

## Integrated approach for assessing climate change impacts on a regional chalky aquifer in Belgium

P. GODERNIAUX<sup>1,2</sup>, S. BROUYÈRE<sup>1</sup> & A. DASSARGUES<sup>1,3</sup>

<sup>1</sup> Hydrogeology & Environmental Geology, Geo<sup>3</sup> Group, ArGEnCo Dpt, B-52/3, Université de Liège, B-4000 Liège, Belgium  
[alain.dassargues@ulg.ac.be](mailto:alain.dassargues@ulg.ac.be)

<sup>2</sup> National Fund for Scientific Research of Belgium

<sup>3</sup> Hydrogeology & Engineering Geology Group, Department of Geology-Geography, Katholieke Universiteit Leuven, Celestijnenlaan 200E, B-3001 Heverlee, Belgium

**Abstract** An integrated hydrological model was developed in order to study the potential effects of climate change on groundwater resources. This model considers most hydrological processes in a physically consistent way. More particularly, groundwater flows are modelled using a spatially distributed finite element approach. The river-aquifer interactions are explicitly taken into account in the model, as well as the spatial heterogeneity of the chalk geology characteristics. After a detailed calibration on the last 30 years and validation on recent periods, quantitative interpretations can be drawn from the groundwater model results. Considering IPCC climate change scenarios, it appears that, on a multi-annual basis, most tested scenarios predict a decreasing trend in groundwater levels in the Geer Basin. These first results indicate that groundwater deficits may be expected in the future in Belgium. Moreover, at this stage of the study, this trend is computed for a very “optimistic” scenario, neglecting all other pressure changes on the groundwater resources (i.e. no change in land use and in pumping conditions).

**Key words** Belgium; chalk aquifer; climate change impact; groundwater; integrated model

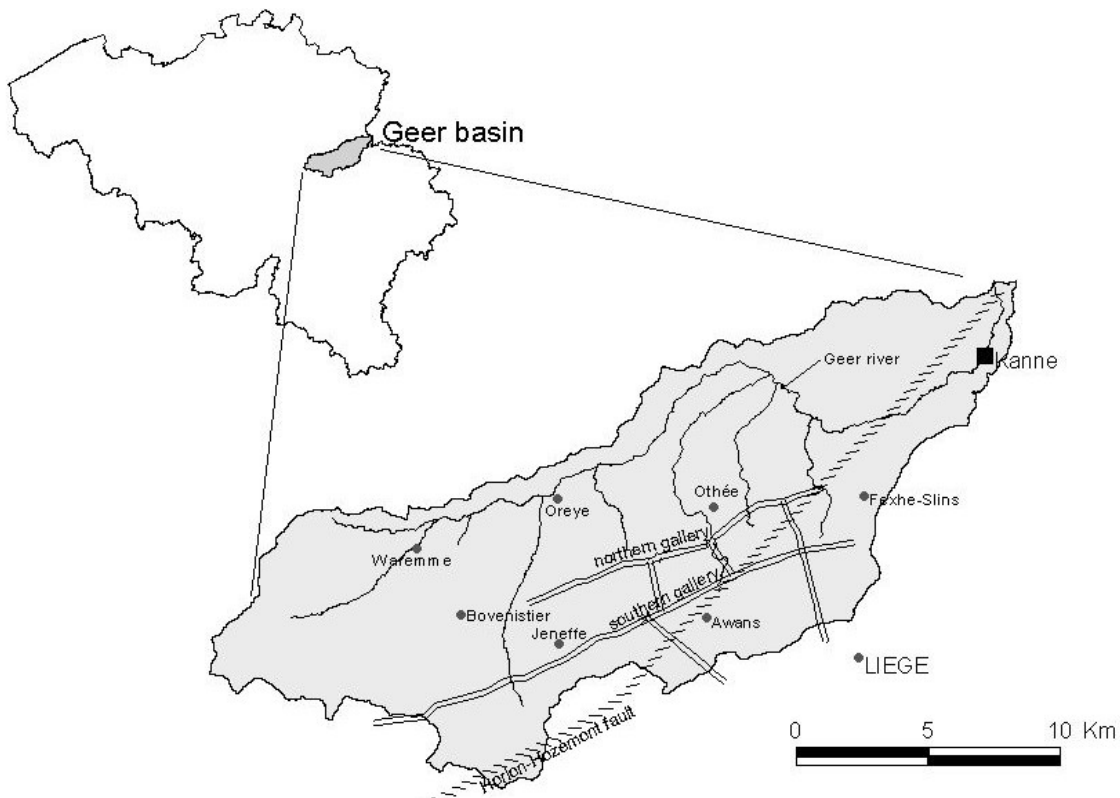
### INTRODUCTION

Variations in temperature and precipitation during the year may have a direct impact on changes in groundwater levels, reserves and quality. In terms of climate changes, an increase in winter rainfall associated with a shorter recharge season are usually foreseen in Belgium. It leads to uncertain trends for the future total recharge of aquifers. Additionally, indirect recharge from surface water bodies and from overland flow may also be affected by changes in streamflow and in overland flow events.

