Modeling the impact of a possible climate change on the water balance in post-mining areas

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Abstract

Post-lignite mining regions in Central Germany are characterized by pit lakes. Therefore, the impact of climate change may be considerable because changes in groundwater recharge patterns and increased evaporation from the lakes can be important for the total water budget.

Groundwater modeling of a post-mining area with low precipitation was carried out using groundwater recharge computed from results of a climate model. A coupled groundwater/soil water budget model based on the models PCGEOFIM and ArcEGMO as well as PCGEOFIM and PCSiWaPro was developed. The groundwater model supplies groundwater levels and base flow; the soil water budget models groundwater recharge. The exchange time step is typically one day with shorter steps possible depending on numeric conditions. The models were successfully applied to sites in Central Germany. Model results show very good agreement with measured values. Preliminary predictions were made. Currently, work is underway to use results from climate models as driving force for the coupled model. Model results are expected to have great importance for planning of activities in the region such as recreational use.

Introduction

Lignite mining has shaped Central Germany for more than a century. Mining had and is still having a profound impact on the water balance and water quality of this area. Currently, active open pits drawing down the groundwater table coexist with reclamation activities such as filling pits to create lakes. The groundwater of the whole region has been modeled over the last two decades with a groundwater model based on the program system PCGEOFIM (Sames et al. 2005, Müller et al. 2003). The time scale for prognosis of hydrologic development is 100 and more years. Therefore in modeling, future changes in climatic conditions need to be accounted for. Furthermore, all water balance terms have to be included in the modeling efforts to get reliable results.

Impact of expected climate changes on post-mining areas

The water budget of post-mining areas in Central Germany is considerably different from pre-mining conditions. Pit lakes draw groundwater by significantly increasing area evaporation. Precipitation in the studied area reaches values from less than 500 to about 700 mm/a. Lakes that currently have evaporation rates of 720 mm/a or more are net sinks of water. The trend of climatic change points towards increased temperatures and a change in precipitation patterns. This can put considerable strain on the water budget leading to undesirable consequences such as strongly varying lake water levels or no flow between lakes. The use of the lakes, for instance for recreation, depends very much on stable water levels and connectivity between lakes. Therefore, the impact of climatic changes needs to be considered today to take appropriate actions in developing the area.

Long-term groundwater modeling with climate-dependent recharge for the post-mining region in the South of Leipzig

The mining region in the South of Leipzig is at the border of the German states Saxony and Thuringia. The groundwater of the area was modeled with a PCGEOFIM-based groundwater model (see section PCGEOFIM in this paper). Climatic change was considered until 2100 by using daily data computed by the WEREX IV model (Spekat et al. 2007), which in turn is a regional climate projection of the global model ECHAM5 (Roeckner et al. 2003). All calculations use scenario A1B. This scenario is based on a moderate growth of the world economy and resulting CO_2 emissions. The statistical model provided results for three scenarios of wet, dry, and most likely conditions including daily values of air temperature, relative humidity, precipitation, global radiation, and others. These values were used to drive the soil budget model ArcEGMO to produce daily groundwater recharge rates.

The model results show that there is a significant impact of the excepted climatic change on the water budget. Table 1 shows the average recharge over the whole model area for the calculation period of 90 years. The difference between the dry and the likely scenario is about a factor of 2.5 demonstrating the immense impact the future climate may have.

Table 1 *Comparison of groundwater recharge rates for different climate scenarios.*

	Wet conditions	**Most likely conditions**	**Dry conditions**
Average recharge in mm/a	79,8	71,6	28,0

The variations in groundwater recharge lead to differences in open pit lake levels of up to 15 meters. This has huge implications on slope stability and general utilisation of the lake.

