What are the key parameters for soil hydrological models in climate impact studies under different settings?

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Abstract As climate models become more and more accurate and climate change becomes less deniable, a demand for applications of various impact models grows stronger. The impact on groundwater budget is often calculated by numerical models, such as SWAP and HYDRUS, using the Penman-Monteith-equation for potential and actual evapotranspiration and the Richards equation (using van Genuchten-Mualem-parameter) for water movement in the vadose zone. On the one hand, using such a detailed model has the advantage to identify seasonal shiftings in the soil water budget; on the other hand applying those models to the meso-scale has the drawback of a high data demand. To show whether an impact model is reliable enough to explain the impact of climate change on the target parameter (e.g. groundwater recharge) its sensitivity to parameter variation has to be tested. Sensitivity studies can also indicate which parameters can be neglected and which need to be investigated in more detail. Two calibrated SWAP models have been applied to estimate the impact of climate change on the water budget for an upland and a polder location. While the first site is a typical groundwater recharge area, the latter is a ditch-drained area where permanent groundwater discharge occurs. For both sites, climate projections from two regional climate models (CLM and REMO) driven by the general circulation model ECHAM5 have been used. The results from two realizations of the SRES CO2-scenarios A1B, B1 and A2 as well as the C20 reference period were available. Instead of using the data directly, two different bias correction methods were applied: a linear bias correction method and the so-called quantile mapping method. The Cramér-von Mises criterion has been applied to show which method is applicable for each site. Afterwards, two sensitivity tests were conducted. The Model-Scenario-Ratio (MSR) has been applied to identify the effect of parameter uncertainty on the relative impact of climate change on the oil water budget. The Scenario-Uncertainty-Ratio (SUR), which we adapted from the MSR, identifies whether the impact of the parameter uncertainty or the climate change impact is stronger. As a result we see that different hydrological settings show different parameters to be sensitive in terms of water budget. While crop and meteorological parameters are sensitive for the upland site, soil and drainage parameters are shown to be more important for the polder site. The study shows that process-oriented model-codes can be applied to meso-scale, if an appropriate sensitivity study is carried out to identify parameters that can be neglected for regionalization.

Key words climate change impact assessment; SWAP; groundwater recharge; BIAS correction methods; sensitivity

INTRODUCTION

To manage groundwater systems, estimating groundwater recharge is an important task. Often modelled groundwater recharge is the essential driver of groundwater flow models.

To quantify the impact of climate change on groundwater recharge, which is at the moment a key aspect in climate change assessment studies, hydrological models with a high temporal discretisation should be used. Many of these (such as Hydrus-1D and SWAP) use the FAO-56 Penman-Monteith equation to calculate hypothetical reference crop evapotranspiration rate on a daily basis.

Since this equation uses standard climatological records of solar radiation, air temperature, humidity and wind speed (Allen *et al*., 1998), these meteorological parameters of the dynamic climate models have been reviewed. Systematic errors were found for each parameter, which made a bias correction necessary. The first aim was to apply simple correction methods in order to make climate projections data usable for impact models using the Penman-Monteith equation. Therefore, a simple linear approach for all parameters and a mixture of linear and quantile mapping methods have been used. To verify these correction methods the Cramér-von Mises criterion (CvM) has been applied on the annual groundwater recharge (GWR) values. The drawback of HYDRUS-1D and SWAP is the high number of parameters demanded, which will often be a limiting factor if either model was applied to the meso or macro scale.

One possibility to reduce this problem is to identify key parameters and to quantify their impact on GWR in order to choose which parameters can be neglected for further investigations. Thus, two ratios were calculated for all parameters of two models for typical hydrological sites. These investigated sites represent a typical recharge area and a typical discharge area which are characteristic for northwest Germany.

METHODS AND AVAILABALE DATA

Model

The SWAP 3.2 model code, which is described in detail in Kroes *et al*. (2009), has been used to calculate the soil water balances of the following sites. Model requirements were the usage of daily meteorological data and the calculation of different types of drainage and crop types, to cover all hydraulic conditions of the metropolitan area of Hamburg, Germany.

