Groundwater recharge balancing under the conditions of climatic changes

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Abstract The exploitation of water resources, which is the foundation of securing the drinking water supply for a commu-nity, is based on calculation rules and estimates from the past. For the exploitation of groundwater resources, groundwater recharge constitutes one of the most important variables which can be calculated using climatic time series of previous decades. Regarding future climatic changes this procedure is more than questionable. One of the expected changes is the increase of precipitation intensity. Even if the mean precipitation amount should remain constant, the rate of groundwater recharge will be changed through the increase of extreme events as well as precipitation events with high intensity. Because the soil has a limited infiltration capacity, surface run-off will be increased during individual precipitation events. With a constant mean precipitation amount, a decrease of the rate of groundwater recharge will be produced. In addition, increased cultivation of energy crops produce an increase of evapotranspiration, which also leads to a decline of the rate of groundwater recharge. In summary it can be said that die rate of groundwater recharge will be reduced significantly through these two effects. Planning and operating water transportation installations therefore requires adapted rules of calculation to guarantee the drinking water supply in the future.

One possibility of identifying the rate of groundwater recharge is the transient modeling of water balance in the unsaturated zone. The simulation program SiWaPro DSS combined with a stochastic weather generator was developed in cooperation with the Institute of Waste Management and Contaminated Sites of the Technische Universität Dresden and the KP Ingenieurgesellschaft Wasser und Boden mbH. Through the implementation of regionalized simulation results of global climatic models the time series generated by the weather generator reflect the climatic changes and thus render the analysis and determination of groundwater recharge possible.

Key words ground water recharge, climate change, transient simulation

INTRODUCTION

In many countries of the world the use of groundwater resources for public water supply constitutes the central pillar of drinking water supply. Even in countries that use mostly surface water the existing groundwater remains an important resource. In Germany, the share of ground water in the public water supply was 74% in 2004 (Source: Federal Office for Statistics). Throughout the world demands on groundwater reservoirs have increased in a way to make natural recharge impossible. Particularly in arid areas of the earth, where evaporation exceeds precipitation, sustained management of groundwater rarely happens.

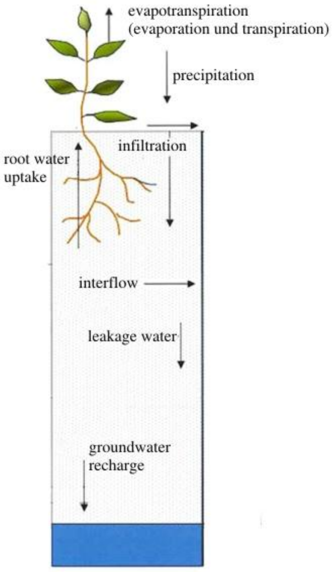

Fig. 1 soil water balance (Dyck, et al., 1995)

For the regeneration of groundwater resources, groundwater recharge constitutes one of the most important variables of water balance.

$$P=ETR+R+\Delta S \quad \text{(water balance equation)}$$

The equation of water balance describes the interrelation between the precipitation P as input variable, and the real evapotranspiration ETR, run off R and storage ΔS as output variables, and displays the connection between the ground water balance and the atmosphere. Real evapotranspiration results from the potential evapotranspiration ETP, which arises with given meteorological conditions and unlimited water supply, and a reduction through the actual water supply. The potential evapotranspiration then comprises ground evaporation, interception evaporation, evaporation of snow and ice as well as evaporation from plant surfaces as a result of biotic processes. Run off R is divided in surface run off, intermediate run off (which happens already below the surface), and deep run off, which equals ground water recharge. Ground water recharge, then, consists of precipitation water that infiltrates into the ground, leaks through the unsaturated soil layers and reaches the ground water surface. In addition, ground water recharge may result from leakage of surface water.

The ground water recharge rate as a quantitative measure of ground water recharge constitutes the corresponding parameter for the use of ground water resources, be it for drinking water supply, be it for irrigation. It corresponds to the water volume that is added to the ground water per time and area. A common designation here is mm/a. This value varies with local conditions of climate, soil, and use of land. The development of this parameter is the more difficult because the actual event of ground water recharge cannot be observed. Thus it can only be determined either based on the processes at the surface and the unsaturated soil zone (water balance calculations) or based on measurement of run off at surface waters and wells and of the ground water level.

