Hydrol. Earth Syst. Sci. Discuss., 4, 4037–4067, 2007
www.hydrol-earth-syst-sci-discuss.net/4/4037/2007/


Hydrology and Earth System Sciences Discussions

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# Prognostic simulation and analysis of the impact of climate change on the hydrological dynamics in Thuringia, Germany

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Received: 1 November 2007 – Accepted: 1 November 2007 – Published: 14 November 2007

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## Abstract

The impact of predicted climate change on the hydrological dynamics and long term hydrological balance in the federal German state Thuringia was investigated and analysed. For this study the prognostic climate data, provided by the statistical regionalisation approach WETTREG, which is based on results of the global climate model ECHAM5/MPI-OM, was used. This regional climate model provides synthetic climate time series for the existent precipitation and climate station in Germany from 2000 to 2100. This data was processed with the hydrological model J2000g which we used for the regionalisation of the climatological time series data and for the computation of potential and actual evapotranspiration, runoff generation and groundwater recharge.

In this study we analysed the two emission scenarios A2 and B1, defined by the Intergovernmental Panel on Climate Change (IPCC) and their impact on the temporal and spatial distribution of temperature, precipitation, evapotranspiration and runoff generation for the time frame 2071–2100 for the entire area of the German state of Thuringia. For this purpose we compared simulation with the scenario data with simulation results based on reference data from 1971–2000. The comparison showed an increase of the mean annual temperature of 1.8 (B1) to 2.2 (A2) °C which is much more distinct during winter. The mean annual precipitation is decreasing only slightly but, the seasonal spatio-temporal rainfall distribution which has major impact on the hydrological water balance is changing significantly. This pattern change results in more precipitation during winter and less in summer. Actual evapotranspiration was computed higher for both scenarios compared to the evapotranspiration of the reference period 1971–2000. As a follow up a decrease in the runoff generation was simulated which was again very variable in space and time.

The overall trends worked out in this study showed that it is likely that the extremes of flooding in winter and dry spells in summer might occur more often in Thuringia because of the changing weather conditions due to climate change.



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## 1 Introduction

The anthropogenetic caused global climate change is exposing the global environment and mankind to a large challenge which is already described and investigated in nearly discountable research projects and publications. The Intergovernmental Panel on Climate Change (IPCC) plays a central role in the coordination and publication of the climate change research. Its fourth Assessment Report will be published in November 2007 (http://www.ipcc.ch/) and will comprise the actual progress and findings of the current knowledge about climate change and its global impact. Parts of this report have already been presented to the public during the first half of 2007.

The fundamental approach for climate change research is the application of various global climate models which are based on different approaches and algorithms to predict the potential climate system of the future. Because such models are carrying a vast amount of uncertainty they are continuously further developed and adapted to progressing knowledge.

As the water balance is highly affected by climate change and is again highly affecting the eco-system and human welfare it was already the subject of a number of research projects which were investigating the impact of climate change on the hydrology on various scales (e.g. Arnell, 2003; Menzel and Bürger, 2002; Eckhardt and Ulbrich, 2003). In such studies the results of climate models were used as drivers for hydrological models which then predict the change of hydrological variables like surface runoff or groundwater recharge caused by climate impact.

Regional investigations of climate change impact in Germany are carried out in the research projects KLIWA and GLOWA which are aiming at the development of management strategies for parts of Germany to deal with the impact of climate change on the hydrological system. As part of the KLIWA project Bronstert et al. (2006) compared three different regional climate models for south-western Germany, including the one used in this study, with respect to their suitability as input for hydrological investigations. In their study Bronstert et al. (2006) found out that the prognosis of extreme precipitation events and other short term predictions are still carrying a large amount of uncertainty but that the suitability for long term analysis of hydrological dynamics is given.

As climate change is happening and cannot be rescind, political and administrative authorities and decision makers have to decide on measurements and strategies how to deal with the potential changes and impacts. For their planning they are in need of reliable information about the mid and long-term trends of changing climate, weather and hydrologic conditions. In Germany such decision are mainly made on the regional scale of federal states by the relevant state ministries and environmental agencies. Such political bodies need adequate information which is providing them with knowledge in relative high spatial resolution and a sufficient degree of certainty.

In this paper we will present such information for the German federal state of Thuringia, which was derived by the application of the conceptual hydrological model J2000g driven with historical and prognostic climate data. The first sections of the paper will briefly present the climate scenarios, the regional statistical climate model WETTREG[1] (UBA, 2007a,b) and the hydrological model J2000g used for this study. The results of estimated climate and hydrological change for the area of Thuringia will be presented and discussed in Sect. 4. Section 5 will present some considerations about the uncertainty of the presented study. Finally, Sect. 6 will summarize the most important findings and draw conclusions and discuss the likely future conditions in Thuringia.

## 2 Climate modelling

There are a large number of existing global climate modelling efforts (e.g. van Ulden and van Oldenborgh, 2006) that can be generally categorized as either Global Coupled Models (GCM) or Atmosphere-Ocean General Circulation Models (AOGCM). The

[1] Data source: Meteo-Research, by order of Umweltbundesamt, 2006



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World Climate Research Programme (WCRP) and the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (Covey et al., 2003) provide a comparative analysis of the results from many of these models which form the basis of the conclusions drawn by the Intergovernmental Panel of Climate Change (IPCC) (Randall et al., 2007; Meehl et al., 2007).

The land-atmosphere-model ECHAM5, which is coupled to the ocean model MPI-OM, was developed by the Max-Planck-Institute for Meteorology and provides the basic climate information for the regional model WETTREG used in this study. In global modelling applications, ECHAM5 uses a spatial resolution of 192 circles of longitude and 96 circles of latitude resulting in a grid size of approximately 200×400 km at the equator. The vertical discretisation of the atmosphere consists of 31 layers which are defined by the pressure of the interfaces between them (Roeckner et al., 2003).

The accuracy of GCMs are often evaluated through the use of a model control run application to a historic period in which comparisons of GCM states and output variables are made to those from other models and historic climate observations. During these control runs, GCMs are initialized with pre-industrial greenhouse gas concentrations, driven with the changing concentrations of the twentieth century, and compared with observed climate conditions. One drawback to this approach is that the changing concentrations of the last century are not perfectly known and, as a result, introduces some level of uncertainty into the evaluation (Randall et al., 2007; McAvaney et al., 2001). The control run of ECHAM05 over the period of 1961–1990 resulted in an underprediction of up to 1°C for the annual mean temperature and an overprediction of the annual mean precipitation of up to 30 mm in Europe (Randall et al., 2007).