Coupled groundwater - soil water budget modeling

The approach above may be described as offline coupling using outputs of models as inputs for others. As long as there is no significant feedback between the models, this solution works well. However, high groundwater levels will be encountered in many post-mining areas that result in a strong feedback between soil water budget, recharge, and groundwater. To account for these feedbacks we developed an online coupling of the models PCGEOFIM and ArcEGMO (for description of the single models see next sections). Figure 1 shows a schematic of the exchange between both models. The groundwater model PCGEOFIM supplies groundwater levels and base flow and the soil water budget model ArcEGMO recharge and fast river discharge. Furthermore, flows at boundaries are exchanged if model areas are not of equal size. All quantities are exchanged with a variable time step that is determined by internal numerical criteria. The time step will decrease if river discharge is high. The maximum specified time step is typically one day, which allows for an intensive feedback between both models.

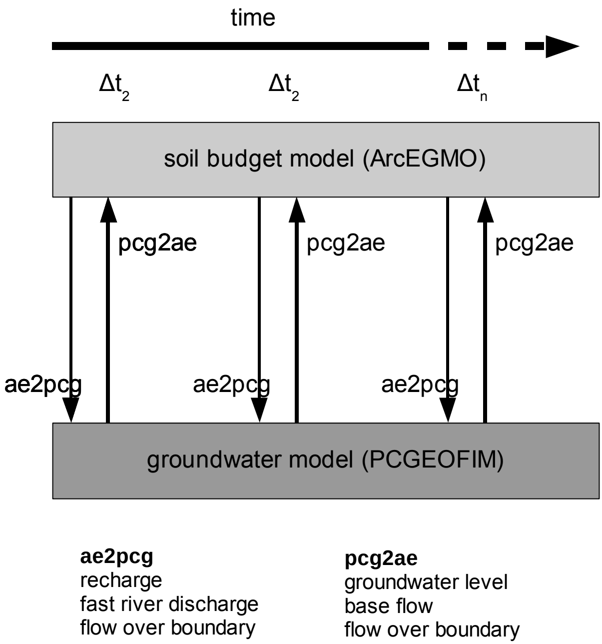

Figure 1 *Schematic of model coupling.*

The flow over boundaries in Figure 1 is river discharge that is handed in from the spatially larger model at the border to the smaller model. This allows to model areas where surface and subsurface catchments do not correspond. Climatic changes can be considered directly because ArcEGMO uses meteorological data as input and therefore reacts to change in climatic conditions.

The modeling system PCGEOFIM

PCGEOFIM (Sames et al. 2005, Müller et al. 2003) is a finite volume groundwater flow and transport model that is specifically designed for mining and post-mining areas. Being developed since more than 35 years, it provides some special features to account for the mining-specific conditions. Subsurface parameters can be specified as time-dependent allowing for modeling the excavation of mine pits, filling with overburden and creation of lakes all in one model run. While working with a regular grid, multiple nested grid refinements that may overlap can be used to get higher resolution in areas of special interest.

The model offers many ways to specify groundwater recharge from constant in time to depending on groundwater level below surface to a sophisticate coupling with a rainfall-runoff-soil-water-budget model.

PCGEOFIM provides a simple but very useful mechanism to account for the interactions between lakes and groundwater. The lake is represented as a water level-volume relationship. In- and outflows such as groundwater and rivers are budgeted. Precipitation and evaporation yield a new lake water volume and hence a new water level. This water level is used as head for Cauchy boundary conditions that act jointly as "the lake". Figure 2 shows how groundwater model elements are either vertically or horizontally coupled to the lake.