All methods of developing the rate of ground water recharge on the basis of water balance calculations use as input data recorded climatic data from the past. These are time series of the most important climatic variables such as precipitation, air temperature, air humidity, global radiation (or duration of sunshine), and wind speed.

Apart from precipitation, which can be recorded directly with rain gauges, all methods need values of potential evapotranspiration. Since this parameter can be measured directly only with high effort, there are acknowledged methods of calculating the potential evapotranspiration with the help of recorded climatic values, such as methods according PENMAN, HAUDE, TURC/IVANOV, or TURC/WENDLING (DVWK, 1993). When sufficient data are available, the method of FAO-reference-evapotranspiration is recommended today, which builds on the physically best founded PENMAN-approach. All of those calculation methods determine the so-called reference-evapotranspiration, for which a sufficiently watered area with a uniform grass cover of 12 cm, an albedo of 23 % and a resistance of crops of 70 s/m is assumed.

Methods of developing the rate of groundwater recharge used in Germany are, for example, SCHROEDER & WYRWICH (1990), DÖRHÖFER & JOSOPAIT (1980), RENGER & WESSOLEK (1996), BAGROV (DVWK, 1993), BAGLUVA (Glugla, et al., 2003) and

TUB_BGR (2003) (Grossmann, 1997), (Hennings, 2000). Those methods are designed to determine averaged values of the rate of ground water recharge over a longer period of time and need as input data long term average values of precipitation and potential evapotranspiration, and, in addition, parameters for the description of the soil, the capillary ascendency in the ground and land use. Using average climatic data, however, conditions that fluctuations between dry and humid years are not taken into consideration.
The rate of ground water recharge is one of the parameters that are considered for the calculation of long term amounts of removal when planning the use of ground water resources. The aim is to avoid an overstraining of the resources in order to secure the conveyance of water over a long period of time. Therefore the average ground water recharge within the drainage area of the conveyor has to deliver enough water to avoid that overstraining.
It remains to be stated that the currently existing methods of calculating the rate of ground water recharge can take into consideration neither fluctuations between dry and humid years nor long term changes of the climatic conditions, since they work exclusively with mean climatic data of the past.

Decrease of groundwater recharge through climatic change

The intensity and distribution of precipitation exert significant influence on infiltration and leakage of water into the ground – and thus on groundwater recharge.
Infiltration as a result of precipitation, irrigation, or flooding can be described quantitatively with the infiltration rate which provides the amount of water which leaks into the ground per time unit. The infiltration rate is influenced significantly by the water conductivity of the soil. This in turn is affected by grain size and the texture of the soil, i.e. number, size, and form of pores, and by water content. There is a non-linear relation between conductivity and content of water which can be described with the help of the relative hydraulic conductivity function. This relation is different with each soil. When the soil is completely saturated, the conductivity corresponds to the saturated conductivity.
Soil properties and water content on the surface thus determine the maximum infiltration rate. With dry soil, it will be very high at the beginning of a precipitation event, since the pore volume in the upper layer of the soil will be filled up first. Later, however, it decreases to a constant value. When the supply of precipitation per time unit exceeds the current infiltration rate, the remaining precipitation water runs off on the surface. The same precipitation amount over a longer period of time with a lower intensity therefore causes higher amounts of infiltration than the same precipitation amount over a shorter period of time with higher intensity which exceeds the maximum infiltration rate.
In order to estimate the already observable climatic change, complex climatic simulations are being used throughout the world. These days, linked ocean-atmospheric-models, so-called general circulation models (GCMs), are used, which simulate the future world climate assuming plausible boundary conditions. However, for conclusions about possible regional and local climatic developments those models have a solution too low even according to the current state of the art. Because of this, in addition regional climatic models are being applied, which as input data use results of global climatic models. With their help the results of global models can be regionalised (downscaling).
The ever improving models show clearly, firstly, an explicit temperature increase (e.g. for Germany 1.1 – 5.4 degrees Celsius by the end of the 21th century), and secondly, a changing distribution of annual precipitation (Sächsisches Staatsministerium für Umwelt und Landwirtschaft, 2005). What is expected for Germany are more humid winters and drier summers. Precipitation in summer may then decrease by up to 22 %, while

precipitation in winter may increase by up to 30 %. Changes of the mean annual precipitation amounts in Germany are expected to be rather differentiated.
The values here range from 15 % (federal state of Mecklenburg-Vorpommern [North East Germany]) to +10 % (lower mountains in the federal states of Hessen and in the Rhineland [Central Germany]) (Spekat, et al., 2007).