The course spatial resolution of GCMs generally precludes meaningful evaluation and investigations of climate change impacts at a local or regional scale (e.g. German state of Thuringia). Regional climate models, which utilize statistical or dynamical approaches to downscale the results from GCMs, have been developed for investigations at the local or regional scale. WETTREG is such a regional climate model that was developed on behalf of the German Environment Agency (Umweltbundesamt) by



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Meteo-Research in Potsdam, Germany to downscale GCM output using a statistical approach. The WETTREG methodology is based on statistical relations of historical time series measured at the surface and in the atmosphere and the evaluation of specific weather synopses. The statistical relationships are then used to derive synthetic time-series values at existing meteorological stations based on comparable weather conditions predicted with ECHAM5/MPI-OM (UBA, 2007a). New extreme values, beyond the historical ones, due to changed climate conditions are estimated by regression analysis. The synthetic time-series values are available at a daily temporal resolution, however, due to uncertainties associated with the statistical approach used in WETTREG the analysis and evaluation of the time-series information should be usually limited to mean values of 10 yrs or more.

An evaluation of the WETTREG model output was performed for Germany over the time period 1971–2000 with data from the control run of ECHAM5 (UBA, 2007a). The analysis demonstrated that the 10-year mean values of various climate variables were reliable (e.g. −0.1°C for mean temperature and 0.0% for precipitation) and that the 30-yr mean were very close to the measured values (underprediction of less than 0.3 °C for the temperature and an overprediction of the precipitation of 1% for the entire area of Thuringia).

WETTREG provides data for the three different scenarios B1, A1B, and A2. Scenario B1 is characterised by an increased ecological and social awareness and stronger global cooperation of the world's population. It assumes that new technologies will lead to a more efficient use of natural resources and less consumption of production material. Population growth is low and will lead to a world population of 7 billion people in 2100. $CO_2$ emissions will rise in the B1 scenario to 9 Gt C at 2050 and will then decrease to the amount emitted in 1990. Scenario A2 is more economically driven than scenario B1 and assumes a significant population growth (15 billion people till 2100), highly variable regional development, and limited technology transfer between the world's nations combined with low initiative to solve global environmental problems together. A2 assumes that $CO_2$ emissions will rise continuously to 17 Gt C in 2050



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and nearly 30 Gt C in 2100. The third scenario, A1B, represents population growth, emission rates, and political conditions somewhere in between those of scenarios A2 and B1, and was not considered in this study since the A2 and B1 scenarios allowed the investigation of the entire span of potential system response to climate change.

## 3 Hydrological modelling

The Thuringian Agency for Environment and Geology (TLUG) has to supervise and manage the water resources for the German state of Thuringia. For long-term and state-wide planning by TLUG, long-term annual mean values of the hydrological balance (i.e. precipitation, actual evapotranspiration, runoff generation, and groundwater recharge) were estimated with a balance calculation tool called GEOFEM (Gabriel et al., 1986, 1998) in a 500×500 m grid resolution. Due to limitations of the GEOFEM tool, higher temporal resolution results were not possible. For predictive hydrological modelling with future climate scenarios a higher temporal resolution is needed for Thuringia because: (1) the analysis of predictive climate data sets for the next 100 yrs indicates that the inner-annual distribution of precipitation will change whereas the absolute annual amount will remain more or less the same; and (2) spring flooding related to snow fall and melt processes will change due to higher temperatures. Since neither issue can be adequately addressed with GEOFEM, a new modelling tool was developed to satisfy TLUG's needs.

The new modelling tool for historical and status quo simulations, as well as long term hydrological forecast estimates, was developed within the following constraints: (1) continuous simulation of important hydrologic characteristics in monthly and daily time steps; (2) applicability to the entire area of Thuringia (16 172 $km^2$) and smaller catchments within the state; (3) process oriented and as physically based as possible; (4) robust with a small number of calibration parameters. To meet these constraints, the hydrological model J2000g was developed.



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## 3.1 The model J2000g

The J2000g model was developed on basis of the J2000 model (Krause, 2001, 2002) within the JAMS modelling framework system (Kralisch and Krause, 2006) and can be classified as a distributed conceptual hydrological model. The primary goal of the modifications was to simplify many of the complex hydrologic relationships within J2000, resulting in a significantly reduced number of calibration parameters, while maintaining, as much as possible, the important hydrologic behaviours exhibited in catchments within Thuringia. The new J2000g model requires spatially distributed information related to topography, landuse, soil type and hydrogeology to estimate parameter values within each modelling unit. The modelling units can consist of raster cells, process units, or subbasins provided that spatial information is available for each parameter within each unit. J2000g also requires meteorological inputs (precipitation, minimum, average and maximum temperature, sunshine duration, wind speed and relative humidity) from one or more point observation stations. The point data is transferred to each model unit with the same regionalisation approach available in J2000, which is a combination of horizontal (inverse distance weighted) and vertical (regression with elevation) variation. The regionalised data is then used to simulate the hydrological processes for each modelling unit. The principal layout of the process components in J2000g is shown in Fig. 1.

After the regionalisation of climate data, net radiation needed within the potential evapotranspiration module is estimated using the methods presented in the FAO guideline of Allen et al. (1998). The actual ET module is also based on Allen et al. (1998) and simulates the evapotranspiration according to the Penman-Monteith equation for various vegetation and land use types.

Snow accumulation and melt is simulated with a simple approach that estimates snow accumulation depending from a base temperature (`Tbase`) and snow melt from a time-degree-factor (`TMF`) and the actual temperature. During time steps when actual temperature is above `Tbase`, precipitation and potential snow melt moves to the soil



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water module. The soil water module consists of a simple water tank with inputs of precipitation and snow melt. The storage capacity is defined from the field capacity of the specific soil type within the respective modelling unit. For calibration purposes, the entire distribution of storage capacity values for all modelling units can be shifted up or down with a constant multiplier (FCA). Water stored in the soil water tank can leave the tank through evapotranspiration. The actual evapotranspiration is determined by the saturation of the soil water tank, the potential evapotranspiration and a calibration coefficient ETR. The ETR coefficient has a value range between 0 and 1 and defines when potential evapotranspiration is reduced due to limited water availability. Runoff occurs in the model only when the soil water storage is saturated. Any surplus is then considered to produce direct runoff or percolation. The partitioning of generated runoff into direct runoff and percolation is based on the slope of the modelling unit and a calibration factor LVD. The direct runoff and percolation components are transferred to catchment wide storages. The outflow from each of these storages is simulated with seperate linear storage routines to calculate fast runoff and baseflow. The total streamflow at the outlet of the catchment is the summation of the direct runoff and the baseflow components from each modeling unit.

