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How can large-scale integrated surface–subsurface hydrological models be used to evaluate long-term climate change impact on groundwater reserves?

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Abstract Estimating the impacts of climate change on groundwater represents one of the most difficult challenges faced by water resources specialists. One difficulty is that simplifying the representation of the hydrological system often leads to discrepancies in projections. This study provides an improved methodology for the estimation of the impacts of climate change on groundwater reserves, where a physically-based surface–subsurface flow model is combined with advanced climate change scenarios for the Geer basin (465 km^2), Belgium. Integrated surface–subsurface flow is simulated with the finite element model HydroGeoSphere. The simultaneous solution of surface and subsurface flow equations in HydroGeoSphere, as well as the internal calculation of actual evapotranspiration, improve the representation of interdependent processes like recharge, which is crucial in the context of climate change. Climate change simulations were obtained from six regional climate model (RCM) scenarios downscaled using a quantile mapping bias-correction technique that, rather than applying a correction only to the mean, also applies a change in the distribution of wet and dry days. For the climatic scenarios considered, the integrated flow simulations show that significant decreases are expected in the groundwater levels and in the surface water flow rates by 2080.

Keywords groundwater; climate change; integrated modelling; HydroGeoSphere; Geer basin, Belgium

1 INTRODUCTION

Estimating the possible impacts of climate change on water resources represents one of the most difficult challenges faced by water managers. However, most of the studies recently published on the topic focus on surface water and generally oversimplify or even neglect groundwater, although groundwater is the main water supply in many parts of the world.

A first requirement for estimating the impact of climate change on groundwater systems is a reliable estimate of the volume of water entering and leaving an aquifer. More specifically, a reliable estimate of groundwater recharge is needed because it represents the connection between atmospheric and surface–subsurface processes and is therefore a key element in the context of the impacts of climate change on groundwater. In previous studies, recharge has been estimated with various degrees of complexity, ranging from simple linear functions of precipitation and temperature (e.g. Chen *et al*., 2002; Serrat-Capdevila *et al*., 2007) to the application of "soil models" simulating variably-saturated groundwater flow and solute transport (e.g. Brouyère *et al*., 2004; Scibek & Allen, 2006). However, none of these previous models can simulate the feedback, or fluid exchange, between the surface and subsurface domains, because water flow in one domain is interconnected with flow in the other domains and the quantitative estimation of exchanged fluxes depends on the simulation of simultaneous hydraulic conditions in the surface and subsurface domains. Therefore, estimating recharge by only considering one part of the whole system is unrealistic, inaccurate and potentially unusable in the context of climate change impact assessments.

A second requirement for estimating the impact of climate change on groundwater systems is that hydrogeological system models must be capable of consistently representing observed phenomena. As an example, the use of empirical transfer functions to represent physical processes may become uncertain if applied stresses go beyond the calibration conditions, which is typical for climate change scenarios. Detailed physically-based and spatially-distributed models that take into account hydrogeological processes provide more realistic simulations of groundwater fluxes.

In addition to the choice of modelling approach, the need for high resolution climate scenarios adds an additional layer of complexity and uncertainty to future projections. Some statistical downscaling of general circulation models (GCMs) to produce finer-scale output is generally required for hydrological modelling. To date, studies examining the impacts of changes in climate on groundwater systems have adopted relatively simple downscaling methods that apply projected changes to mean temperature and precipitation (Prudhomme *et al*., 2002; Yusoff *et al*., 2002) but that fail to reflect changes in the distribution of wet and dry periods.

The objective of this study is to provide improved methods for the estimation of the climate change on groundwater reserves, by developing a modelling approach that alleviates the simplifying assumptions presented above. To demonstrate the approach, a numerical model of the Geer basin (465 km^2, Belgium) has been implemented and calibrated. This physically-based and spatially-distributed numerical model provides a realistic representation of the system. The model fully integrates surface- and subsurface- flow in the saturated and partially saturated zones, with a simultaneous solution of the flow equations in all domains using finite elements, and the internal calculation of actual evapotranspiration at each node of the defined zones. Integrating surface and subsurface flow calculations in the same model also enables use of both surface and subsurface observed data for calibration, which better constrains the parameter values. The approach also includes an improved climate downscaling method that applies a correction across the distributions of temperature and precipitation using output from state-of-the-art RCM simulations.

