(Proceedings ModelCARE2011 held at Leipzig, Germany, in September 2011) (IAHS Publ. 355, 2012).

Simulation and prognosis of the impacts of climate changes on groundwater recharge under local conditions

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Abstract Climate changes mainly occur to the Earth's temperature and precipitation, which increase water resources stress in many regions. The purpose of this study was to simulate the effects of potential climate changes, especially the changes of temperature and precipitation intensity, on groundwater recharge rate, because the infiltration rate is influenced by hydraulic conductivity, current water content, properties and texture of the soil, through implementation of different scenarios using the simulation program PCSiWaPro® which is combined with a stochastic weather generator (WettGen). Precipitation and evapotranspiration of the soil-plant system are considered in the program as source and sink of water balance. The simulation results using PCSiWaPro® indicate the role of land use and land cover on groundwater recharge rate. The initial and boundary conditions of the models are crucial in the simulation results. In general, the results show an increased surface runoff, which leads to a decreased groundwater recharge.

Key words groundwater recharge; climate changes; water balance; numerical methods; transient simulation

INTRODUCTION

Approximately 1.7% of water existing on the Earth is below ground, in the form of groundwater. Groundwater supplies about two-thirds of the world's population (Pinder & Celia, 2006). Therefore groundwater is a very vital resource for human beings. As the world population continues to grow, more people will come to rely on groundwater sources, particularly in arid and semi-arid areas (Simmers, 1990). The groundwater recharge is estimated by the water balance, which is based on the mass balance principle: Input = Output + Change in storage. The general equation for the soil-water budget in unsaturated zones is derived by considering the mechanisms by which water can enter, exit or be stored in a predefined region of the vadose zone. The inflow across the upper boundary of the vadose zone, as shown in Fig. 1, is infiltration (I), which changes as a function of time and it is influenced by physical factors and chemical properties of the soil, surface characteristics including vegetation and land use, antecedent moisture conditions, seasonal factors, topography and precipitation characteristics that influence the soil's permeability. The outflow from the upper boundary is evaporation (E) and transpiration (T), and outflow from the lower boundary is groundwater recharge (R). Netflow (inflow minus outflow) must equal the change in soil water stored in the vadose zone (Δs) over the time interval Δt: $I - E - T - R = \Delta s$ (L/T). The equation of water balance has also the following form: $P = ETR + R + \Delta s$ where ETR is the real evapotranspiration, which results from the potential evapotranspiration ETP, ETR = ETP when P > ETP and ETR= P + $|\Delta s|$ when P < ETP, which arises with given meteorological conditions and unlimited water supply, and a reduction through the actual water supply. Physical runoff processes are not modelled in the water balance. The water balance can be computed for any area having uniform climate and soil characteristics. Determining the available water capacity is helpful to identify the level of soil moisture at the same time when the water balance begins, but if it is not known the model will eventually converge on the correct value (Thompson, 1999).

We can summarize the regional groundwater balance by the following equation: {Groundwater inflow} – {groundwater outflow} + {natural replenishment} + {return flow} + {artificial recharge} + {inflow from streams and lakes} – {spring discharge} – {evapotranspiration} – {pumpage and drainage} = {increase in volume of water stored in aquifer}, where all terms are expressed as volume of water during the balance period. To evaluate the hazard to groundwater there are two possibilities:

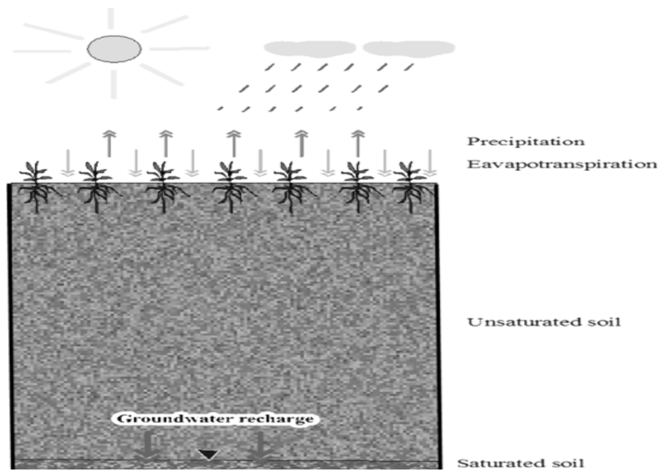

Fig. 1 Parameters of soil water balance.