### 3.2 Model application, calibration and evaluation

The state of Thuringa was partitioned into 221 121 modeling units resulting from a GIS overlay of slope, aspect, landuse, soil type and hydrogeological unit. Slope and aspect were classified into 5 and 3 classes in advance. After the overlay for each unit the coordinates of its centroid, the area, the mean slope, the most frequent aspect, the soil type, the landuse and the hydrogeological unit were extracted and transformed into a J2000g compliant data table. The soil type and the landuse information are correlated to specific tables during model initialization to derive physical values for field capacity and vegetation specific parameters like the leaf area index.

Climatological input data (min, max, mean temperature, precipitation, relative humidity, sunshine hours, and wind speed) was derived from the meteorological station



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values provided by WETTREG and transferred to each modelling unit by the regionalisation approach of J2000. This approach is a combination of inverse distance weights (IDW) and an optional elevation correction. The data regionalisation is carried out for each modelling unit by the information of the five closest stations. For the optional elevation correction the degree of correlation between the variable values and their respective station elevation is calculated by a linear regression for each time step. If this regression shows a coefficient of agreement ($r^2$) of equal or greater 0.7 the specific elevation dependent lapse rate calculated from the regression is used for the further processing together with IDW. If $r^2$ is smaller 0.7 only IDW is used.

Values of the six J2000g parameters (`Tbase`, `TMF`, `FCA`, `ETR`, `GWK`, and `LVD`) had to be estimated through a calibration procedure – none of these parameters could be directly estimated from the spatial information available in Thuringia. As the model could not be calibrated for the entire state of Thuringia, calibration was done in a number of different catchments within the state boundaries with sufficient streamflow observations. The selection of suitable catchments was complicated by the fact that J2000g does not explicitly recognize anthropogenic influences on the hydrologic processes and does not account for subsurface water losses to groundwater – both important behaviours in many of Thuringia's catchments. As a result, only catchments with minimal or no anthropogenic influence and mostly impermeable bedrock were selected for calibration.

Eight catchments were identified that met the above constraints for calibration; Bode, Ilm, Wilde Gera, Gera, Zahme Gera, Roda, Orla, and Hasel. The contributing area of these basins ranges between 13 and 320 km$^2$ and are distributed throughout the state (see Fig. 2). For each catchment, values for the six parameters were estimated with the Shuffled Complex Evolution – University of Arizona (SCE-UA) method (Duan et al., 1994). The calibrated parameter values are shown together with the resulting Nash-Sutcliffe efficiency values (NSE) in Table 1.

Inspection of Table 1 reveals that the degree of variability for each parameter among the eight catchments varies for each parameter. The values for `Tbase` vary the least among catchments, probably since it is the most "physically based" and its independence from other factors in the catchment. The values for parameters `LVD` and `GWK` also indicate low variability among the catchments. The NSE, however, was determined to be very sensitive to all three of these parameters and "good solutions" were only possible within a narrow range of values.

The remaining parameters, `TMF`, `FCA`, and `ETR` exhibit considerable variability among the catchments compared to the other three parameters. `TMF` was found to be strongly related to `Tbase`, however, the NSE was not very sensitive to changes in `TMF` (or `FCA` and `ETR`) which may account for the wide range in values. The NSE values for seven catchments ranged between 0.51 and 0.85 and demonstrate that the J2000g simulated the observed streamflow reasonably well. Only the Roda catchment could not be simulated by J2000g with a comparable quality. Because of the geological conditions in the Roda catchment it can be assumed that the groundwater flow processes are governing the hydrological dynamics and that direct runoff plays only a limited role. With J2000g this specific conditions can only be reproduced to some extent because of the simplified algorithm for partitioning runoff into the two runoff components.

For the state-wide application of J2000g, it was assumed that the average of the parameter values from the five calibration catchments would result in reasonable estimates for the remaining "uncalibrated" areas. To test this assumption, the averaged parameter values were used in each of the five calibration catchments. The resulting NSE value (NSE(avg)) for each catchment is shown in Table 1. While there was some reduction in model performance for each catchment, the range of NSE(ave) values (0.55 and 0.81) is very close to those obtained with the optimal parameter values for each catchment. Only the Roda catchment shows a very bad NSE(avg) value of only 0.22.



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## 4 Results for Thuringia

The evaluation of the climate change scenarios and their impact on the hydrological dynamics and balance was done by regionalisation, modelling and comparison of the reference (time frame 1971–2000) and the predicted future state (time frame 2071–2100) based on the WETTREG data for the scenarios A2 and B1. For the analysis a 10 yr average value and then a 30 yr average value was computed which is considered to be representative for the climate of the respective 30 yr time frames. In addition, seasonal averages or sums were computed for winter (December–February), spring (March–May), summer (June–August) and fall (September–November) to analyse potential changes in the interannual variability.

The computation and analysis was done for the important drivers of the hydrological water balance: temperature, precipitation, evapotranspiration and runoff generation. These state variables were analysed in a distributed manner to detect and quantify potential regional differences and dependencies. The direct impact of predicted climate change on the catchment runoff was analysed for the river Ilm catchment, which can be considered representative for Thuringia.

### 4.1 Temperature

The long term mean annual temperature showed an increase due to climate change of +2.2°C for scenario A2 from 1970–2000 to 2070–2100. Scenario B1 showed a milder increase of +1.8°C. The temperature increase in the single seasons was very different. The strongest increase occurred during winter with +3.9 (A2) respectively +3.3°C (B1), the lowest increase in spring with +0.7°C. The analysis showed, that already after the first decades of the 21 century the average monthly temperature stayed always above 0°C throughout the year. The winter season showed a spatially differentiated warming pattern with an higher increase (up to +4.4°C for scenario A1) in the low land areas and the eastern part and a lower increase in the higher mid-mountain regions. The temperature change in the other seasons showed no significant regional differences or patterns. The most important impacts of the temperature increase on the hydrological balance will be an increase of potential evapotranspiration and a decrease of snow accumulation during winter. The latter will have significant impact on the runoff in rivers from the mid-mountain range as snow melt can be a very important contribution to spring peak discharge in Thuringia.