2 GEER BASIN HYDROGEOLOGICAL CONTEXT

The main aquifer of the Geer basin (465 km^2) (Fig. 1) is the Hesbaye aquifer, which corresponds to a series of chalk layers, whose thicknesses range from a few metres to 70 m (Brouyère, 2001). This chalky aquifer is bounded at its base by 10 m of impermeable clays and at the top by a thick layer (up to 20 m) of loess that controls the water infiltration rate from the land surface to the chalky aquifer. The aquifer is mainly drained by the Geer River. The chalk’s porous matrix enables the storage of large quantities of water while fast preferential flow occurs through fractures. The chalky aquifer is largely exploited for drinking water, primarily through a network of pumping galleries.

3 MODELLING

3.1 Mathematical and numerical model

The Geer basin hydrological model has been developed with the HydroGeoSphere finite element model (Therrien *et al*., 2005), which fully integrates 3-D variably saturated groundwater flow and 2-D overland flow. HydroGeoSphere simulates the dynamic interactions between all sub-domains at each time step. In the subsurface domain, the hydraulic head, the degree of saturation, and the water Darcy flux are calculated at each node in the grid. In the surface domain, water elevation and fluid flux are calculated for each node of the 2-D grid. The model of Kristensen & Jensen (1975) is used to calculate the actual transpiration and evaporation as a function of the potential evapotranspiration, the soil moisture at each node belonging to the specified evaporative and root zones, and the cover of leaves over a unit area (LAI).

3.2 Discretization

The subsurface domain of the Geer basin is discretized using 11 layers of 6-node triangular prismatic elements (Fig. 2). Five layers are used for the first five metres below the ground surface,

