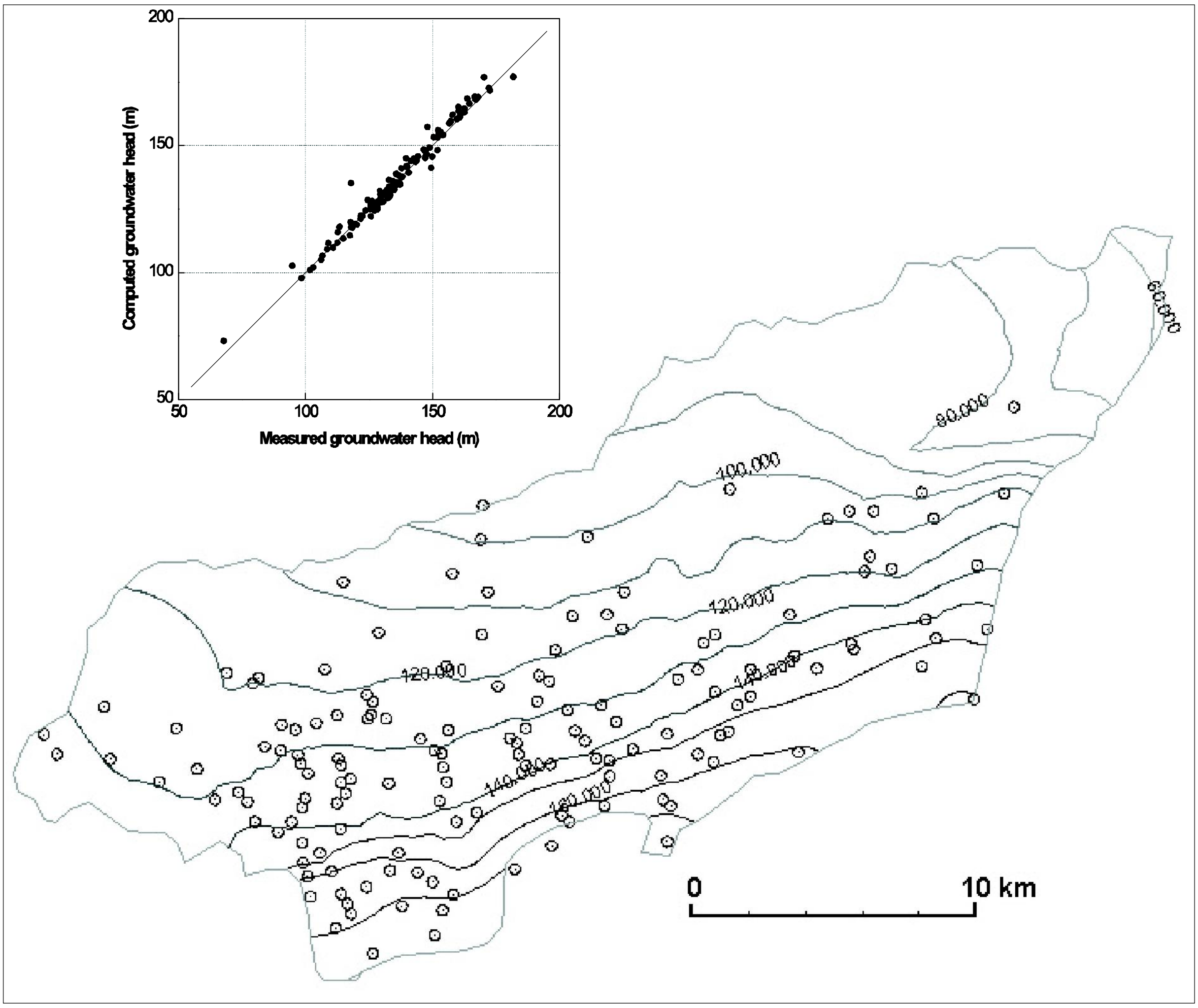

Figure 5. Computed piezometric map and scatter plot diagram comparing computed and measured groundwater heads for September 1984 (on the map, the circles correspond to observion wells for the piezometric campaign of September 1984)