### 4.2 Precipitation

Precipitation is the most important driver for hydrology. In recent times the summer and winter precipitation amount was very well balanced in Thuringia. The simulation with the WETTREG data shows only a very slight decrease of the annual precipitation sum of −1.2% for scenario A2 and −0.7% for scenario B1 from today to 2071–2100. Much more important is the seasonal distribution of precipitation which is changing significantly. For both scenarios a strong increase of +29.1% (A2) and +22.7% (B1) of the winter precipitation was computed as the spatial mean over the entire area of Thuringia. In spring a slight increase of +1.2% (A2) and +2.9% (B1) occured. In summer a significant decrease of −14.3 and −12.7% for scenario A2 and B1 was computed which is continued in fall with values of −17.2% and −12.6%. The spatial distribution of precipitation in the four seasons and the reference periods and the scenarios is shown in Fig. 3. The maps indicate that the increase in winter occurs over the entire state, but in the mid-mountain regions in the south and west the increase is stronger than in the other parts with lower elevations. In spring only minor differences in the distribution pattern were computed. In summer and fall the decrease in precipitation is obvious. In these seasons the low land areas are slightly more affected but also the preciptiation in the higher areas decreases significantly. Translated into hydrological balance it could be expected from the interannual change of precipitation that both extremes, high flows and flooding mostly in winter as well as very low flows and dry spells in summer and fall, will occur more frequently in the future.

### 4.3 Evapotranspiration

Potential evapotranspiration (PET) is mainly driven by energy supply, whereas actual evapotranspiration (AET) is also governed by water availability. From the change in temperature and the innerannual change of precipitation distribution a change in both PET and AET can be expected.

The simulation showed a long term station wide mean increase of AET by +7.6% for scenario A2 and +7.0% for scenario B1. The highest increase was computed in the summer season for both scenarios with values of +16.8% (A2) and +14.8% (B1). The maps in Fig. 4 are showing the seasonal patterns of AET in the reference period and for the two scenarios. In winter AET is low due to low temperature and only minimal changes are resulting from the higher temperature. In spring an increase of AET occurs mainly in the western and south-eastern part. The summer shows the greatest change and nearly the entire state area is affected. The absolute amount of the increase in the higher elevation areas is stronger than in the lowlands because of the larger amount of available water for transpiration of the vegetation in the mid-mountain areas and the water limitation in the central lowlands which are already very dry during summer in recent and historical times. Fall shows also a slight increase in particular in the higher areas.

### 4.4 Runoff generation

Runoff generation is computed by J2000g as the resultant from precipitation and actual evapotranspiration and potential changes in the two storages for soil moisture and groundwater. For the spatial averaged and long-term mean runoff generation a decrease of −47 mm for the B1 scenario and −55 mm for the A2 scenario was computed. The distribution in space and time shows distinct patterns which are related to the distribution of precipitation and evaporation. In the winter season for both scenarios a decrease of 13 mm (A2) and 9 mm (B1) for the entire state was calculated. The maps in Fig. 5 show, that this decrease is very heterogenously distributed throughout the area. For the mid-mountain region in the north-west, the south and in particular in the south-west of the state a significant increase due to higher rainfalls was calculated, whereas for the lowlands in the central and northern parts a decrease of runoff generation was simulated. In spring a slight decrease of −7 mm (A2) and −4 mm (B1) was computed resulting from a mixture of an increase in the higher areas and a decrease in the lowlands. A slight decrease for the entire area of Thuringia was also estimated for the summer season. The decrease is only moderate because the runoff generation in Thuringia is in general very low during summer and was often close to zero already in recent times. Because of the general low runoff generation, the reduction of precipitation and the increase in AET does not have a significant impact on runoff generation in summer, but the higher deficit in water leads to a stronger reduction of the water content in the soilwater and the groundwater storages. In fall a significant decrease of −33 mm (A2) and −35 mm (B1) was calculated for the entire area. The spatial distribution in Fig. 5 show that the higher regions are experiencing the largest decrease because of the larger increase of AET and the decrease of precipitation in particular in those regions. The strong decrease of runoff is also partly caused by the more emptied storages resulting from the drier and warmer summer conditions. A major amount of precipitation in fall is used to fill the soilwater storage before runoff can occur. Both scenarios show in general the same spatial and temporal pattern but the amplitude of the A2 scenario is slightly higher than the one of B1.

### 4.5 Streamflow

The impact of the changed spatial and temporal runoff generation patterns on streamflow was investigated for the Ilm catchment. The Ilm was selected because of its central location in Thuringia and its physio-geographical features which are considered representative for entire Thuringia. A second reason for the selection was the fact that the Ilm is relatively less managed. Slightly problematic are the existence of karstic limestone in the middle of the basin, as it is known that a significant amount of water is lost and transferred to neighbourhood catchments. Because J2000g is not able to account for such features a moderate overprediction of the runoff in the central and lower part compared to the measured hydrograph could be expected. In the context of the objectives of this study this is no too problematic, since only the change in runoff, resulting from changed climate conditions, is analysed and not the absolute runoff.

For the comparison and analysis of the climate change scenarios streamflow for the three gauges Gräfinau-Angstedt (408 m a.s.l., Ac: 155 $km^2$), Mellingen (223 m a.s.l., Ac: 627 $km^2$) and Niedertrebra (133 m a.s.l., Ac: 894 $km^2$) was calculated. For the analysis the computed runoff was aggregated to long term monthly mean values and compared to those of the reference period 1970 to 2000. The catchment of the river Ilm and the location of the three gauges are shown in Fig. 6.

Figure 7 shows the simulated long term mean monthly runoff (blue line) for the reference period 1970–1990 and the two climate scenarios A2 and B1 for 2070–2100 for the three gauges of the river Ilm. The upper plot of the figure shows the large increase of runoff for both climate scenarios in the winter and spring months at gauge Gräfinau-Angstedt caused by the higher runoff generation in the mid-mountain region. During summer the hydrographs of the future scenarios are slightly below the one of the reference period due to higher AET and lower rainfall. The rise of the hydrograph in fall is lower for the two scenarios compared to the reference simulation.

In the middle gauge Mellingen the runoff of the scenarios in winter is slightly above the one from the reference period. In spring summer and fall significant lower runoff values were computed. At the lower gauge Niedertrebra the scenario hydrographs are always below the one of the reference period indicating a strong decrease of runoff in particular during spring, summer and fall.

The comparison of the streamflow of the two scenarios show that the simulated hydrographs are very similar in their dynamics and their volume. Only in March some larger deviations occur which probably are related to snow accumulation and snow melt. The changing form of the hydrograph from the reference period to the two scenarios in December to March is also related to snow accumulation. In the reference period a longer lasting snow cover, which melts in March and April, in the southern



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part of the catchment is a common feature. This is reflected in the hydrograph by the local depression caused by relative low runoff values in January and February. This feature is not longer existent in the scenario hydrographs as longer periods of snow accumulation will not occur any more due to higher winter temperatures.

The example of the river Ilm shows that the predicted climate change will have significant impact on the runoff dynamics in Thuringia. In the higher regions a significant increase of the streamflow will occur in winter and spring whereas in summer and fall the streamflow will decrease in particular in the lowland regions.

