CLIMATE CHANGE EFFECTS ON THE WATER BALANCE IN THE FULDA CATCHMENT, GERMANY, DURING THE 21ST CENTURY

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ABSTRACT
Although a lot of progress towards the understanding of the impact of 21\textsuperscript{st} century possible climate change on the global water cycle has been made in recent years, the picture of the corresponding hydrological behavior on the regional and local scale is still blurred. Thus, even adjacent catchments in a relatively small country as Germany can react differently to changing climate conditions. The present study tries to improve the understanding the effects of predicted 21\textsuperscript{st} century climate changes on the regional water cycle in the 6930 km\textsuperscript{2} Fulda catchment in central Germany. Furthermore, the intention is to provide administrative bodies with new guidelines and tools to be better prepared for the expected future effects on the water resources. Using the IPCC-Scenarios A1B, A2, and B1 for the 21\textsuperscript{st} century in the ECHAM5 MPI-OM and its dynamically downscaled regional model REMO, high resolution climate data for the Fulda catchment were generated. These are then used as input in the distributed hydrological model SWAT (Soil and Water Assessment Tool) to simulate the future surface water budget in the basin. SWAT is calibrated and validated in the period 1977 – 2004 with measurements from around 80 rain gauges, 23 climate gauges, and several runoff gauging stations. A good agreement between calculated and measured daily, monthly and yearly amount of runoff in the sub-basins is obtained, as indicated by high $R_N^2$ of 0.89, 0.94 and 0.97, respectively. The 21\textsuperscript{st} century runoff calculations and the analyses of the water balance result in statements, firstly, with regard to precipitation: In the period 2001 – 2100 there are sequent years with significant higher yearly precipitation than in the reference period 1960 – 2000. Although there is no trend in yearly precipitation, a redistribution to more precipitation in the winter and less in the summer is observed. Secondly, despite no precipitation change there is a significant decrease in the yearly runoff amount, especially for scenario B1. Within one year, the runoff will increase in winter, but will stay more or less constant in summer. The distribution of the yearly runoff is not stationary over the total 21\textsuperscript{st}-century period. Thus multi-annual oscillations complicate trend detection. Due to a warmer climate, under the assumption that land use will not change in the future, the evapotranspiration will decrease slightly because of less soil water content, resulting in more water stress.

1. INTRODUCTION
Since the 1970’s the modeling of global climate has made great progress. This led to a much better understanding of how the hydrologic cycle as an integral part of the climate system reacts to changes in the radiation balance due to anthropogenic green house gas emissions. So, more and better analyses of water resources in a changing climate enable policymakers to transform new scientific knowledge into necessary programs to react on possible climate change, because »(...) a future climate change would not only affect the magnitude or reliability of existing water resources, but it would also make available resources that had not previously been considered as such or result in the total loss of many
existing resources.« (ASKEW, 1987). Regarding the global hydrologic cycle there is now a good understanding of how the hydrosphere has reacted in the past decades and how it will react in possible future scenarios of recent and future global climate changes: The average annual runoff will decrease in higher latitudes, in equatorial Africa, and in Asia. It will decrease in most of the subtropical regions (ARNELL, 1999). The most sensitive reactions of runoff to climate change appears to be in northern Africa (LABAT et al., 2004). The IPCC Third Assessment Report (IPCC, 2007) is the most comprehensive documentation to-date of recent climate research. Here a few excerpts: (past decades) »Long-term trends from 1900 to 2005 have been observed in precipitation amount over many large regions. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia«. Regarding the future precipitation in Europe and Africa, the above-named report predicts a clear decline in southern Europe and northern Africa, while precipitation increases in northern Europe. Interestingly enough, Germany is located in a transitional area between decreasing precipitation in the south and east and increasing precipitation in the north.

In contrast to the global view the regional assessment of past and future changes in Germany’s climate does not reveal distinguished spatial patterns. In central Europe, especially in Germany, some studies show a patchwork of small areas with increasing or decreasing precipitation for the 21st century (UBA, 2008). Even sub-basins of a large catchment may react oppositional to climate change (e.g. HLUG, 2005). Hence, most of the time it is not possible to transfer results for climate change effects in a particular basin within Germany to another one.

In this study we investigate the Fulda catchment area in central Germany (Fig.1) for possible surface water balance changes under the impact of predicted 21st century climate change of, namely, temperatures and precipitation. The aim is firstly to get new information about local changes of the Fulda river discharge, secondly, to set the results into a global context. Another particular goal of the study – but which is not further explored in the present paper (see Fink and Koch, 2010b) - is the statistical analysis of predicted future extreme discharges of the Fulda river, i.e. flood events, in order to provide water authorities with tools to wither and to mitigate possible detrimental effects of 21st century climate changes to that regard in the basin.