either experimental analysis or simulation using suitable modelling programs. Groundwater models describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. These assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions. The equation of water flow and solute transport in saturated and unsaturated soil zones, which the modelling programmes depend on, have to be assessed. By reference to the water balance equation it is obvious that the atmospheric conditions, especially changing precipitation (intensities) and temperature regimes, are critical factors of the groundwater recharge. This is why climate change has a vital impact on the groundwater recharge rate.

One of the commonly used means of calculating groundwater recharge is direct measurement using lysimeters. This paper presents a comparison between the measured values of groundwater recharge rate using lysimeters, and the numerically computed values using the simulation program PCSiWaPro®.

MATERIALS AND METHODS

PCSiWaPro®

PCSiWaPro® is a 2D computerized leachate forecast advisory system for the vadose zone and uses the Finite-Elements Method to solve Richards equation. The software is a decision support system developed by the Technical University of Dresden in cooperation with partners from practice and serves as a tool for risk assessment. To obtain a maximum groundwater recharge, or rather to optimize an artificial wetland, the processes in the unsaturated zone have to be calculated and described by these models. The program is based on the commonly used simulation code SWMS_2D (Šimunek *et al.*, 1994). The simulation program PCSiWaPro® is able to compute the 2D vertical plane and rotationally symmetric flow and transportation processes including the degradation and sorption in the un/saturated zone. An implemented weather generator simulates the time series of precipitation, solar radiation and the parameter evapotranspiration (Nitsch *et al.*, 2007). A soil database is also implemented in PCSiWaPro®.

The applicability of a model depends on how closely the mathematical equations approximate the physical system being modelled. Because of the simplifying assumptions embedded in the mathematical equations and the many uncertainties in the values of data required by the model, a model must be viewed as an approximation and not an exact duplication of field conditions.

The flow model using the simulation program PCSiWaPro® describes the vertical flow in the unsaturated zone and it is given by the Richards equation (RE). RE is a standard, frequently used approach for modelling flow in variably saturated porous media (Miller *et al*., 2006). RE is obtained by combining Darcy's law (equation (2)) with the mass conservation or continuity equation (equation (1)), under the assumption that the air phase remains at constant (atmospheric) pressure and the water phase is uncompressible (Koorevaar *et al*., 1983). RE is a highly nonlinear partial differential equation that can be cast in several forms, depending on whether pressure (h-based form), moisture (θ-based form), or both (mixed form) are used as state variables (Arampatzis *et al*., 2001):

$$q = -k\frac{\partial H}{\partial z} = -k\frac{\partial (h+z)}{\partial z} = -k\left(\frac{\partial h}{\partial z}+1\right) \quad (1)$$

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} \pm s \quad (2)$$

where q is flux density ($m^3\ m^{-2}s^{-1}$); H is head equivalent of hydraulic potential (m); K is hydraulic conductivity (ms^{-1}); h is pressure potential (m); z is elevation (positive upward (m); θ is volumetric water content ($m^3\ m^{-3}$); t is time (s); s is sink/source term ($m^3\ m^{-3}s^{-1}$).