## 5 Considerations about uncertainty

The study presented here contains a large amount of uncertainty from various sources. In this section we will look at those sources in a descriptive and more qualitative way, as a precise quantification is not possible for all parts.

First of all it has to be noted, that the results produced by climate models for the future are not precise predictions. Moreover they should be considered as prognosis which were computed based on specific assumptions about the global development in the next 100 yrs. Various factors with a uncertain future development are involved in the evolution and change of climate. This implicates that the climate scenarios are only more or less likely trends based on our current knowledge and perception (UBA, 2007a).

The results of climate models itself, which are used to calculate the scenarios, are of course also uncertain to some degree. Even if the global circulation model are continuously enhanced, does multi-model ensemble simulation produce more reliable results than every single models can (Randall et al., 2007). IPCC accounts for this uncertainty of single models by the use of the results of 23 models to base their assumptions of the effect of climate change. Because of the regional character of this study such an approach was not feasible due to missing regional climate model results.

For regional studies as the one presented here only a limited number of models exist



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which can be used and ensemble prediction is not possible. The regional models are introducing again uncertainty by their downscaling or redistribution approaches. The regionalisation model WETTREG is a statistical model based on the physical relations in the atmosphere of the past and present. With this information synthetical time series are produced and projected into the future. The quality of this projection can not be quantified precisely. As WETTREG is based on simulation results of the global model ECHAM5/MPI-OM any uncertainty of this global model is also contained in the regional one (Zebisch et al., 2005).

Another source of uncertainty of the WETTREG climate data is the low density of climate stations (see Fig. 2) which provide data for the area of Thuringia. Only 7 of the 33 climate stations used for the simulations in this study were lying inside the state boundaries. In particular the mid-mountain range is under-represented by the station distribution. Hereby, the regionalisation of the climate values temperature, relative humidity, wind speed and sunshine duration is based on very less data in some regions which results in an increased amount of uncertainty. Fortunately the distribution of precipitation station is much more dense. Around 100 of the 300 stations were located in Thuringia and are distributed sufficient in space all over the area.

The hydrological modelling with J2000g is of course also a source of uncertainty, because of the simplified model concept which is not integrating all processes in all details. The simple concept on the other hand results in a limited number of calibration parameters which makes the modelling and the parameter estimation a transparent process. A detailed investigation of the uncertainty and parameter sensitivity of J2000g was carried out and will be presented in this issue soon. This study showed that the calibrated model is able to reproduce the hydrological conditions in selected subbasins quite well and that the uncertainty of the results are in a range which allows a use of the model for long term trend analysis as presented here.

Alas, there are other factors which might be relevant if predictions and trends for the next 100 yrs are calculated. First of all, the model assumes that the landuse/landcover will remain constant from 2000 to 2100 without any change. It is very likely that the climate change will have impact on landuse and landcover, which is impacting the hydrological dynamics. The same is true for the soil physical properties, which will very likely also change in the next 100 yrs because of changing climate, landuse and weather conditions. Integration of such likely changes could result in more reliable model results but the assumptions itself about such changes would again introduce a significant and hard to quantify amount of uncertainty.

The large amount of uncertainty in the different parts of the methodology is limiting the results of this study to some extent. Unfortunately it is not possible to quantify all different sources of this uncertainty precise. Anyway, assuming that the input data from the climate model is showing a reliable trend, it can be expected that the trend computed with the methodology and tools used here is also a likely projection of the future.

## 6 Conclusions

In this study the IPCC emission scenarios A2 and B1 in their regional impact on temperature, precipitation, evapotranspiration and runoff generation in Thuringia for the time frame 2070–2100 were analysed. The analysis showed trends which can be summarized as follows:

The predicted temperature increase due to climate change will have impact on other climatological, meteorological and hydrological processes. Both scenarios showed an increase in temperature which is stronger in scenario A2. In the temporal distribution the winter months will experience the larger impact with temperature increases of 3–4°C.

Annual precipitation amounts showed nearly now change if considered for the entire state area, but a significantly changing temporal and spatial distribution was simulated. This change will result in more rainfall in the winter months and less in summer and fall. During winter the higher elevation areas will experience the strongest increase, whereas the low lands will be less affected.



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The increase of the temperature and the change in precipitation will have impact on the actual evapotranspiration (AET). For AET an increase in particular in summer and fall was computed whereas the AET rates in winter and spring will not change significantly. The increase will mainly be located in the higher elevation areas because these regions the necessary water is available. In the low lands only a slight increase of AET was computed due to limited water availability.

The changing climate conditions will have impact on the runoff generation and streamflow production in Thuringia. The higher precipitation rates in the mid-mountain regions in winter will lead to an increased runoff generation and streamflow production. Because of the rise in temperature it is very likely that longer lasting seasonal snow covers will occur less often or will vanish completely in Thuringia. In the low-land regions the runoff generation can be expected to decrease significantly because of lower precipitation and slightly higher actual evapotranspiration rates. This is in particular true for the summer and fall. During these seasons Thuringia is already a very dry region of Germany, which will be even more intensified in the future. This could also be shown for the streamflow in the lower parts of the river Ilm catchment.

It is indisputable that the presented study and the derived trends carry a large amount of uncertainty which is obvious but unfortunately not easy to quantify. The uncertainty results from various sources including the climate model, the hydrological models and its input data, but also the climate scenarios and the assumptions such scenarios are based on. Beside the changing weather conditions due to climate change there are other additional side effects e.g. on the landuse or soil physical properties, which will also have impact on the hydrological processes but which are very hard to predict precisely.

Assuming that at least the overall trend and direction worked out in this study are correct, the predicted climate change will have significant impact on the hydrological dynamics and the water availability in Thuringia. Such impact, caused by the changed seasonal and spatial precipitation pattern and amount, enhanced by the increased evapotranspiration rates, can be summarised as a likely intensification of the extremes:

Floods in winter and severe dry spells in summer.

*Acknowledgements.* The authors thanks the Thuringian Environment Agency (TLUG) for funding and D. P. Boyle from the DRI, Reno, Nevada for valueable advises and proof reading of parts of the mauscript.