Up-to-date a comprehensive water budget analysis of the whole Fulda catchment area has not yet been endeavored. In fact, due to the presence of big hydraulic structures like the Eder reservoir this poses a particular challenge, as the complex water management of this reservoir requires the implementation of a specific reservoir module into a regular surface water model, like SWAT (NEITSCH et al., 2005) used here. Thus Brahmer (2004) analyzed only the upper part of the Fulda basin which is not yet influenced by the complex discharge from the Eder reservoir. Our study, in contrast, overcomes this deficiency by coupling the SWAT-model with an external newly developed Eder reservoir model. In addition, more recent and higher resolved future climate projections of the dynamical downscaling model REMO (UMWELTBUNDESAMT, 2008) under the IPCC scenarios (SRES) A1B, A2 and B1 (IPCC, 2000) are used to drive the SWAT hydrological models. Another novel feature – though not discussed further here (Fink and Koch, 2010c) - is the use of neural networks to better calibrate the SWAT-modeled river flow discharges at several gauging stations.
MATERIALS AND METHODS

Study Area
The study area is the Fulda catchment located in the center of Germany (Fig. 1). Defined by the outlet gauging station Bonaforth, a few km upstream of the confluence of the Fulda with the Werra - giving birth to the Weser river - the basin covers an area of 6930 km². Climatically the Fulda catchment area lies in a transitional band that divides region of maritime climate of western Europe and that of the continental climate of eastern Europe. Most of the temperatures and precipitation in this moderate climate zone are affected by the Golf stream and the variations of the north Atlantic current (cf. Markovic and Koch, 2005).

From the CORINE Land Cover 2000 data (Keil et al., 2004) one retrieves that the main land use classes are deciduous, coniferous and mixed forests as well as non-irrigated agriculturally cultivated lands. Because of the stringent environmental laws of Germany, it is to be expected that there will be no major land cover change throughout the 21st century investigation period. Within the Fulda basin there are four small flood detention reservoirs and a big one, the Eder reservoir, the latter serving mainly for the management of the water flow to ensure waterway navigation in the Weser river.

SWAT
SWAT (Soil and Water Assessment Tool) is a distributed hydrological model that has originally been developed in the 1990’s to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al., 2005). In recent times SWAT has also increasingly been used in climate impact studies on water resources (Borah & Bera, 2003). The SWAT model consists of various physically based, conceptual and empirical model components describing the different sub-compartments of the surface water cycle. The input to the model requires specific information about weather variables, soil properties, topography, vegetation, and land management practices. For the calculation of the stream flow response the catchment is divided into sub-basins as balance units that are furthermore subdivided into hydrologic
response units (HRU’s). HRU’s are bonded areas with similar combinations of land use and soil. The computation of the model’s output (river discharge) from the input (precipitation) is endeavored in two phases: the land phase and the water routing phase. The first one consists in numerous model components to calculate evapotranspiration, areal runoff, soil water content, recharge to the groundwater aquifer, etc. within each of the HRU. In the second phase the water flow after concentration in the river network is estimated. A more detailed model description can be found in Neitsch et al. (2005).

**Eder Reservoir Model**

The major purposes of the Eder reservoir, with its regular accumulation target of about 200 hm³, are flood protection, generation of hydroelectricity, but primarily, low water management for waterway navigation in the Weser river, downstream to the Fulda catchment. Although SWAT contains a reservoir model, it is not applicable here, as this model provides only the four classical possibilities for the calculation of the volume of outflow: measured daily outflow, measured monthly outflow, average annual release rate, and controlled outflow with target release rate. In all of these options the outflow is defined at each time step. When the outflow additionally depends on other time independent variables, as is the case for the Eder reservoir, SWAT’s reservoir model fails. For this reason, an external Eder reservoir model was developed and coupled with SWAT.

The new reservoir model is based on the classical storage equation for a reservoir (Eq.1).

$$\Delta S = V_{Z, Sch} + V_{Z, R} + V_{Z, P} - V_E - V_A$$

(1)

The storage change $\Delta S$ [m$^3$] during a time step is the sum of the Eder river inflow volume $V_{Z, Sch}$, surface runoff into the reservoir $V_{Z, R}$, and volume of precipitation onto the lake surface $V_{Z, P}$, less the losses due to evaporation $V_E$ and outflow volume $V_A$. Evaporation and precipitation volumes are derived from the storage-volume-dependent surface area of the water body:

$$A[m^3] = f(S[m^3])$$

(2)

Now, in contrast to the SWAT’s internal reservoir model the new model’s special feature is the calculation of $V_A$. The challenge here consists in the correct simulation of the reservoir’s water release as determined by the regulation policy of the “Waterways and Shipping Office” in Hann. Münden. To that avail a complex algorithm was developed that approximates the office’s decision considering (1) ecological river flow aspects, (2) the assessment of snow water content and (3) snow melting in sequential days, (4) runoff at the gauging station Hann. Münden (Weser river) and, (5) flood protection. Further details of the new reservoir module are provided in Fink and Koch (2010a).