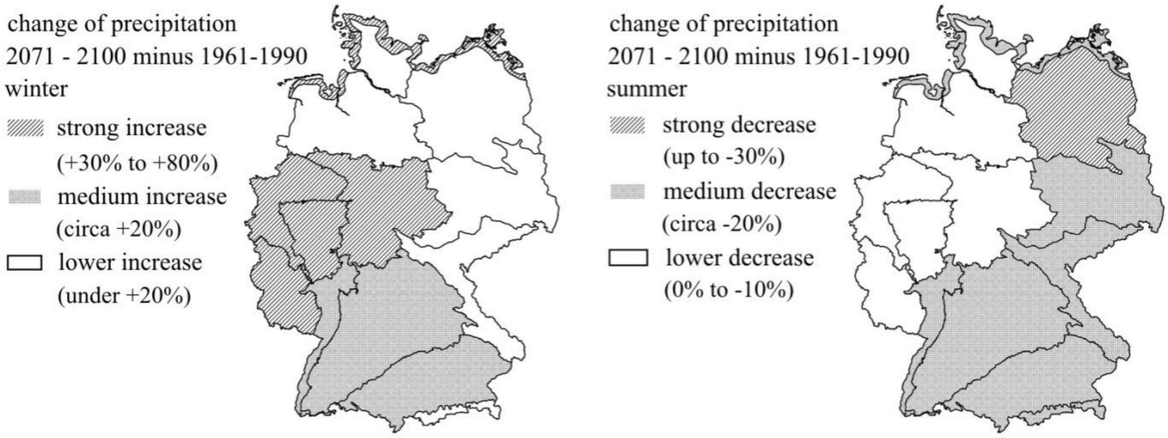

Fig. 2 Intensity of the climate signal of precipitation change for Germany from (Spekat, et al., 2007)

Estimating the occurrence of extreme precipitation events with the help of the existing climatic models is by far more difficult than predicting the future temperature sequence, however, with the help of the latest regional models, quite reliable estimates are even possible here. For Germany it is assumed that longer dry spells as well as extreme precipitation events will increase significantly. That may be, for instance, local showers of high intensity and thunder storms. During the winter time, there are no significant changes of precipitation events to be anticipated (Sächsisches Staatsministerium für Umwelt und Landwirtschaft, 2005).
Drier summers plus an increased occurrence of extreme precipitation events during that time means that in the future the number of precipitation events will decrease. Those extreme precipitation events will lead to clearly higher surface run off. Heavy rain, in Germany defined as 5 l/m² in 5 min or 17 l/m² in 60 min, exceeds the maximum infiltration rate of many soils by far (sandy soil has an infiltration rate of ca. ≥ 35 l/m² in 60 min). Therefore groundwater recharge will decline through the increase of precipitation events of high intensity.
In addition, during the growing season plants draw parts of the infiltrated water from the soil. That means that at least in our part of the world groundwater recharge will happen mainly during the winter time. Although an increase of extreme precipitation events are not to be anticipated during winter and more humid winters will hopefully refill the groundwater resources, the growing season will be sustained through the temperature increase, which will contribute to a decline in ground water recharge. For the federal state of Saxony, an extension of the growing season of at least 10 days up to 31 days is assumed (Sächsisches Staatsministerium für Umwelt und Landwirtschaft, 2005).

Necessity of new calculation methods

Through the results of the climatic prognoses and their effects on the soil water balance, a decrease of the rate of groundwater recharge must be expected during the up-coming decades. These changes will be regionally differentiated, in the same way as the climatic change may affect various regions differently. Records of climatic data over the last years already show changes of distribution of precipitation and an increase of extreme events. Approaches of calculating the rate of groundwater recharge based on monthly – or yearly values will lead to misinterpretations. Water supply companies, who have to plan the extraction of ground water over longer periods of time, need new and adapted calculation methods of rates of groundwater recharge. Methods are needed which can deal with high-resolution precipitation time series (e.g. hourly values) as input data. One possibility would be the transient simulation of soil water balance with the help of a corresponding model. However, this requires the existence of time series of the climatic boundary conditions in a high time resolution (e.g. daily values). An example of such a simulation programme is SiWaPro DSS, linked with a weather generator.