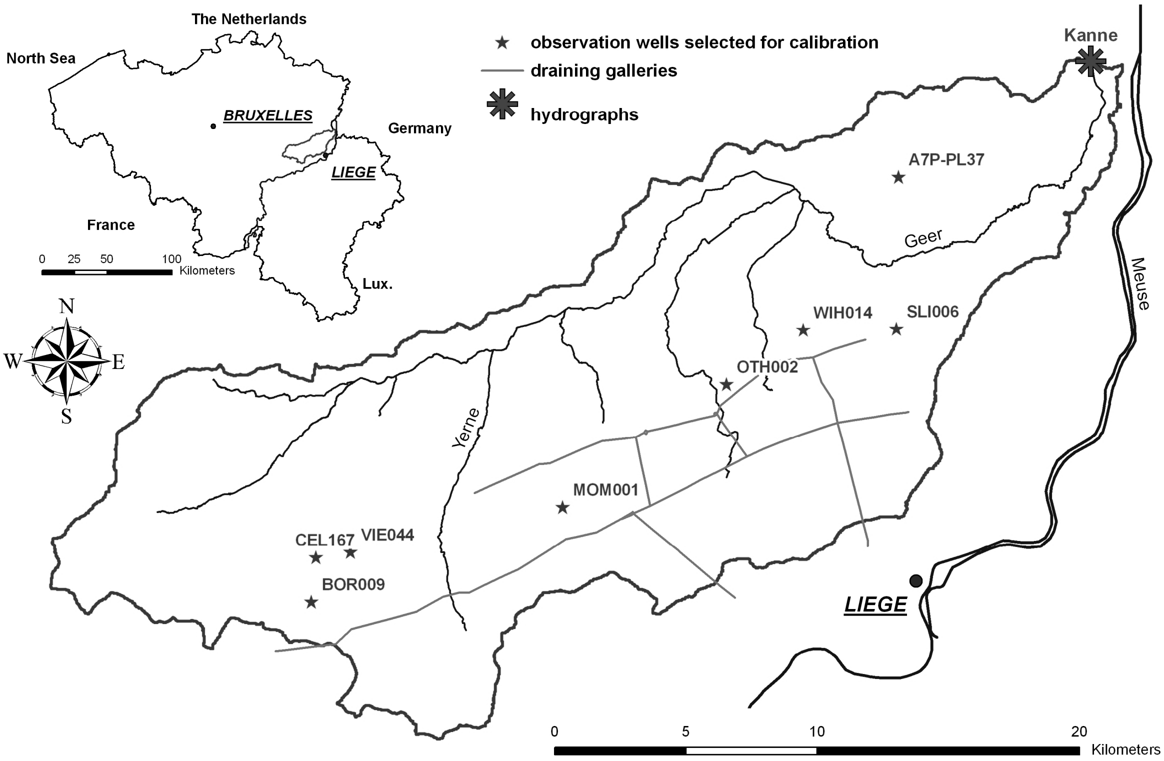

Fig. 1 Location of the Geer basin.

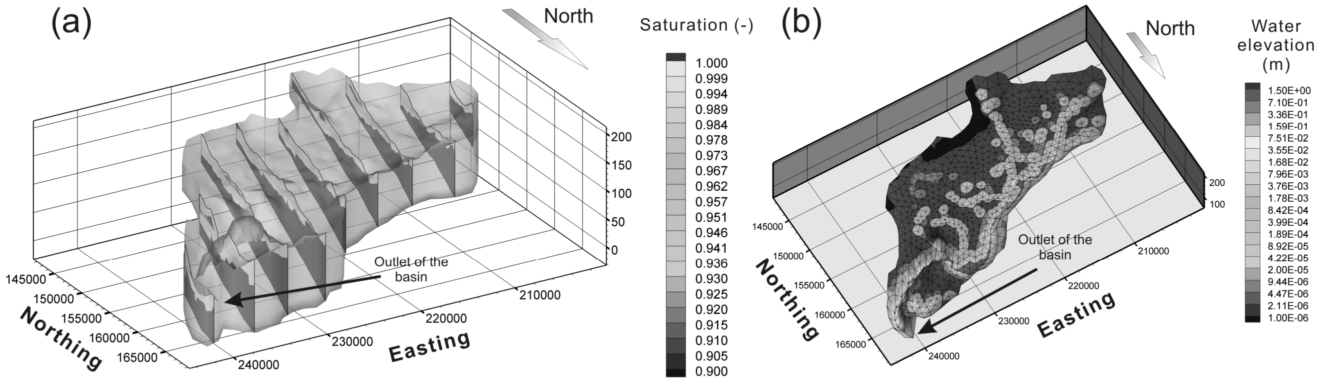

Fig. 2 (a) Simulated subsurface saturation at one specific time step, with full saturation shown in red (b) Simulated surface water elevations at one specific time step

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with each layer having a thickness of one metre. The finer vertical discretization near ground surface represents more accurately river–aquifer interactions as well as recharge processes at the interface between the surface and subsurface domains. The elements have lateral dimensions equal to approximately 500 m. The ground surface is discretized using a layer of 2-D finite elements and the Geer basin Digital Terrain Model. A critical-depth boundary condition is prescribed at the nodes corresponding to the catchment outlet.

Specified hydrological fluxes within the Geer basin consist of precipitation, evapotranspiration and groundwater abstraction by draining galleries and pumping wells. Complete 30-year precipitation and potential evapotranspiration time series are available for 6 and 1 climatic station in the Geer basin, respectively.

3.3 Calibration procedure

The model is calibrated to observed hydraulic heads from eight observation wells and surface flow rates measured at the outlet of the basin (Fig. 1) during the period 1967–2003. Due to huge computing times which make automatic inversion of the model very difficult, the calibration was performed by “trial and error”, by adjusting sensitive parameters within reasonable ranges of values as given by field and laboratory tests. The most sensitive parameters are the saturated hydraulic conductivities and the parameters controlling flows in the partially saturated zone (Van Genuchten parameters). Parameters of the surface domain, such as Manning friction coefficients, present lower sensitivities in a basin where run-off is limited due to the relatively flat topography. Other parameters such as those controlling the calculation of actual evapotranspiration were defined using values found in the scientific literature.