**REMO**

For the evaluation of the future climate in Germany, the Max Planck Institute for Meteorology (MPI-M), Hamburg, developed the physically based regional model REMO (UBA, 2008). REMO is dynamical downscaling model that is embedded by double nesting within the global circulation model ECHAM5 MPI-OM, with a resolution of 1.875° (atmosphere model) and of 1.5° (ocean model). High resolution (0.088°≈ 10km) climate predictions for the 21st century, as well as for the recalibration period 1960-2000, have been made with the ECHAM5/ REMO downscaled models, using the IPCC- SRES Scenarios.
A1B, A2 and B1. According to the required SWAT model’s setup the following climate data are used in present study: $T_{\text{max}}$ [$^\circ$C] and $T_{\text{min}}$ [$^\circ$C] (daily maximum and minimum temperature), $r_F$ [%](relative humidity), $G$ [MJ/m²](global irradiance) and $P$ [mm](precipitation). The temporal resolution is one day.

The time series of various climate variables are processed in SWAT as a mean of a sub-basin using the areal average of all REMO grid points covering this sub-basin. For this purpose regression equations between the REMO grid area and sub-basin’s areal mean are set up. These equations are derived from measured data by interpolating them, on the one hand, onto the REMO grid areas and, on the other hand, onto the sub-basin’s area.

**RESULTS AND DISCUSSION**

**Calibration/Validation of the SWAT Model**

The model combination SWAT / Eder reservoir model has been validated for the time period 1977 – 2004. As can be seen from Figure 2, a very good fit of the calculated to the observed daily runoff is achieved at the gauging station Bonaforth ($R_N^2 = 0.89$). The agreement between the monthly and the yearly amount of modeled and observed runoff is even better, with $R_N^2 = 0.94$ and 0.97, respectively.

**The 21st century water cycle in the Fulda catchment**

The validated hydrological model was driven by the REMO projections A1B, A2 and B1 as well by the REMO recalculation of the period 1960-2000 (C20). Some of the following results compare changes between the periods Z0 (recalculated period 1960-2000), Z1 (2001-2033), Z2 (2034-2066) and Z3 (2067-2100) were each of this periods is long enough to be statistically significant.

**Precipitation**

Figure 3 shows the annual precipitation for the Fulda catchment derived from the REMO calculations. In a comparison of the precipitation in the periods Z1 - Z3 and C20 there are significant augmentations of the mean in Z1 and Z2 in scenario B1, in Z1 of A1B, and in Z3 of A2 ($\alpha=0.05$). Figure 4 shows the change of precipitation within a year: In all scenarios there is an increase in winter and decrease in summer.
Figure 3: Annual precipitation in the Fulda catchment as predicted by REMO downscaling.

![Figure 3](image1)

Figure 4: Mean annual precipitation within the periods Z0 (1960-2000), Z1 (2001-2033), Z2 (2034-2066), Z3 (2067-2100) for the SRES- scenarios A1B (a), A2 (b), and B1 (c)

**Runoff**
The SWAT-calculated time series of the annual runoff indicate a slightly but not significant trend for the SRES-scenario A2 (Fig.5). The moving average of Figure 5 additionally shows an oscillation of the mean runoff. In agreement with more precipitation in the winter season there is also more runoff in the months November to May (Fig.6). In summer, on the other hand, is no significant runoff change is observed.
Figure 5: Annual runoff, together with moving average at gauging station Bonaforth (Fulda river) for scenarios A1B, A2, B1 (2001-2100) and in the reference period C20 (1960-2000).

Figure 6: Mean monthly runoff at the gauging station Bonaforth (Fulda river) in the periods Z0 – Z3 for the SRES-scenarios A1B, A2, and B1.
Evapotranspiration
In all the three SRES scenarios the actual evapotranspiration ET will decrease, while the potential evapotranspiration PET increases (Fig. 7). Due to higher temperatures, PET rises, but the SWAT calculations for the soil show more water stress for the plants. So the difference between PET and ET rises when the vegetation is considered as constant between 2001 and 2100.

CONCLUSIONS
Interestingly enough, the SWAT based assessment of the water balance in the Fulda catchment for the 21st century does not result in the detection of dramatic changes. Of course this is a consequence of the rather benign climate predictions of the REMO dynamical model for the central Germany. Thus, although there are slight increases of the winter runoff and winter precipitation, a decrease of summer precipitation, and a retrogressive evapotranspiration, these changes do not impact much the present water resources, let alone pose a particular risk for the latter. The distribution of the yearly runoff is not stationary over the 21st century. Thus multi-annual oscillations complicate trend detection.

For policy makers working on the international scene this study proves again that they have to prepare themselves for special future challenges. Because when we set the present results into a global view, we see dramatic changes in poor regions like Africa and less of a change in the rich central Europe. So climate change may exacerbate the disparities.

It should be noted that the present study makes a lot of assumptions, namely, IPCC-scenarios, no changing land use, invariable Eder reservoir management, etc. A more exhaustive analysis should consider these limitations, though.
REFERENCES