Investigation sites

Two different sites have been investigated. One can be declared as a typical soil situated in a groundwater recharge area. The site, which will further be referred to as Hamerstorf-site, is situated 80 km southeast of Hamburg in a region called “Ostheide”. The area is dominated by agricultural lands. The landscape has been built during the glacial and interglacial periods. The basic soil type in the region is a Cambisol. The groundwater level at the site is situated 6 m below the surface. Soil physical parameters were estimated in the laboratory (K. Schmelmer, personal communication). These parameters were taken as a starting point in the calibration process. The SWAP model was calibrated with measured soil moisture data from TDR probes for the vegetation period 2010, which were compiled by the project partner Leuphana University.

The other site is situated in a polder called Altes Land, southwest of Hamburg in the Elbe valley. The investigated soil is a fluvimollic Gleysol and its hydraulic parameters have been taken from the LBEG Soil database (LBEG, 2010) and Quast (1979). The ground level is about sea level, while the groundwater potential is approximately 10 cm above. The aquifer is confined by 8 m thick clay-silty marsh sediments. The “Altes Land” Polder has been drained by ditches since the 12th century (Kleefeld *et al*., 2007) and can therefore be seen as a typical groundwater discharge area in a strongly tide-influenced estuary system. A SWAP model for this site has been calibrated by Scharnke (2010) using tensiometer data from Quast (1979). The land use is apple orchards. This site is further referred to as Estebruegge-site.

Data

Meteorological datasets have been taken from the KL-Collective of the German weather survey (Deutscher Wetterdienst, DWD). Data of the DWD stations Uelzen (for the Hamerstorf-site) and Jork (for the Estebruegge-site) have been chosen as input. Precipitation has been corrected by a method suggested by Richter (1995). Global radiation values, which are mandatory for the Penman-Monteith formula, have been calculated from daily sums of sunshine duration, using the formula of Ångström (1924). Relative humidity has been transferred to vapour pressure using the Magnus formula (Sonntag, 1994). For greater gaps, data from nearby stations have been taken and minor gaps have been filled with interpolated data. Daily data for a hydrological time span from 1961 to 1990 have been used.

As input for climate projections, results from the regional models REMO and CLM were available. Both models are nested within the ECHAM5 global climate model. In a first step data has been downloaded from the CERA database. No single cell values of regional climate models should be used, therefore, an arithmetic mean of four respectively nine cells nearest to the modeling sites have been calculated for all parameters.

The models have been driven by DWD data and C20 data of REMO (Jacob & Mahrenholz, 2006d; Jacob *et al*., 2009) and CLM (Lautenschlager, 2009a,b) for a reference period (1961–1990) for the first and second realization to test the applied bias correction methods. Additionally the models have been driven by projection data from first REMO realization of SRES-scenarios A1B (Jacob & Mahrenholz, 2006a), B1 (Jacob & Mahrenholz, 2006b) and A2 (Jacob & Mahrenholz, 2006c) for a future time span (2071–2100) to apply the MSR and SUR sensitivity measures.

Bias correction methods

Since the data showed a bias in various parameters, two different bias correction methods were chosen to manipulate the data. Especially for precipitation data, many different bias correction methods have already been tested (Themeßl *et al*., 2010).

At first, a linear bias correction method was used where for each parameter monthly differences (temperatures) or monthly factors (precipitation, solar radiation, wind speed, humidity) have been calculated by comparing monthly means of observed (DWD) and modelled (C20) data. To create the SWAP input these monthly bias factors and differences have been applied to modify the values for projections of the corresponding realizations and scenarios. In the following this method will be called the linear method.

Secondly we created a mixed approach of linear corrections and quantile-mapping methods. The monthly linear approach was also used for wind speed and temperatures. For solar radiation, precipitation and humidity, the bias was corrected by applying a quantile-mapping method like Themeßl *et al*. (2010), but on a monthly basis. For measured DWD values, as well as for C20 scenarios, monthly empirical cumulative distribution functions (ecdf) were created. For each daily projection value X we applied a transfer function to receive the bias corrected value Y. First the quantile for the specific value was determined by the ecdf of the corresponding C20 reference period. The bias corrected value Y is the value given by the ecdf of the DWD values at the same quantile (see Fig. 1):

$$Y_{Scenario-bias-corrected} = ecdf^{DWD^{-1}}\left(ecdf^{C20,RCM,\mathrm{Re}alization}\left(X_{Scenario}\right)\right) \quad (1)$$

In the following, this method will be called the mixed method.