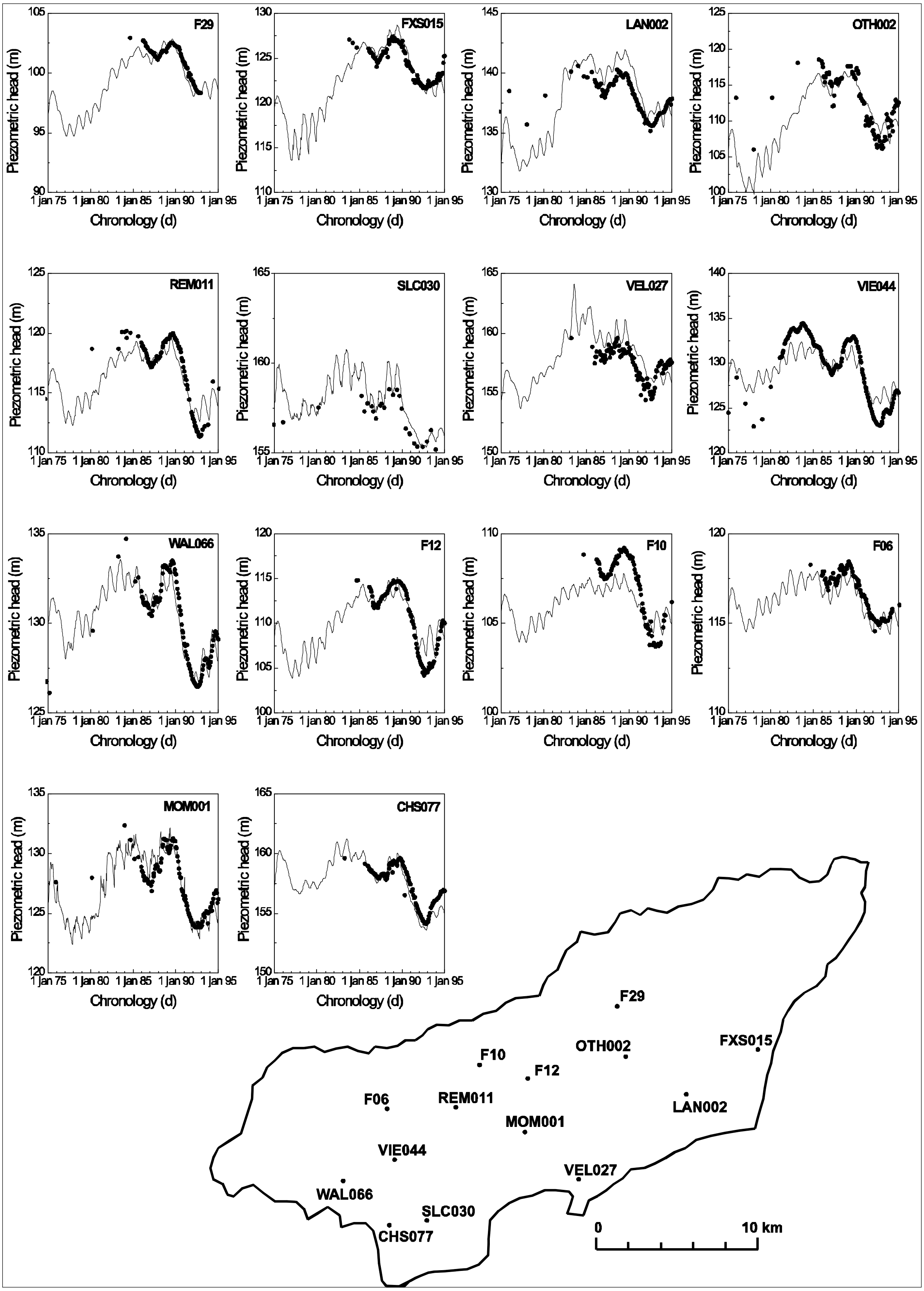

Figure 6. Comparison between measured and computed groundwater level fluctuations at several selected observation wells for both validation and calibration periods; the dots

represent measured groundwater levels; the continuous lines represent the computed evolution of groundwater levels at the well