## References

Allen, R. G., Pereira, L., Raes, D., and Smith, M.: Crop evapotranspiration: Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper, 56, 1998. 4044

Arnell, N. W.: Effects of IPCC SRES Emissions Scenarios on River Runoff: A Global Perspective, Hydrol. Earth Syst. Sci., 7, 619–641, 2003, http://www.hydrol-earth-syst-sci.net/7/619/2003/. 4039

Bronstert, A., Kolokotronis, V., Schandt, D., and Straub, H.: Vergleich und hydrologische Wertung regionaler Klimaszenarien für Süddeutschland, Hydrologie und Wasserwirtschaft, 50, 270–287, 2006. 4039

Covey, C., AchutaRao, K. M., Cubasch, U., Jones, P., Lambert, S. J., Mann, M. E., Phillips, T. J., and Taylor, K. E.: An Overview of Results from the Coupled Model Intercomparison Project (CMIP), Global Planet. Change, 37, 103–133, 2003. 4041

Duan, Q., Sorooshian, S., and Gupta, V. K.: Optimal Use of the SCE-UA Global Optimization Method for Calibrating Catchment Models, J. Hydrol., 158, 265–284, 1994. 4046

Eckhardt, K. and Ulbrich, U.: Potential Impacts of Climate Change on Groundwater Recharge and Streamflow in a Central European Low Mountain Range, J. Hydrol., 284, 244–252, 2003. 4039

Gabriel, B., Ziegler, G., and Jacobs, H.: Das Festgesteinsmodell GEOFEMLAW als Grundlage für die neue Methodik der Grundwasserneubildungsberechnung im Festgesteinsbereich, Wasserwirtschaft – Wassertechnik, 2, 33–36, 1986. 4043

Gabriel, B., Jacobs, H., and Ziegler, G.: Anwendungsbeschreibung GEOFEM light'98, Tech. rep., Thüringer Landesanstalt für Geologie, 1998. 4043

Kralisch, S. and Krause, P.: JAMS – A Framework for Natural Resource Model Development and Application, in: 7th International Conference on Hydroinformatics, HIC, Nice, France, 2006. 4044

Krause, P.: Das hydrologische Modellsystem J2000: Beschreibung und Anwendung in groen Flueinzugsgebieten, Schriften des Forschungszentrum Jülich: Reihe Umwelt/Environment, Band 29, 2001. 4044

Krause, P.: Quantifying the Impact of Land Use Changes on the Water Balance of Large Catchments using the J2000 Model, Phys. Chem. Earth, 27, 663–673, 2002. 4044

McAvaney, B. J., Covey, C., Joussaume, J., Kattsov, V., Kitoh, A., Ogana, W., Pitman, A. J., Weaver, A. J., Wood, R. A., and Zhao, Z.-C.: Climate Change 2001, The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, chap. Model evaluation, 471–523, Cambridge University Press, 2001. 4041

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J., and Zhao, Z.-C.: Climate Change 2007, The Physical Science Basis of Climate Change, Contributions of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, chap. Global Climate Projections, 740–844, Cambridge University Press, 2007. 4041

Menzel, L. and Bürger, G.: Climate Change Scenarios and Runoff Response in the Mulde Catchment (Southern Elbe, Germany), J. Hydrol., 267, 53–64, 2002. 4039

Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, R., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Sinivasan, J., Stouffer, R. J., Sumi, A., and Taylor, K. E.: Climate Change 2007, The Physical Science Basis of Climate Change, Contributions of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, chap. Climate Models and their Evaluations, 589–662, Cambridge University Press, 2007. 4041, 4053

Roeckner, E., Baeuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U., and Tompkins, A.: The Atmospheric General Circulation Model ECHAM5 – Part 1: Model Description, MPI-Berichte, 349, Hamburg, Tech. rep., Max-Planck-Institute for Meteorology, Hamburg, 2003. 4041

UBA: Neue Ergebnisse zu regionalen Klimaänderungen. Das statistische Regionalisierungsmodell WETTREG, Tech. rep., Umweltbundesamt, 2007a. 4040, 4042, 4053

UBA: Neuentwicklung von regional aufgelösten Wetterlagen für Deutschland und Bereitstellung regionaler Klimaszenarios auf der Basis von globalen Klimasimulationen mit dem Regionalisierungsmodell WETTREG auf Basis von globalen Klimasimulationen mit ECHAM5/MPI-OM T63L31 2010 bis 2100 für die SRESSzenarios B1, A1B und A2, Tech. rep., UBA, 2007b. 4040

van Ulden, A. P. and van Oldenborgh, G. J.: Large-scale atmospheric circulation biases and changes in global climate model simulations and their importance for climate change in Central Europe, Atmos. Chem. Phys., 6, 863–881, 2006, http://www.atmos-chem-phys.net/6/863/2006/. 4040

Zebisch, M., Grothmann, T., Schröter, D., Hasse, C., Fritsch, U., and Cramer, W.: Climate Change in Germany – Vulnerability and Adaptation of Climate sensitive Sectors, UBA, Germany, 2005. 4054



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**Table 1.** J2000g parameter values from SCE optimisation for different catchments together with best Nash-Sutcliffe efficiency (NSE) achieved and the efficiencies obtained with the average parameter set (NSE avg).

| | Bode | Ilm | Wilde Gera | Gera | Zahme Gera | Hasel | Roda | Orla |
|---|---|---|---|---|---|---|---|---|
| Ac ($km^2$) | 104 | 155 | 13 | 175 | 65 | 320 | 254 | 255 |
| LVD | 2.80 | 1.54 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| GWK | 4.09 | 3.38 | 2.32 | 2.96 | 3.24 | 4.14 | 8.07 | 6.76 |
| Tbase | −4.37 | −4.79 | −4.69 | −4.61 | −4.61 | −3.91 | −5.44 | −4.34 |
| TMF | 1.33 | 8.73 | 9.99 | 4.40 | 5.39 | 9.99 | 1.00 | 1.22 |
| FCA | 18.78 | 19.99 | 1.00 | 2.15 | 20.00 | 2.64 | 12.62 | 10.79 |
| ETR | 0.06 | 0.02 | 0.99 | 0.58 | 0.01 | 0.59 | 0.03 | 0.04 |
| NSE | 0.85 | 0.75 | 0.65 | 0.84 | 0.75 | 0.80 | 0.30 | 0.51 |
| NSE (avg) | 0.75 | 0.73 | 0.55 | 0.81 | 0.77 | 0.77 | 0.22 | 0.36 |