Reliable estimation of groundwater levels, reserves and base flow to the streams ideally requires an accurate and physically consistent simulation of the different parts of the hydrological cycle (Dassargues *et al.*, 1999), especially in drought conditions. Many integrated hydrological models use transfer functions or lumped models (linear reservoirs) for simulation of the groundwater component. From a groundwater perspective, these approaches, which are oversimplified, should rather be qualified as “calibrated” 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 may not be reliable when predictive

computations are performed with aquifer stresses (i.e. recharge, pumping, boundary conditions) 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.

Results relating to the groundwater component of an integrated hydrological model, developed for the Geer basin in Belgium (Fig. 1), are used here to illustrate and discuss the potential impact of climate change on groundwater resources.



**Fig. 1** Location of the Geer basin in Belgium.

## **DETAILED GROUNDWATER MODEL EMBEDDED IN AN INTEGRATED HYDROLOGICAL MODEL**

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 on a multi-node parallel work-station. The EPIC-GRID soil model (Sohier *et al.*, unpublished data) is a semi-distributed model that computes, in each 1 km<sup>2</sup> cell of a regular grid, a water budget at the soil surface and in the unsaturated zone. It is 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) solves one-dimensional (1-D) Saint-Venant equations to model water flows in the river network. Groundwater flows are computed using the finite element simulator SUFT3D (Carabin & Dassargues, 1999). The three sub-models exchange computed water flow rates at different locations and times using spatial and temporal mapping procedures. The spatial discretization used in the groundwater finite element model is not necessarily identical to the regular grid of the soil model. 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 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 & Dassargues, 2000).

## HYDROGEOLOGICAL CONDITIONS

Groundwater resources located in the Geer basin (350 km<sup>2</sup>) provide about 60 000 m<sup>3</sup> day<sup>-1</sup> of drinking water for the city of Liège and its suburbs (Dassargues & Monjoie, 1993). From top to bottom, the substratum is made up of: (1) a Quaternary loess of variable thickness, up to 20 m; (2) a maximum of 10 m of a conglomerate; (3) locally, several meters of Tertiary sand deposits; (4) Cretaceous chinks forming the main reservoir (thickness up to 70 m), this layer is divided by a thin layer of hardened chalk called the “Hardground”; and (5) at the bottom, several metres 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 river Geer.

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. Fractured zones in the chalk also correspond to dry valleys visible in the surface morphology. 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 places, but an important quantity of water is also recharged from the gallery into the aquifer in other zones, depending on local differences between water levels in the aquifer and in the galleries. Apart from the galleries, the aquifer is exploited by pumping wells owned by water companies, local industries and agricultural settlements.

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 3-D finite element discretization 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 “hard ground”, one layer for the upper fractured chalk, one layer for the conglomerate and finally one layer for the loess. Laterally, the layers may represent different geological units. Hence, the “hard ground” is not present everywhere, and the conglomerate layer

disappears toward the north where it is replaced by the Tertiary sands. Galleries are modelled using 1-D highly conductive finite elements. Globally, the 3-D 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 *et al.*, 2001).

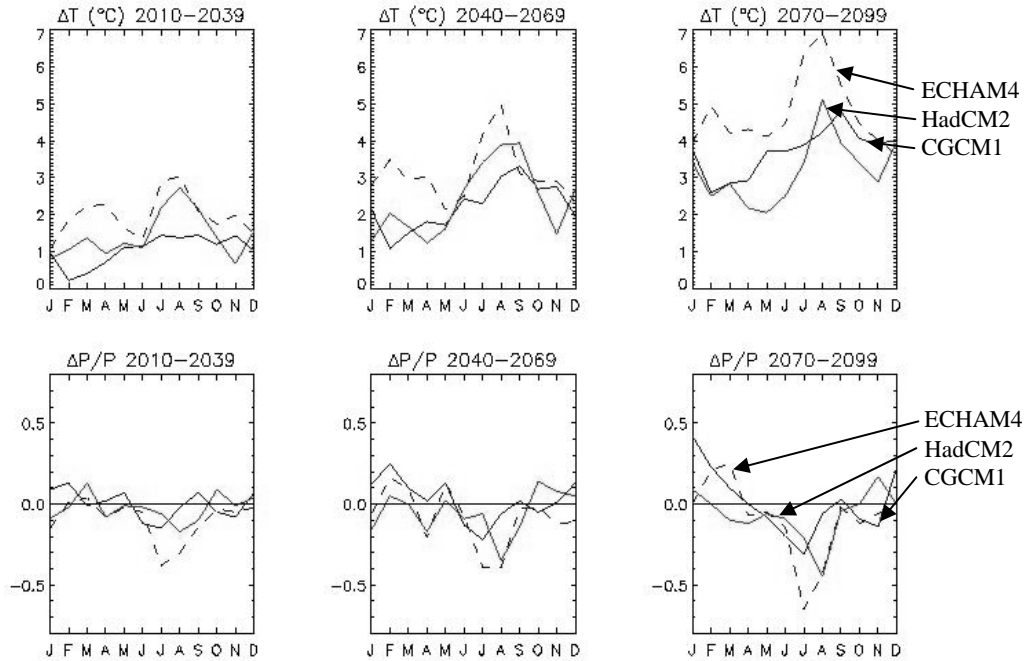
## **CALIBRATION AND VALIDATION OF THE GROUNDWATER MODEL**