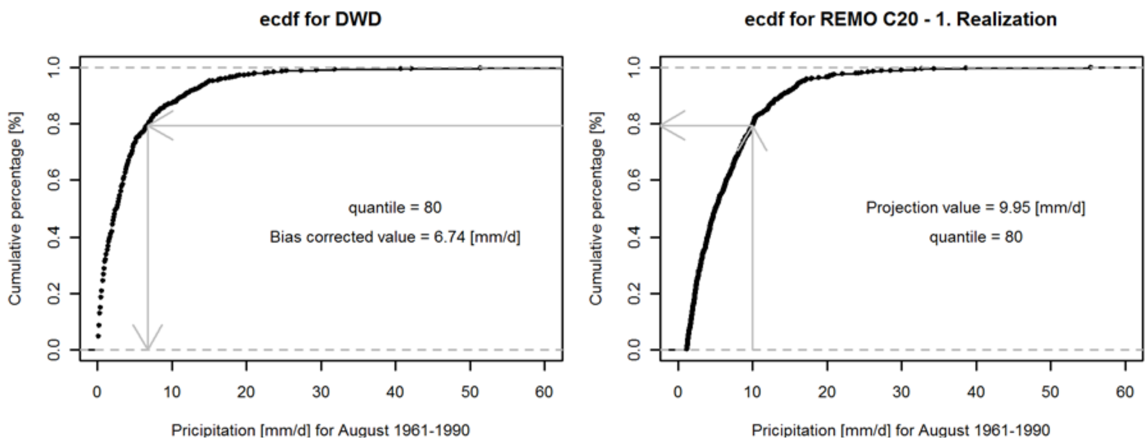

Fig. 1 Scheme for correcting projection values by the quantile mapping method.

Statistical evaluation of Bias correction methods

To prove that the chosen Bias correction method is sufficient, in order to create SWAP input data from C20 projections, and to provide the same groundwater recharge distribution as the DWD data driven SWAP model results, the Cramér-von Mises criterion (CvM) has been applied. The CvM is based on the sum of squared differences between two ecdfs (Sachs & Hedderich, 2009). For every regional climate model and realization, the SWAP-modelled distribution of annual groundwater recharge (x_i; i = 1,..., n_1) has been compared to the SWAP-modelled groundwater recharge rate distribution resulting from DWD input (y_j; j = 1,..., n_2). The test statistic is calculated as:

$$C = \frac{n_1 \cdot n_2}{(n_2 + n_2)^2} \left\{ \sum_{i=1}^{n_1} \left(F(x_i) - G(x_i)\right)^2 - \sum_{i=1}^{n_2} \left(F(y_i) - G(y_i)\right)^2 \right\} \quad (2)$$

with the corresponding cumulative percentages *F* and *G*. If *C* is lower than the critical value of 0.461, the examined distribution are not significantly different (Sachs & Hedderich, 2009). A low *C* value indicates a good fit of the bias correction for the C20 projection.

Identification of key parameters

To identify key parameters the Model-Scenario-Ratio (MSR) introduced by Droogers *et al*. (2008) was used. First a scenario impact on the mean groundwater recharge (GWR) was calculated for a calibrated model. Afterwards the impact on GWR is calculated for a model, where one parameter was perturbed to its maximum or minimum, which is believed to be a possible range of inaccuracy of this parameter. The MSR value is calculated as follows:

$$MSR = 1 - \left| \frac{Scenario_{calibrated} - C20_{calibrated}}{C20_{calibrated}} - \frac{Scenario_{pertubed} - C20_{pertubed}}{C20_{pertubed}} \right|. \quad (3)$$

MSR values can range from 1 to –∞, where 1 indicates that the parameter inaccuracy does not play a role, and the results are only a function of the scenario impact. Values lower than 0 indicate that the model results are dominated by parameter inaccuracies. Droogers *et al*. (2008) also showed that MSR can also have the value 1, even though a parameter perturbation can lead to a significant change in the absolute result of the model. In one case it was 50% different. Therefore the MSR shows only whether the parameter inaccuracy changes the relative impact of the climate change. Results of groundwater recharge modelling are often used in numerical groundwater flow models, therefore the absolute impact value is of higher relevance. To identify the impact on the absolute result we introduced a simple Scenario-Uncertainty-Ratio (SUR):

$$SUR = 1 - \left| \frac{Scenario_{calibrated} - Scenario_{pertubed}}{C20_{calibrated}} \right|. \quad (4)$$

The SUR directly measures the difference of the modelled climate change impact by a calibrated model to the impact of a model where one parameter is perturbed. By a simple screening of all parameters the key factors for each site can be determined.