SiWaPro DSS linked with a weather generator

The programme SiWaPro DSS was developed by the Institute of Waste Management and Contaminated Sites at the Technical University Dresden in collaboration with the KP Ingenieurgesellschaft für Wasser und Boden mbH.

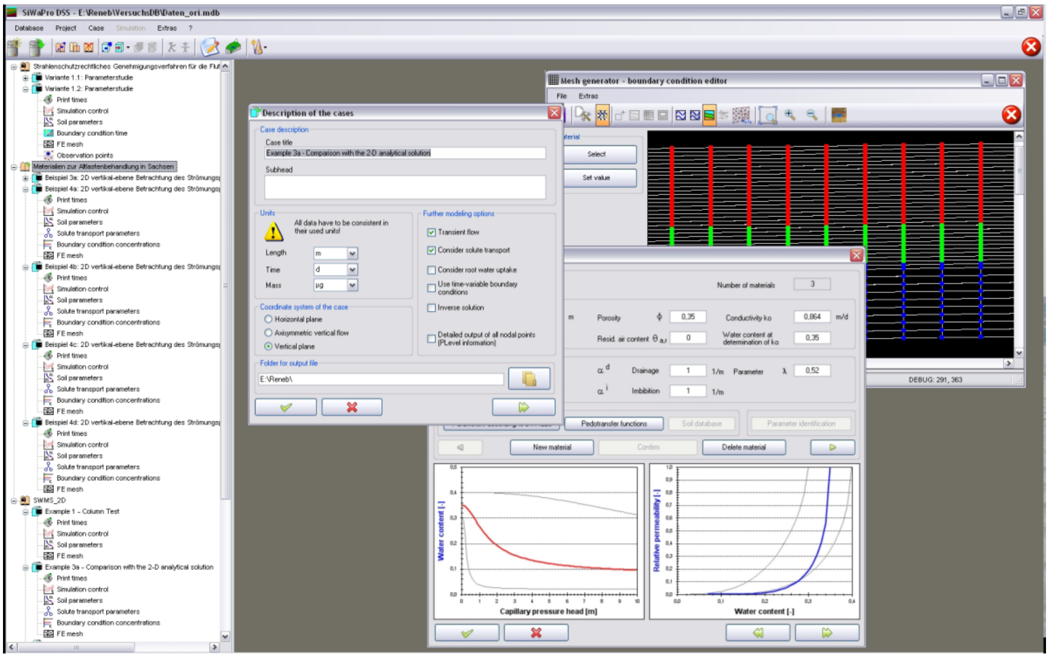

Fig. 3 graphic user interface of the simulation software SiWaPro DSS

It is based on a physical soil model, namely adapted version of the simulation core SWMS_2D. Flow processes are calculated with the Richards-equation; transport processes are simulated with help of the convection-dispersion-equation. At the same time, SiWaPro can take into consideration flow and transport processes both under stationary and transient conditions as well as zero- and first-order degradation processes. The software combines the simulation core for the numerical simulation in partly saturated media with additional modules for the graphical display of results, identification of parameters, interfaces to soil- and material-databases, and integrates them into a graphic user interface. With the help of the programme, 2D horizontal and vertical as well as rotation-symmetrical models can be set up. An integrated mesh generator can generate triangle networks and so allows the users to provide any geometry and supports them with the input of boundary conditions, initial

conditions and assignation of material. An integrated model for the root water uptake allows taking plant cover and its effects on the soil water balance into consideration.
In order to transiently simulate the soil water balance, time series of the atmospheric boundary conditions, i.e. precipitation at the surface, potential soil evaporation and potential transpiration (if there is a plant cover) are required. Data of the necessary meteorological values precipitation, air temperature, and global radiation often exist only for gauging stations which are far away from each other, and thus have to be interpolated for the observed location. Afterwards the diverse hydrological values, such as potential evapotranspiration, real or maximum evaporation, interception, snow evaporation, potential soil evaporation, and potential transpiration, have to be calculated. For this task, a weather generator has been developed, which makes it possible to generate time series of any length for the observed location on the basis of existing time series from surrounding gauging stations.