Results of the transient simulations, using the calibrated parameters (Fig. 3), show that simulated hydraulic heads satisfactorily reproduce the multi-annual variations in groundwater levels. Seasonal variations in groundwater levels are too high at some observation wells. In the surface domain, simulated flow rates match well to observed values in summer, for low flow rates and recession periods. Differences remain for the winter, where simulated flow rates are too high compared with observed flow rates. These differences are due to the difficulty of the model in simulating some high discharge peaks during winter months when runoff is higher compared to summer months. The use of a finer spatial discretization in the surface domain may help to improve the calibration of flow rates during winters, but with an additional increase of the computing times.

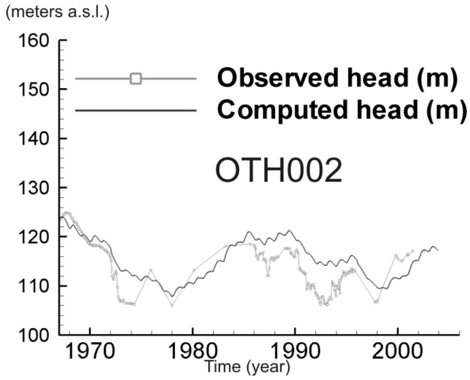

Fig. 3 Transient calibration of observation well OTH002.

4 SIMULATION OF THE CLIMATE CHANGE SCENARIOS

As a next step, climate change scenarios were applied to the basin model to assess the impact on groundwater levels and surface water flow rates.

4.1 Climate scenarios

Climate change scenarios were downscaled from six Regional Climate Models (RCMs) with boundary conditions derived from two Global Climate Models (GCMs). These large scale climatic models corresponds to greenhouse gases emissions that are medium-high (emission scenarios A2). The climate change scenarios were downscaled using the quantile mapping bias correction technique (Wood *et al*., 2004) that applies changes to the mean monthly precipitation and temperature, and that also forces the probable [?] distribution of extrapolated daily temperature and precipitation to match the distribution of the RCM. Downscaling techniques used in most hydrological impact studies do not consider this change in the distribution of climatic variables and use the same distribution as for the observed control period. In this study, climate change scenarios were produced for three time periods (2011–2040, 2041–2070, 2071–2100), each of them representing a stationary climate over 30 years. Precipitation and temperature changes gradually increase from the first time period to the third one.

For the period 2071–2100, the six climate change scenarios show a general increase in temperature throughout the year. The annual mean temperature increase ranges from +3.5°C to +5.6°C, with the largest increases during summer (between +7.5°C and +9.5°C) and the smallest increases during late winter (between +2°C and +5.5°C). Climate change scenarios project a decrease in annual precipitation ranging from –1.9% to –15.3%. These precipitation decreases are a consequence of large projected decreases during summer months but are partly offset by increases in winter precipitation.

4.2 Projected changes in hydrological regime

Using the calibrated flow model and the six downscaled RCM scenarios, hydrological simulations were run to evaluate the direct climate change impacts on the groundwater system of the Geer catchment for the three time periods 2011–2040, 2041–2070 and 2071–2100. Future change are compared to an additional hydrological “control simulation” driven by the observed climate data. Groundwater abstraction flow rates are kept constant through all simulations. During 2011–2040, no clear changes from the observed control simulation 1967–1997 can be identified (Fig. 4). However, by 2041–2070 and 2071–2100, the simulations project a significant decrease of almost all groundwater levels and flow rate at the outlet of the basin compared to the control simulation. By 2071–2100, mean groundwater levels are expected to decrease by 2 m to 8 m depending on location in the Geer basin and the climate change scenario analysed. For an equivalent unsaturated zone depth, which smoothes recharge fluxes, the variability of the groundwater levels is projected to increase. For the same period, flows at the outlet of the basin are expected to decrease by between 9% and 33%. The decrease in flows is not significant in winter, but in summer all mean flow values and standard deviation intervals for the 2071–2100 time period are lower than the mean flow value of the control period. For all simulations, evapotranspiration and groundwater abstraction gain an increasing importance compared to the annual rainfall flux, which is expected to decrease in the future.