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: high groundwater levels (1983–1984), and low groundwater levels (1991–1992). For this calibration step, the groundwater model was run in stand-alone mode, assuming a constant and uniformly distributed recharge. In a second step, the calibration was improved by running transient simulations within the integrated hydrological model. Details on the calibration and validation results can be found in Brouyère *et al.* (2003). 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.

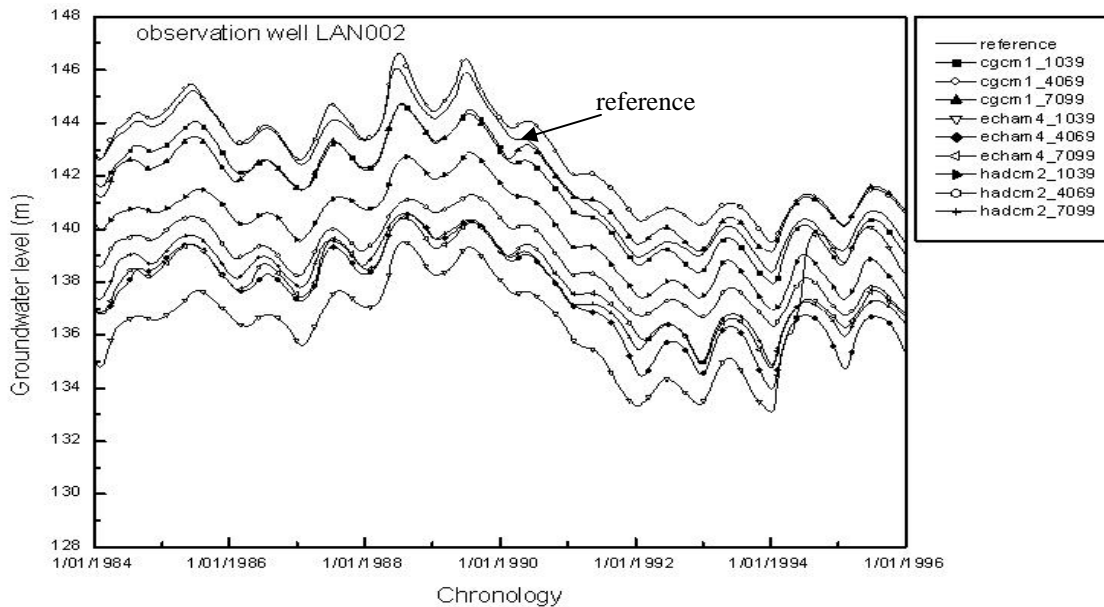
## **MODELLING CLIMATE CHANGE IMPACT**

A subset of three General Circulation Models (GCMs) was selected in 2001, 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 considering the 1969–1995 period as a baseline. For these three scenarios, monthly increments of precipitation and temperatures were computed for three periods 2010–2039, 2040–2069, and 2070–2099 (Fig. 2). Using these increments, “local” 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. It can be observed that the quantity of rain is increased during the winter time and decreased during the summer time, compared to current climatic conditions.

In order to reflect only the direct impact of rain and temperature changes, other stresses (mostly extracted flow rates) were maintained as constant for the scenarios simulations. Since historical extracted flow rates were actually not constant, a “reference simulation” 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 assessed on the basis of a comparison between the “reference” historical scenario and the climate change scenarios, rather than on a comparison between the actual historical scenario and the climatic scenarios.



**Fig. 2** Calculated increments of change in temperature and precipitation in Belgium from IPCC scenarios for the three considered periods (calculated in 2001 by the Royal Institute of Meteorology of Belgium—IRMB).



**Fig. 3** Evolution of water levels in one well located in the Geer basin for the three different climatic scenarios and the three computed periods.

We observed that climatic scenarios ECHAM4 and HADCM2 predict a clear decrease of groundwater levels (Fig. 3), while scenario CGCM1 leads to fluctuations around reference groundwater levels or slightly higher. Climate change will rather have a multi-annual impact on groundwater resources, leading globally to a monotonic

decrease with time of groundwater levels, rather than an impact on seasonal fluctuations of water 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 changes simulations.