Substitution of equation (1) and equation (2) results in the Richards equation (equation (3)): For 2D-flow modelling, as in PCSiWaPro, the Richards equation is given in the following form:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[k\ \left(K_{ij}^{A}\frac{\partial h}{\partial x_i}+K_{iz}^{A}\right)\right]-s \quad (3)$$

With θ as the volumetric water content, x_i are the spatial coordinates (x, y, z), h is the capillary pressure head, t is the time, K_{ij}^{A} and K_{iz}^{A} are the components of the dimensionless anisotropy tensor **K** and K is the function of the unsaturated hydraulic conductivity. The variable s represents the sink or source term, which depends on the capillary pressure head in the soil, and in this case is considered as the amount of water which is removed by plant roots. The water content in the medium depends on the capillary pressure head in the pores and can be described using equation (4):

$$\theta_b = A + \frac{\phi - A - B}{\left[1+(\alpha . h_c)^n\right]^{1-\frac{1}{n}}} \quad (4)$$

where A is the function of the residual water content, B the function of the residual air content, ϕ is the porosity of the medium (soil), h_c the capillary pressure head in the pores, α the scale parameter and n the slope parameter (α and n are Van Genuchten Parameter).

Lysimeter

In this study lysimeters are used as a direct measurement method of evapotranspiration and drainage, which confirms in this case the groundwater recharge. The site of research is Brandis (a town in the Leipzig district) the state of Saxony in Germany. It is located at 136 m above sea level.

Table 1 Soil parameters.

		Lysimeter 05			Lysimeter 07			
Depth in (mm)		0–350	350–1750	1750–3000	0–500	500–1350	1350–2200	2200–3000
Soil type according to DIN 4220		Su3	mSgs	mSfs	Slu	Ls4	Ls3	mSfs
Porosity		0.39	0.39	0.39	0.41	0.42	0.42	0.39
Conductivity [mm/d]		980	6700	6700	600	680	740	6700
Residual water content		0.05	0.04	0.04	0	0.03	0.03	0.04
Van–Genuchten Parameters	n	1.35	1.35	1.35	1.18	1.16	1.16	1.35
	m	0.26	0.26	0.26	0.15	0.14	0.14	0.26
	λ	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	α^{α}	0.007	0.026	0.026	0.008	0.013	0.011	0.026
	α^{ι}	0.014	0.052	0.052	0.016	0.026	0.022	0.052

Table 2 Cultivated crop plants of lysimeters.

2000	2001	2002	2002	2004	2005	2006	2007	2008	2009	2010
peas	wheat	barley	rape	wheat	barley	rape	wheat	barley	rape	wheat

The lysimeter has a depth of 3000 mm and 1130 mm diameter. Two lysimeters were filled with various types of soil, as shown in Table 1 (Haferkorn, Staatliche Betriebsgesellschaft fuer Umwelt und Landwirtschaft Lysimeterstation FB 31 – Brandis, 2000) and for the period from 2000 to 2010 the cultivated crops plants in the parameter are shown in Table 2.

The meteorological applied data for the modelling is obtained to a great extent from the lysimeter-station in Brandis. The daily data of temperature and participation from 2000 to 2010 are represented in Fig. 2.

Figure 3 shows the daily groundwater recharge rate of the lysimeter 07 for the same period. These values of groundwater recharge rate corresponds the daily drainage rate from the outlet of each lysimeter.