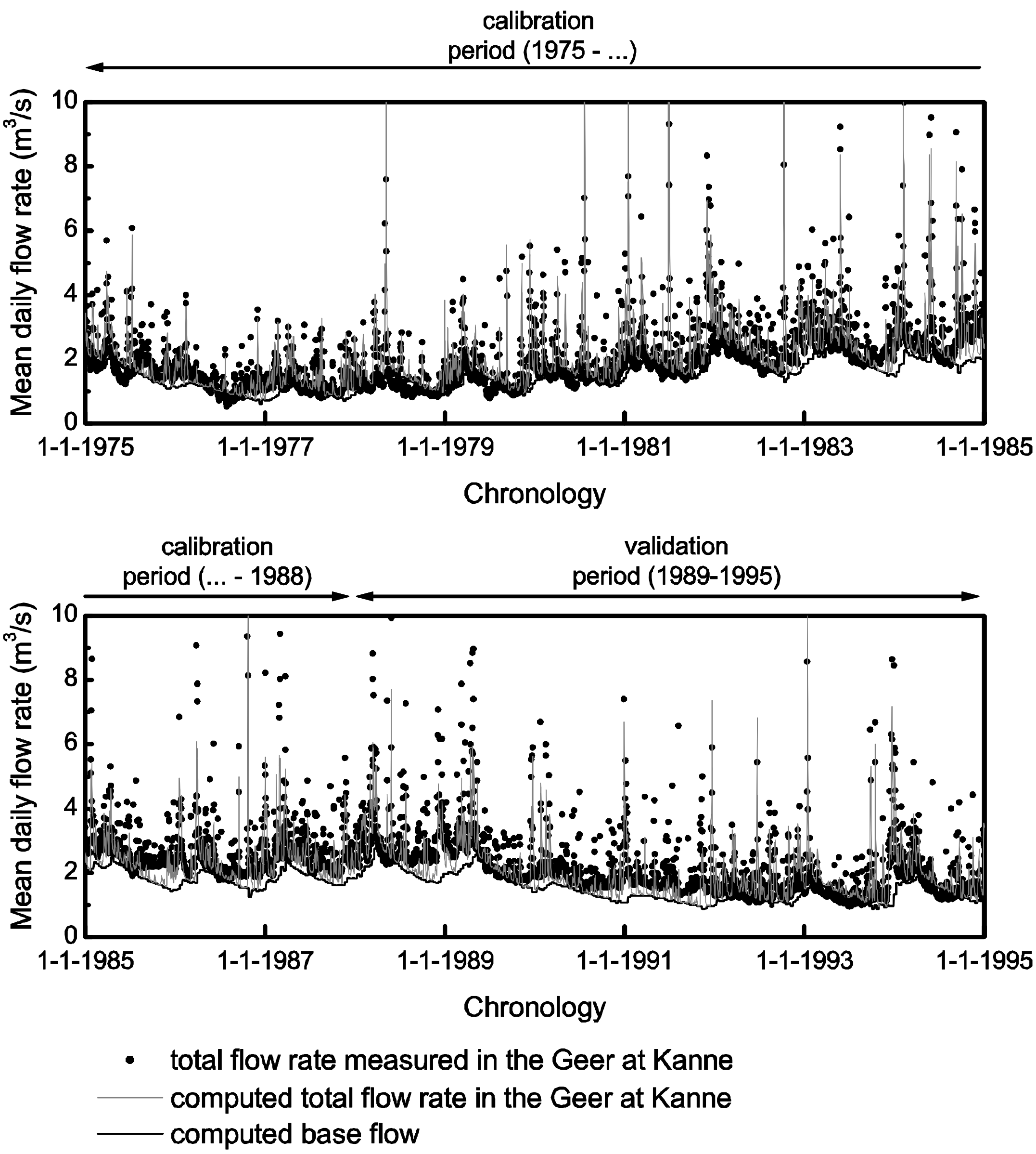

Figure 7. Observed and computed flow rates at the outlet of the Geer basin at Kanne