A simplified water balance analysis was performed (Brouyère *et al.*, 2003), year-by-year, at the scale of the Geer basin, indicating that for relatively “dry years”, groundwater deficits are boosted; in the same time, for relatively “wet years”, groundwater excesses are attenuated. The conclusion of this analysis is that, provided that the population distribution of “dry” and “wet” years does not change in the future (which is not considered in the present analysis), in the worst case scenario (ECHAM\_1039), a generalized deficit of groundwater piezometric heads can be expected in the Geer basin. This effect could be minimized if an increase number of wet years is observed in the future.

## CONCLUSIONS

It appears that evaluation of the impact of climate change on groundwater reserves and on base flow is not straightforward. On a multi-annual basis, most tested scenarios predict a decrease in groundwater levels. These conclusions are in accordance with works published recently that deal, in a physical way, with the modelling of groundwater resources (Loaiciga *et al.*, 2000; Yusoff *et al.*, 2002). De Wit *et al.* (2001), studying the impact of climate change on the hydrology of the river Meuse, concluded that catchments with dominance of fast runoff over groundwater base flow are more sensitive to climate change than others. However, in their modelling approaches (MEUSEFLOW, van Deursen, 1998; SCHEME, Roulin *et al.* 2001), the groundwater flow was simulated by linear reservoirs or multiple reservoirs and applied on several sub-catchments where groundwater flow is far less important than in the Geer basin.

The integrated analysis presented here focuses on the direct impact of rain and temperature changes on groundwater resources in a sub basin where the groundwater flow is clearly dominant. Soil degradation and changes in water demand, irrigation practices or land use can also be expected, enhancing the demand for groundwater exploitation or even groundwater quality (e.g. Arnell, 1998). It thus seems realistic to claim that climate change is likely to have a large impact on groundwater resources, due to the combined effect of direct and indirect factors.

## REFERENCES

- Arnell, N. (1998) Climate change and water resources in Britain. *Climatic Change* **39**(1), 83–110.
- Brouyère, S., Carabin, G. & Dassargues A. (2003) Climate change impacts on groundwater resources: modelled deficits in a chalky aquifer, Geer basin, Belgium. *Hydrogeol. J.* **12**(2), 123–134.
- 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. In: *Proc. Computational Methods in Water Resources 2000* (ed. by L. R. Bentley, J. F. Sykes, C. A. Brebbia, W. G. Gray & G. F. Pinder) **2**, 1107–1113. Balkema, The Netherlands.
- Dassargues, A. & Monjoie, A. (1993) The Chalk in Belgium. In: *The Hydrogeology of the Chalk of North-West Europe* (ed. by Downing R.A., Price M., Jones G.P.), 153–269. Oxford Science, Clarendon Press, UK.

- Dassargues A., Maréchal J. C., Carabin G. & 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* (ed. By L. Gottschalk, J. -C. Olivry, D. Reed & D. Rosbjerg), 165–170. IAHS Publ. 255. IAHS Press, Wallingford, UK.
- 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.
- Gogu, R., Carabin, G., Hallet, V., Peters, V. & Dassargues, A. (2001) GIS-based hydrogeological databases and groundwater modelling. *Hydrogeol. J.* **9**, 555–569.
- 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.
- Roulin, E., Cheymol, A. & Gellens, D. (2001) Impact of climate changes on the water resources in the river Meuse basin. In: *Proc. of the International Conference on Integrated Water Resources Management for Sustainable Development*, (ed. R. Mehrota, B. Soni & K.K.S. Bhatia), 1045-1054, National Institute of Hydrology, Roorkee, India.,
- Smits, J., Everbecq, E., Deliège, J. -F., Descy, J. -P., Wollast, R. & Vanderborght, J. -P. (1997) PEGASE: a methodology and a forecasting simulation tool for surface water quality management (in French). *Tribune de l'Eau* **588**, 73-82.
- Sohier C., Moeremans B., Deglin D. & Dautrebande S. (2000) Validation of the new catchment hydrological model EPIC-GRID for soil moisture evaluation and discharges simulation. Leuven, Belgium (unpublished).
- Van Deursen, W. P. A. (1998) MEUSEFLOW 2.1, Laagwaterstudies Maasstroombgebied, RIZA project RI-2988A. RIZA, Arnhem, The Netherlands.
- Yusoff, I., Hiscock, K. M. & Conway, D. (2002) Simulation of the impacts of climate change on groundwater resources in eastern England. In: *Sustainable Groundwater Development* (ed. by K. M. Hiscock, M. O. Rivett & R. M. Davison), SP193, 325–344. Geological Survey, London, UK, special publication.