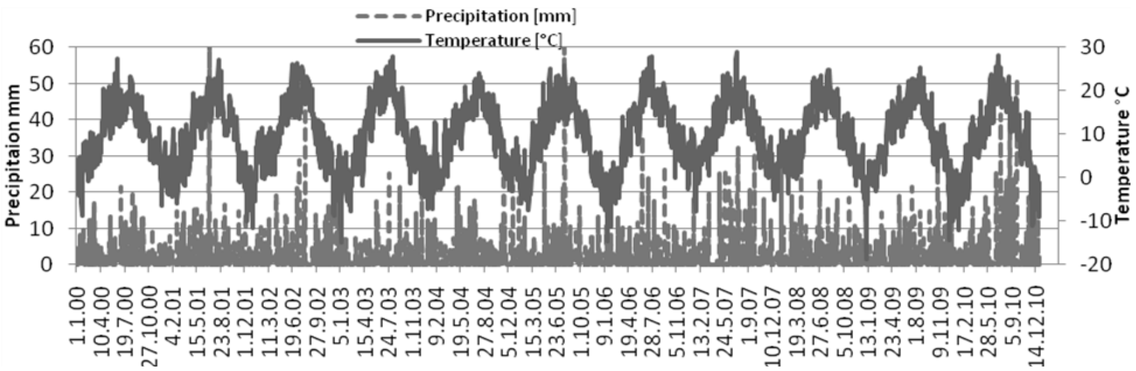

Fig. 2 Climate data from 2000 to 2010 obtained from lysimeter-station of Brandis.

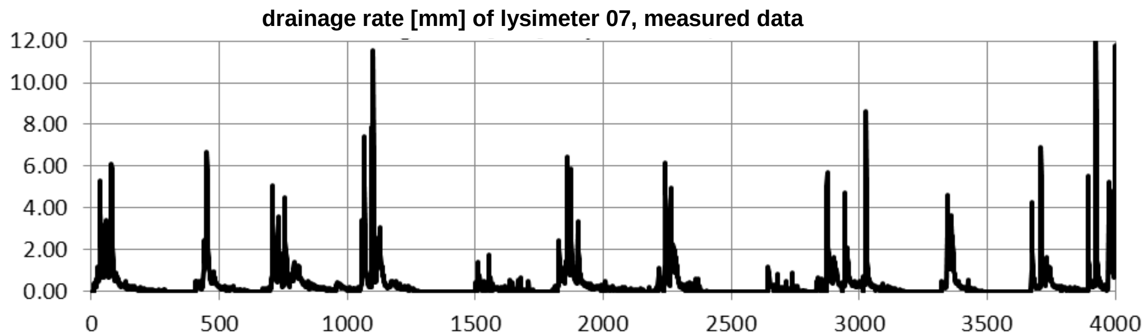

Fig. 3 Daily groundwater recharge from 2000 to 2010 according to the lysimeter-station (lysimeter 07) in Brandis.

SIMULATION AND MODELLING

Shown in Table 1 is the data of the two lysimeters that were used for the modelling using the program PCSiWaPro®. The atmospheric boundary conditions were considered by the implementation of time-variable boundary conditions. The drainage outlet is located 110 mm above the lysimeter bottom at the side of the lysimeter. The materials parameters were taken from Haferkorn (2000) and used for the characterization of each soil layer of the lysimeters. The hydraulic soil parameters were not estimated and are based, for the simulation, on the given DIN

4220 values, not on actual measurements. The outlet is characterized with a free drainage boundary condition.

Parameterization of the weather simulation tool is done on the basis of available weather data from the lysimeter station in Brandis

The simulation results of groundwater recharge for lysimeters 05 and 07 are shown in Figs 4 and 5, respectively.

PCSiWaPro® is a 2D simulation program but a lysimeter is a 3D-object, therefore the computed values should be divided by 1000 mm. Moreover, the simulation results are computed for every time increment, and therefore the results of every day should be added to get daily values (Fig. 6).

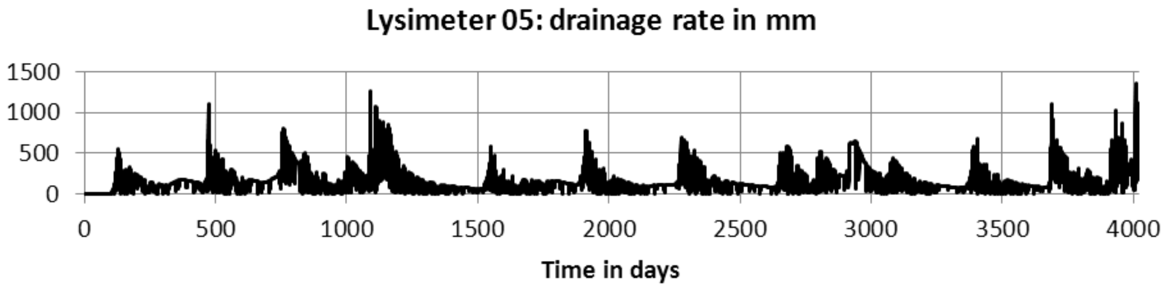

Fig. 4 Drainage rate of lysimeter 05 from 2000 to 2010.