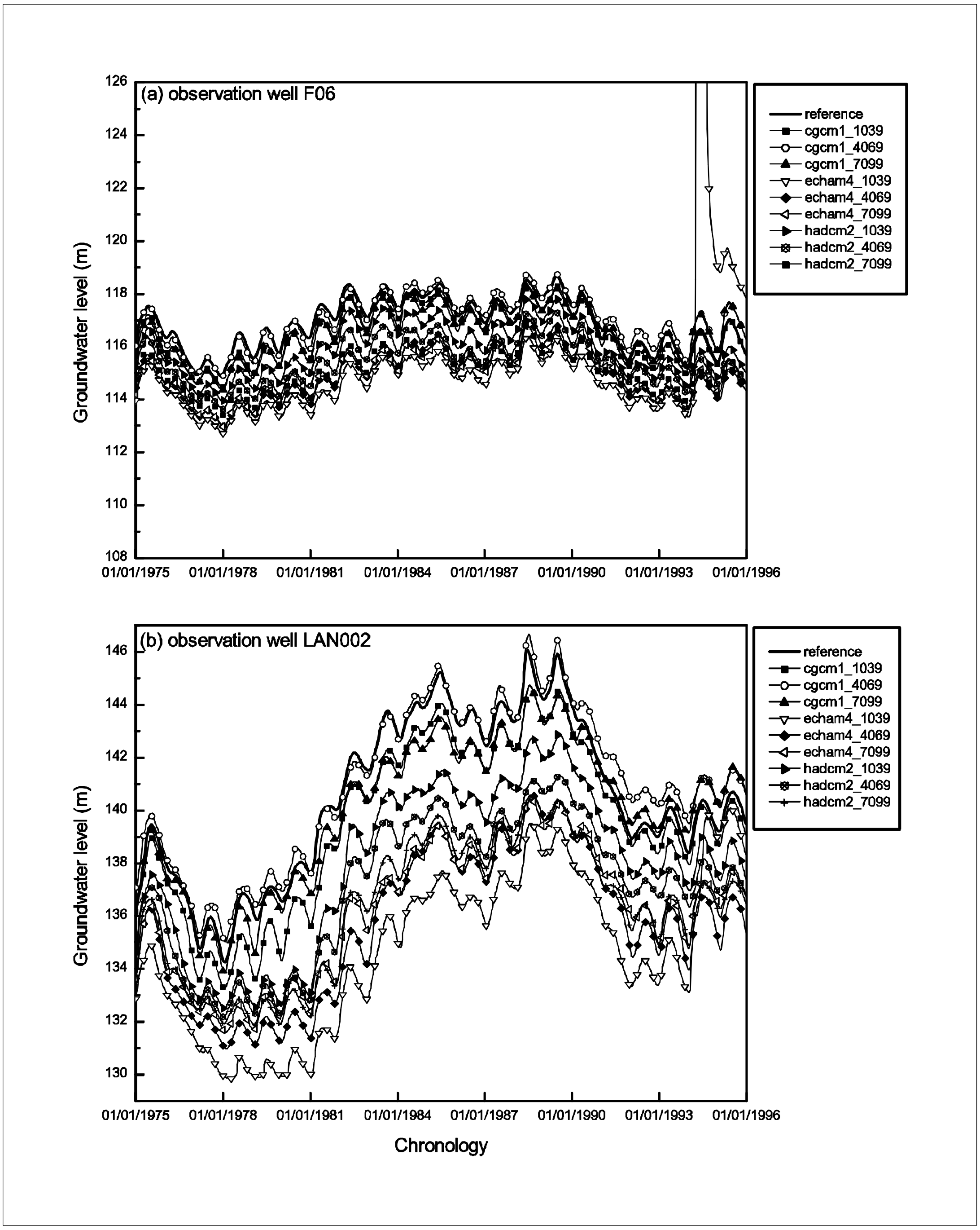

Figure 8. Evolution of water levels at (a) well FO6 and (b) well LAN002 located in the Geer basin (climatic scenarios).