RESULTS

Evaluation of Bias correction

The results of the CvM can be seen in Table 1. For the Hamerstorf-site model both bias correction methods lead to GWR distribution, which are not significantly different. Therefore both bias

Table 1 C-values of the Cramér-von Mises criterion of GWR of comparing C20 model results with DWD model results for linear bias and mixed bias correction methods.

	Hamerstorf-site		Estebruegge-site	
	Linear method	Mixed method	Linear method	Mixed method
C20 REMO 1/ DWD	0.082	0.042	1.221	0.016
C20 REMO 2/ DWD	0.148	0.098	2.788	0.009
C20 CLM 1/ DWD	0.054	0.034	2.409	0.198
C20 CLM 2/ DWD	0.113	0.052	1.277	0.271

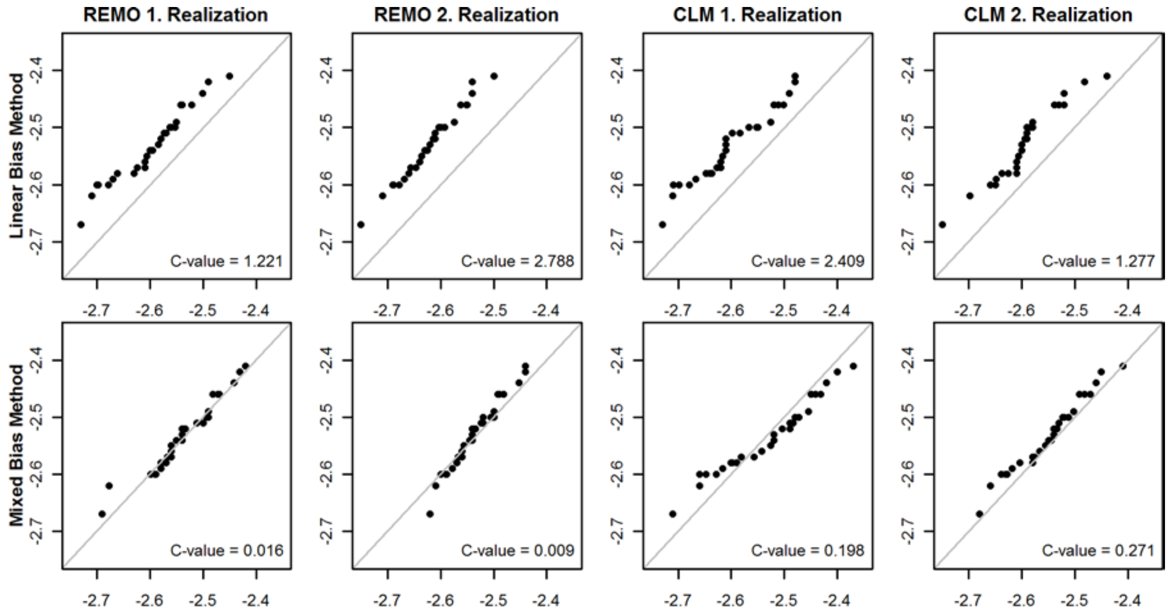

Fig. 2 Scheme QQ-Plots of annual groundwater recharge (cm a^{-1}) for the Estebruegge-site, x-axis are modelled values with bias corrected input data; y-axis are the modelled GWR by DWD-input data. Since the Estebruegge-site is a discharge area, negative GWR-values indicate discharge.

Table 2 Selected MSR and SUR values for each site and each scenario for the first realization of REMO and the usage of the mixed method.