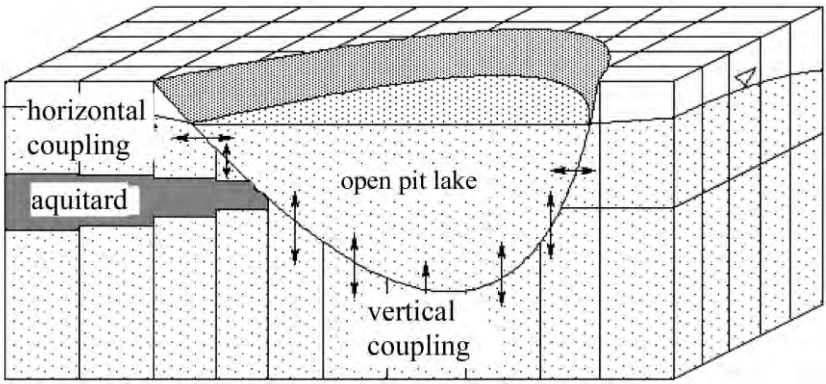

Figure 2 *Representation of boundary condition "lake" in PCGEOFIM.*

Rivers can also be represented by several Cauchy boundary conditions that act jointly while the discharge is calculated with Manning's formula. Lots of special boundary conditions such as vertical and horizontal multi-level wells and defined outflow levels of lakes as well as sophisticated connections between rivers, lakes, and pipelines with control mechanisms provide a high level of representation of the real system.

The modeling system ArcEGMO

The model ArcEGMO with its extension PSCN is a GIS-based, multi-scale modeling system for spatially distributed simulation of hydrological sub-processes in river catchments. In addition to usual model approaches for describing the lateral surface and subsurface water flows at river basin scales (Becker et al. 2002, Pfützner 2003) it contains complex growth models for forest and agricultural areas and a detailed soil model (water, heat, carbon/nitrogen budget). Through implementation of a crop rotation generator, the agricultural land-use structure of a region can be exactly reproduced. Air temperature, precipitation, humidity, and global radiation in daily resolution are the required climatic driving variables. The spatial resolution is carried out on the basis of hydrotopes. Each hydrotope is characterized by a particular land use, topography, and soil profile and is associated with a fixed space within the study area. Vegetation dynamics are simulated in dependence on land use in the individual hydrotopes. Four different plant models have been integrated into the model.

The modeling system PCSiWaPro

This model also accounts for the soil water budget. Its basis is the physical-based Richard's equation (Blankenburg et al. 2007) that describes the water flow, water balance, solute and heat transport in variably saturated porous media. To consider atmospheric boundary conditions, time series of precipitation, temperature, transpiration, and evaporation are needed in daily resolution. Characteristics of land use can be represented by two different plant models. Since the input time series can be derived from regionalized data of global climatic models, it is possible to simulate future changes in climatic conditions. Currently, a direct coupling to the groundwater model PCGEOFIM is developed. The coupling scheme is similar to that shown in Fig. 1 except that no fast river fluxes are exchanged. The coupling allows the detailed vertical-plane simulation of groundwater recharge and the resulting water content distribution, including external slopes of pit lakes. Since the water content is an essential factor of geotechnical stability, it is important to simulate the distribution of water content within the external slopes under possible future climatic condition.

Application of the coupled models

PCGEOFIM and ArcEGMO

The coupled model has been successfully applied to large scale modeling an area in the south of the city of Leipzig. The discretization of both models, PCGEOFIM and ArcEGMO, was chosen to be the same. Hence, each cell of the upper layer of the groundwater model has exactly one corresponding soil water budget cell. Furthermore, the upper 2 meters of the subsurface were considered in both models to account for the moving groundwater table. Soil layers in the soil water budget and groundwater model are of equal size and have the same parameters. If a layer is unsaturated, it will be part of the soil water budget model. As soon as it becomes saturated, it will become part of the groundwater model. This means there is a spatially moving interface between the two models. If the groundwater level reaches the soil surface, all layers will be part of the groundwater model. Groundwater that seeps out at the surface will be put in surface storage from where it can evaporate or flow into the next river if the storage capacity is exceeded.

The extent of the model area of the soil water budget and the groundwater model are different. Hence, the river flows at the edges of the models have to be exchanged between both models. An exchange time step of one day proved useful and allowed stable calculations.