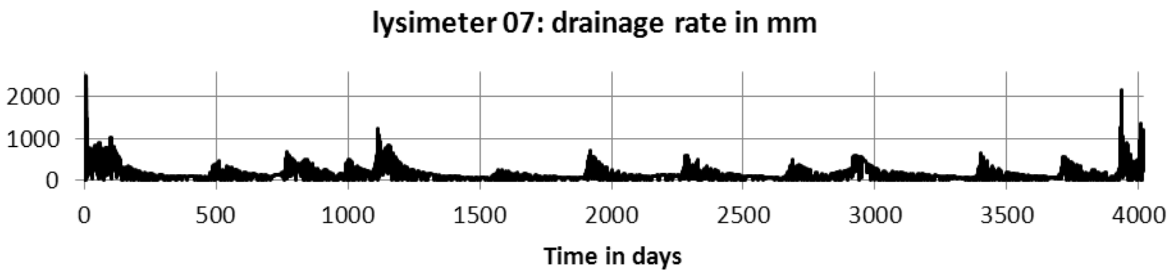

Fig. 5 Drainage rate of lysimeter 07 from 2000 to 2010.

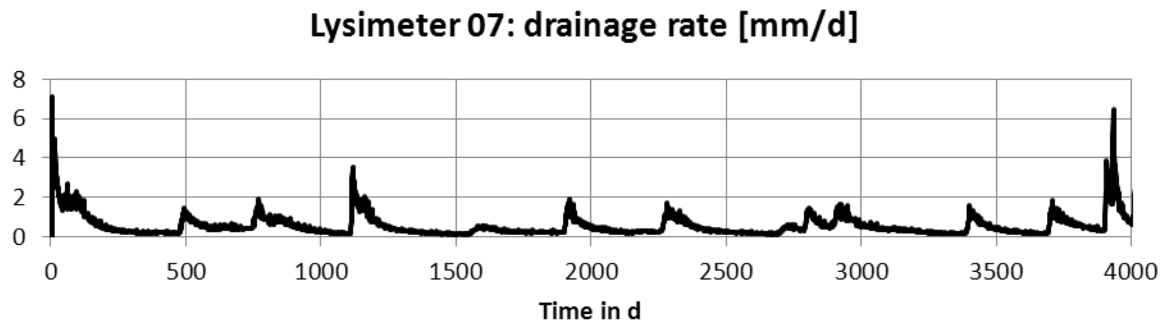

Fig. 6 Computed drainage rate (after the conversion) of lysimeter 07 in mm/d.

Depending on the prognosis of the Saxony ministry for environment and agriculture "SMUL" (Klimawandel in Sachsen, 2005) for the expected changes of climate parameters, especially precipitation and temperature, until 2050 in Brandis; precipitation: +15% in winter half-year and –15% in the summer half-year; Temperature +4.5°C, a prognosis was done using the simulation program PCSiWaPro®. Figure 7 shows the drainage rate from lysimeter 07 for the year 2000, while Fig. 8 shows the forecast values of drainage rate from the same lysimeter for 2050. Another scenario is also shown in Fig. 8, which depends on the prognosis of the model region of Dresden; this prognosis was presented through the project REGKLAM (2011) and it forecasts that the precipitation in winter half-year would increase by about 5 mm until 2050, while it would decrease in the summer half-year by about 20 mm; the potential evaporation would increase about 20 mm. The simulation results show a general decrease of drainage rate until 2050, except some days in the first half of the year, where the drainage rate would be higher than in the reference year 2000, which means a decrease of groundwater recharge rate (Fig. 8 presents just the simulation results up to 5 mm/d to show the difference between the two scenarios.