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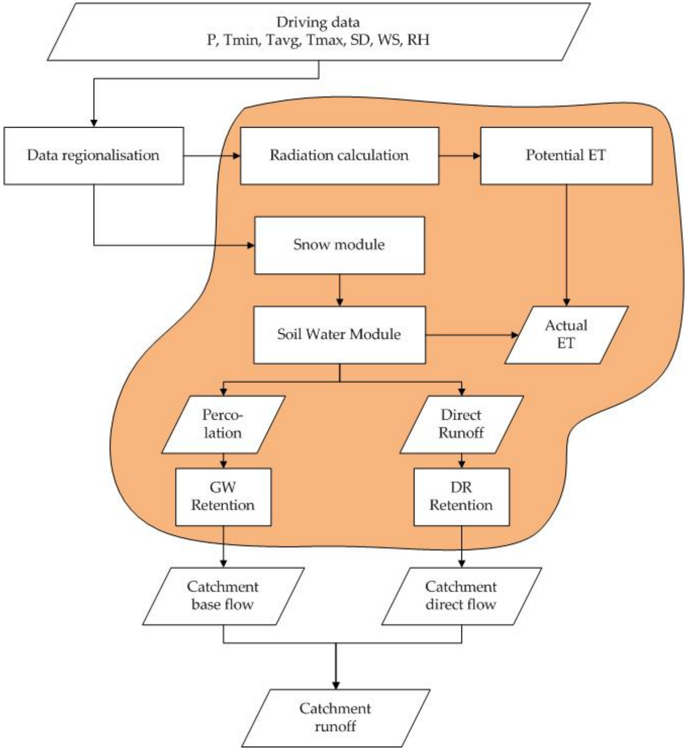


**Fig. 1.** The principal layout out the model J2000g. The orange area symbolizes a modelling unit.




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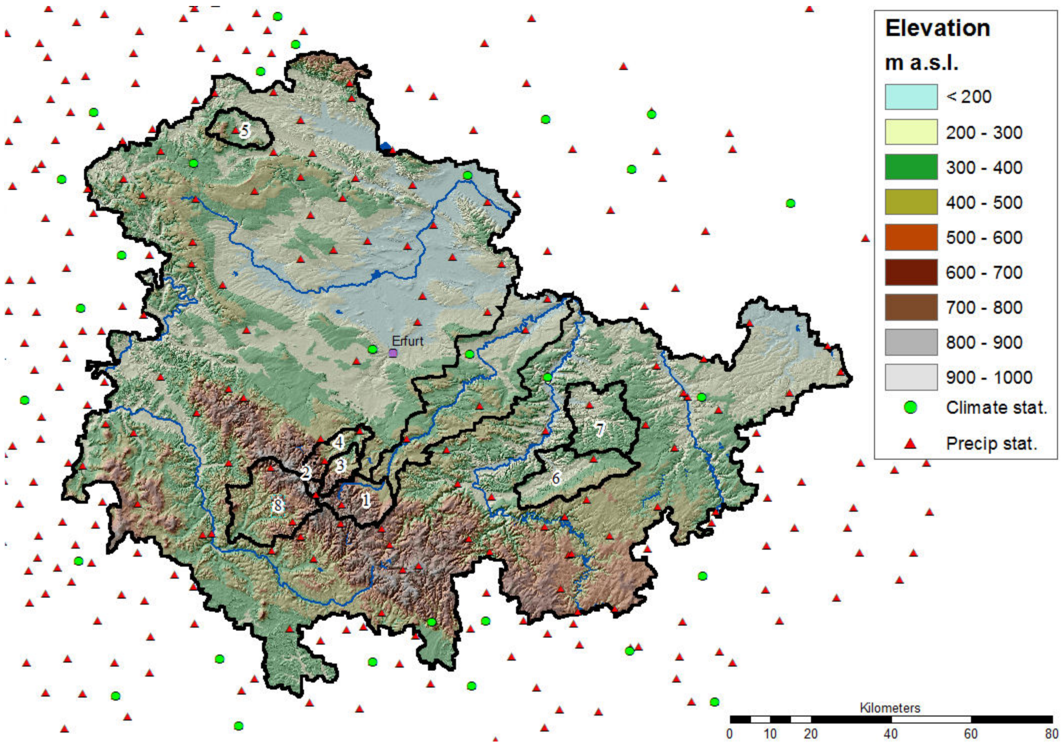


**Fig. 2.** The state Thuringia in Germany. The map shows the elevations above sea level and the location of climate and precipitation stations used for this study. The map shows also the subbasins used for calibration marked with numbers (1 Upper Ilm, 2 Wilde Gera, 3 Zahme Gera, 4 Gera, 5 Bode, 6 Orla, 7 Roda, 8 Hasel). Additionally the catchment of the entire river Ilm is outlined, which is discussed later in the paper.



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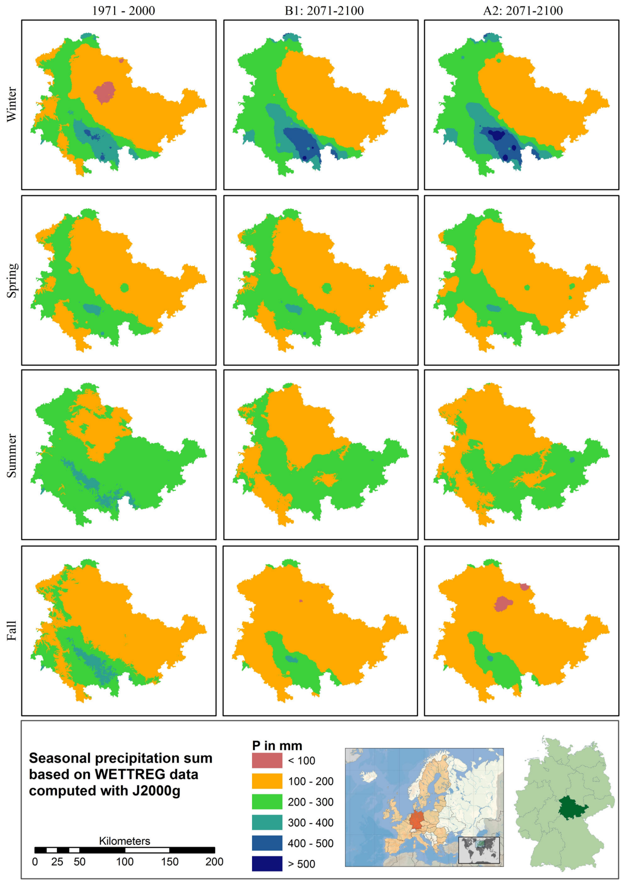


**Fig. 3.** Spatial distribution of seasonal precipitation sums. First column shows the regionalised values of 1970–2000, second and third column the regionalised values for the B1 and A2 scenario for the time frame 2071–2100.