	Hamerstorf–site						Estebruegge–site					
	MSR			SUR			MSR			SUR		
	A1B	B1	A2	A1B	B1	A2	A1B	B1	A2	A1B	B1	A2
Precip ×0.9	1	1	1	0.8	0.79	0.79	1	0.99	1	1	1	1
Precip ×1.1	1	1	1	0.79	0.79	0.79	1	1	1	0.99	1	0.99
CF ×0.86	1	1	1	0.9	0.9	0.9	1	1	1	1	1	1
CF ×1.14	1	0.98	0.99	0.75	0.75	0.74	1	1	1	0.97	0.97	0.97
HUM ×0.9	0.99	1	1	0.87	0.86	0.86	1	1	1	0.99	0.99	0.98
HUM ×1.1	0.99	1	0.99	0.86	0.86	0.86	1	1	0.99	1	1	1
Level ×1.29	–	–	–	–	–	–	0.98	0.99	0.99	0.68	0.68	0.69
Level ×0.71	–	–	–	–	–	–	0.91	0.89	0.86	–1.8	–1.79	–1.72
Kf ×0.1	1	1	1	1	1	1	1	1	1	–9.1	–9.25	9.23
Kf ×10.0	1	1	1	1	1	1	0.97	0.99	1	0.11	0.1	0.1

corrections methods are usable for the reference period. This is not true for the Estebruegge-site, where only the C values of the mixed method are below the critical value of 0.461. By comparing all C values, the mixed method shows in both sites the best correction values for GWR. This is true for all used regional models and projections. In Fig. 2 QQ-plots visualize the model results for the Estebruegge-site.

Key parameters for modelling climate change impact on groundwater recharge

In Table 2, MSR and SUR values are listed for selected sensitive SWAP model parameters. As can be seen, the MSR is not very sensitive to the chosen parameter, and is often close to 1. The inaccuracy of all parameters would show only a relative shift of the climate change impact. Therefore, relative conclusions drawn for either model seem to be allowed. Reviewing the SUR values for the two sites, it becomes obvious that the model for the typical recharge site Hamerstorf is sensitive to the parameters directly used in the calculation of the actual evapotranspiration, such as humidity (HUM), precipitation (Precip) and crop factor (CF).

These parameters did only play a minor role for the Estebruegge-site. At this site, upwards groundwater flow is dominant, thus the parameters determining upward flow, such as hydraulic conductivity (Kf), water level in ditches (Level), GW potential, and thickness of the aquifer confining soil units (both not listed) are the most sensitive parameters.

The minor differences in SUR as well as MSR values between the A1B, B1 and A2 scenarios are the result of rather similar impacts of these scenarios on GWR.

DISCUSSION AND CONCLUSION

Bias correction method

As shown, different bias correction methods seem to be applicable for different site characteristics. While the linear method seems to be applicable to reproduce groundwater recharge in upland settings, this is not the case for discharge regions such as the Estebruegge-site. To confirm this, statistical tests have to be carried out. Our first attempt to use the Kolmogorov-Smirnov test failed since this test is only valid for ecdfs, which do not cross each other. Therefore the statistical criterion has to be selected carefully. As a result of the presented investigations the CvM criterion is suggested for these purposes. The mixed bias correction method seems to be applicable to both test-sites. More sophisticated methods have been presented by Themeßl *et al*. (2010) and Piani *et al*. (2010).

Since the linear approach was sufficient for the upland site, it seems possible to use simple bias correction methods to create input for climate assessment studies in certain hydrological settings. But it has been shown that prior to the use of climate projections for the future scenarios the CvM criterion has to be applied to check whether the chosen bias correction method is adequate. This should be done for all hydrological settings, each regional climate model and all realizations.

Key parameters in different hydrological settings

As has been shown, different key parameters are relevant for different hydrological settings. In upland sites the parameters controlling actual evapotranspiration are important, while for lowland sites such as the Altes Land polder, the parameters that control the groundwater flux from the confined aquifer are the key parameters. To create meso or macro scale models using the code of HYDRUS-1D or SWAP it is advisable to first investigate which parameters are important for each setting. As shown, a screening method with an adequate statistical indicator (as in our case SUR) can reduce sensitive parameter combinations, which should be significantly regionalized. Using such a technique enables the usage of process-oriented models for GWR on a larger scale, because only a limited number of sensitive key parameters combinations must be applied on a regional scale.

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