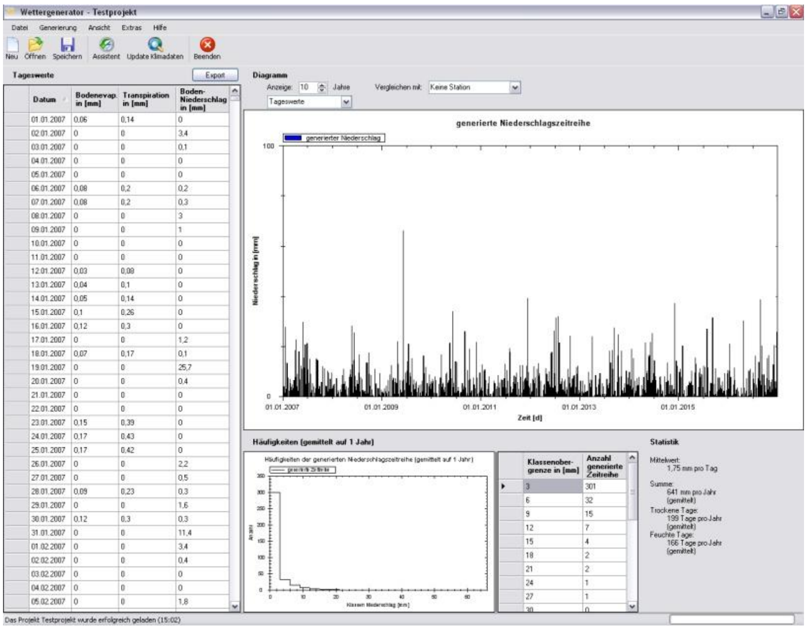

Fig 4. graphic user interface of the weather generator

The weather generator determines statistical parameters on the basis of the recorded data and interpolates them for the unknown location. With the help of these parameters it generates a stochastic time series of the length provided by the user.
The synthetic generation of precipitation series is based on a first-order Markov-chain for the description of the condition (humid or dry), and on a two-parametrical Weibull-distribution for the precipitation amount. Temperature, global radiation, and wind speed are generated with a continuous, multivariate stochastic model, in which mean values and standard deviation depend on the precipitation conditions of the day (Richardson, et al., 1984). All parameters required for the calculation of the hydrological values (e.g. specification of declination and orientation as well as land use and plant cover) are conveniently asked from the user by an assistant. As far as possible, sensible default settings are provided. The programme exists as a stand-alone tool, from which the generated time series can be exported into any simulation programs, and as a plug-in for SiWaPro DSS. Through this linking the user is enabled to easily and conveniently set up a two-dimensional model of the soil zone, to generate the necessary atmospheric boundary conditions for any location, and to run simulations for the calculation of the rate of ground water recharge.

In several case studies, e.g. in the simulation of a landfill lining in Norway, the ease of use of the two linked programmes for the transient simulation of the soil water balance has been demonstrated.

Further Development – Integration of results of climatic models

For the calculation of the rate of ground water recharge with the help of transient simulation of the unsaturated soil zone, regionalised results of climatic models in the form of time series with a high time resolution are necessary. There are a variety of regional models that are able to simulate regional climatic scenarios and to provide time series of important meteorological values (e.g. precipitation and temperature) for individual locations (mostly gauging stations with existing recordings of climatic data) (Sächsisches Staatsministerium für Umwelt und Landwirtschaft, 2005). The starting and boundary conditions of these models are the latest results of general circulation models. Their data allow, in contrast to the results of global models, for conclusions about regional climatic change and are the foundation of simulation of the soil water balance. The resolution of these data is mostly daily values. In the further development these simulated time series which reflect the expected climatic change will be integrated into the weather generator. The aim is an easy generation of synthetic time series of precipitation, temperature and global radiation based not only on the recorded climatic data of the past, but also on simulated data about the future climatic development.
Therefore the weather generator, once thus extended, linked with the simulation programme SiWaPro DSS, constitutes an extensive and yet conveniently useable tool for the calculation of the rate of ground water recharge and, what is more, of other components of the soil water balance in the light of climatic change.

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