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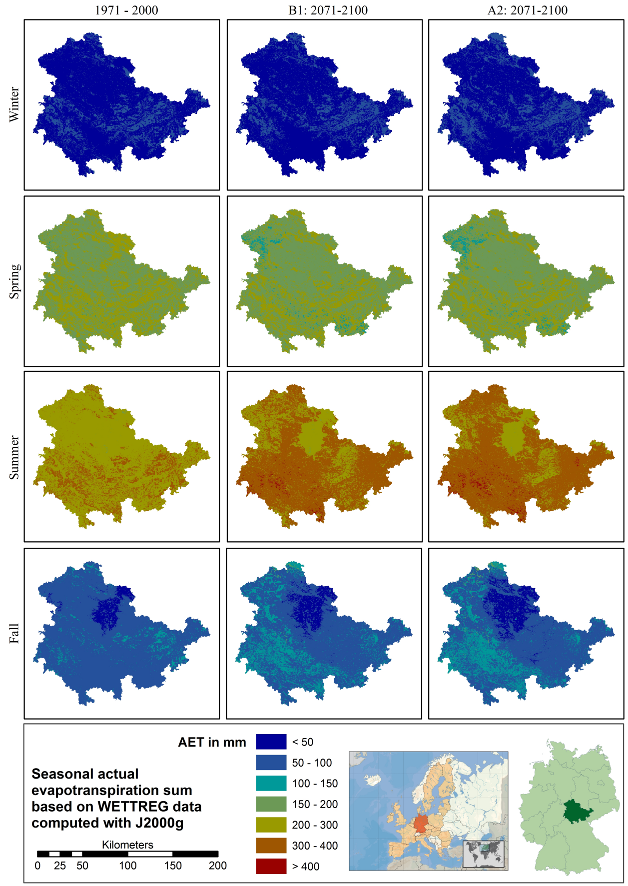


**Fig. 4.** Spatial distribution of seasonal actual evapotranspiration sums. First column shows the computed values of 1970–2000, second and third column the computed values for the B1 and A2 scenario for the time frame 2071–2100.

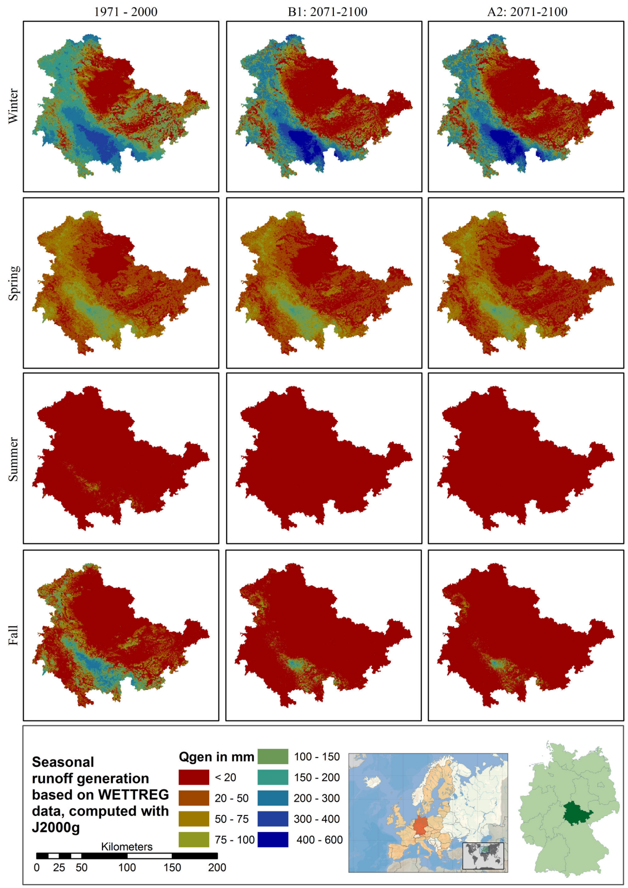


**Fig. 5.** Spatial distribution of seasonal runoff generation. First column shows the computed values of 1970–2000, second and third column the computed values for the B1 and A2 scenario for the time frame 2071–2100.



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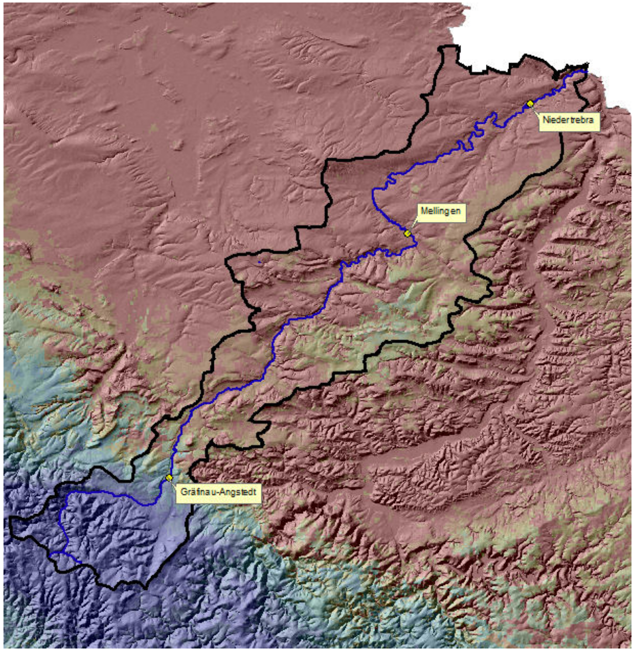


**Fig. 6.** The Ilm basin with the three runoff gauges Gräfinau-Angstedt, Mellingen, and Niedertebra. The background shows the long term mean runoff generation in winter of the scenario A2.

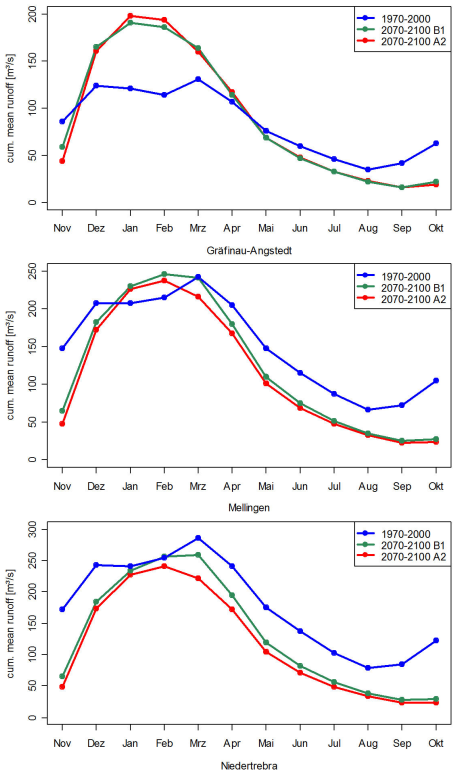


**Fig. 7.** Long term mean monthly runoff values for three gauges of the river Ilm. The blue line shows the time frame 1970–2000, whereas the red and green line shows the runoff computed for 2070–2100 with the WETTREG data for the climate scenarios B1 and A2.