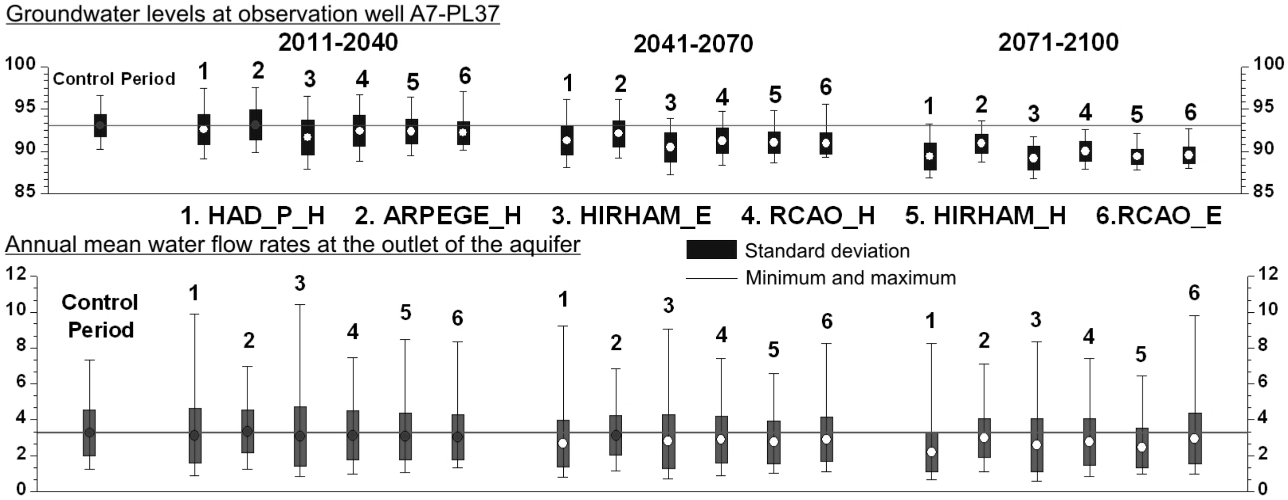

Fig. 4 Evolution of groundwater levels at one observation well and surface water flow rates at the outlet of the basin for each climate change scenario.

5 CONCLUSIONS

This study presents a robust methodology and guidelines that can be used to assess impacts of climate change on groundwater reserves. The methodology combines the advantages of a fully-integrated surface–subsurface models, spatially-distributed evapotranspiration rates and sophisticated multi-model ensemble climate change scenarios. The use and the combination of these three techniques advance the study of climate change impacts on groundwater reserves. Integrated surface–subsurface models are usually not used in the context of climate change impact evaluation, because simulated periods are large and this leads to extremely long computing times (Jones, 2005; Li *et al*., 2008). Additionally, the calibration performed with the Geer basin model is original as it is performed using both observed hydraulic heads and surface water flow rates. Most studies where fully integrated surface–subsurface hydrological models are used do not present any calibration results for observed subsurface hydraulic heads. In this study, the climate change scenarios use a multi-model ensemble of RCMs. Doing so, uncertainties in the multi-model response resulting from structural and parameterisation deficiencies within these climate models can be analysed and the uncertainties surrounding the hydrological response better understood.

6 PERSPECTIVES

This study focuses on direct impacts of climate change on groundwater reserves but other factors may also affect indirectly, but importantly, the groundwater reserves in the context of climate change. These indirect factors offer opportunities to further use and develop the model. Further work will also be devoted to the application of stochastic climate change scenarios on the model to assess climate change impacts and their probability.

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