Model runs were carried out in two phases. After a calibration period, the model was run with constant average boundary conditions until 2010. Afterwards, a predictive calculation was done for 90 years until 2100. The models could reproduce past measured values of groundwater levels and river discharges with good accuracy. Especially in regions of high groundwater levels and thus strong interactions between groundwater and soil water significant improvements of model representations could be achieved. Figure 3 shows good agreement between modeling results and measured values for an observation well close to a river. Furthermore, the scenario A1B predicts for the model domain an increase of the temperature of about 2-4 °C which results in a 30-50 % lower groundwater recharge due to a higher evaporation rate.

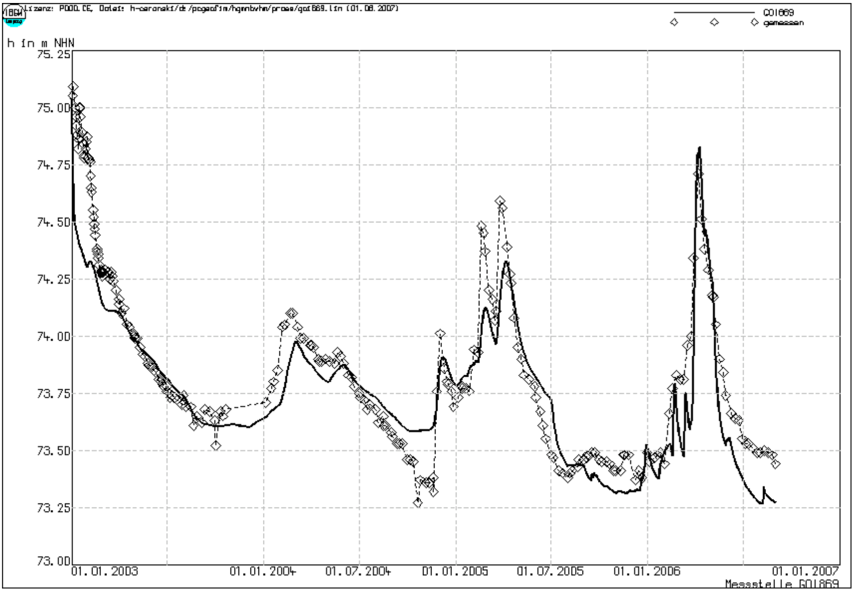

Figure 3 *Comparison of measured (rhombs) and modeled heads (solid line) at an observation point in the vicinity of a river.*

PCGEOFIM and PCSiWaPro

The development of the coupling of the two models is still in early stages. Hence, results of practical tests are not presented here. The areas of the models overlap each other in such a way that the soil water budget model is fully included in the groundwater model domain. The difficulty in that approach is the different scale between the soil water budget and the groundwater model leading to different discretizations of the model domains.

Future work

Currently, we are working on using results of climate prediction models as direct input for the coupled models. This will allow a good estimate of the impact of climate change on the total water budget of the region. Calculating different climate scenarios will provide information about the range of the water budget variations. Modeling results can be used for planning of future uses of lakes and their vicinity. Connecting channels between lakes need to be adapted to expected lake water levels and resulting flow rates. Water gates and other structures need to be designed adequately.

Conclusions

The expected change in climate has profound influence on the water budget in the post-mining regions in Central Germany. The use of regionalized data from the global climate model ECHAM5 provided an insight in possible future changes in the water budget. The coupled model, consisting of PCGEOFIM and ArcEGMO was successfully applied at a site in Central Germany. It provides a full coverage of all surface and subsurface water budget components. Calibration and first predictions are promising. Current work focuses on incorporating localized output of climate models as driving force of the coupled model.

The results from the coupling between PCGEOFIM and PCSiWaPro can be the basis for geotechnical computations such as slope stabilities. However, since climate models have a high uncertainty, there is a need to investigate the resulting uncertainties of the coupled model before expensive works are considered.

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