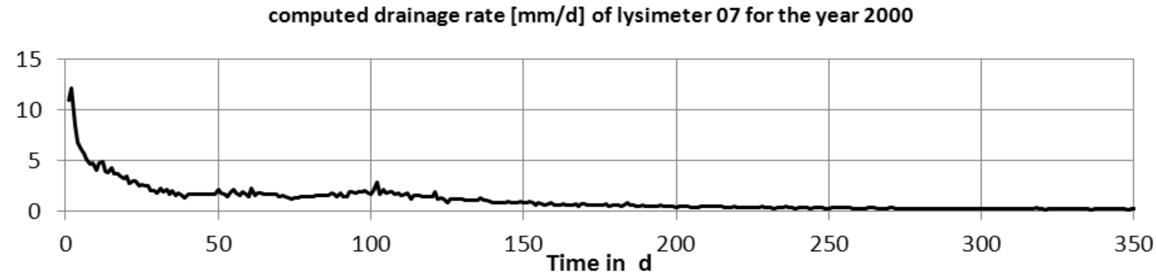

Fig. 7 Drainage rate of lysimeter 07 for the year 2000.

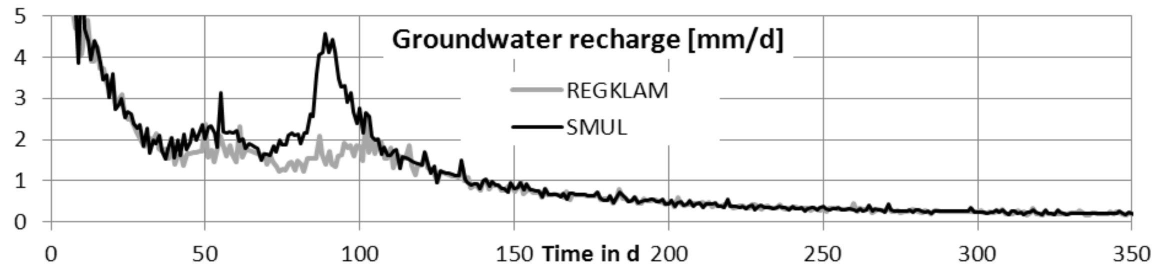

Fig. 8 Forecast values of drainage rate (groundwater recharge) in the year 2050 for lysimeter 07 (according to REGKLAM and SMUL).

CONCLUSIONS AND RECOMMENDATIONS

The simulations results of this study indicate clearly that the change of precipitation and temperature, in the form of evapotranspiration, in Saxony caused by climate change would cause a decrease of groundwater recharge in this region in the next 40 years. Climate changes would not be the same in all German states because of the different climatic, vegetation, hydrogeological and industrial conditions; therefore the study area is not representative for other areas. However, lowlands in the eastern part of central Germany will likely show similar behaviour to natural conditions, close to those in Brandis, and future climate change will similarly affect them. The agreement between the measured values and the computed ones was good according to the slight deviation average 0.22 (mm) between computed and observed values presented in Figs 3 and 6. Additionally the diagrams of both results show similar behaviour. The disagreement between the measured and the computed values could be caused by poorly estimated hydraulic soil parameters, as these are based on the given DIN 4220 values and not on actual measurements. Moreover, uncertainties of the results exist because of the climate change data. This can only be considered with average values of the change of precipitation. The predicted increase of heavy rainfall events was not considered. However, these will lead to even higher surface runoff and decrease groundwater recharge. To consider these events more precise climatic input data is necessary. The study also shows an ability of the models, using PCSiWaPro®, to simulate a long period of 10 years, with continuous scale.

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