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Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range

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Abstract

General Circulation Models simulate significant changes of temperature and precipitation over Europe as part of the anthropogenic climate change. In this study, the impacts of climate change on groundwater recharge and streamflow in a central European low mountain range catchment are investigated using a conceptual eco-hydrologic model, a revised version of the Soil and Water Assessment Tool (SWAT). To improve the reliability of our simulations, we compile plant physiological studies concerning the influence of elevated ambient CO_2 concentrations on stomatal conductance and leaf area. Using this information to parameterise the model, we evaluate the impacts of two climate change scenarios, which represent a wide range of assumptions concerning future greenhouse gas emissions and climate sensitivity. The resulting effects on mean annual groundwater recharge and streamflow are small, as increased atmospheric CO_2 levels reduce stomatal conductance thus counteracting increasing potential evapotranspiration induced by the temperature rise and decreasing precipitation. There are, however, more pronounced changes associated with the mean annual cycle of groundwater recharge and streamflow. Our results imply that due to the warming a smaller proportion of the winter precipitation will fall as snow. The spring snowmelt peak therefore is reduced while the flood risk in winter will probably increase. In summer, mean monthly groundwater recharge and streamflow are reduced by up to 50% potentially leading to problems concerning water quality, groundwater withdrawals and hydropower generation.

Keywords: Climate change; Groundwater recharge; Streamflow; Stomatal conductance; Leaf area

1. Introduction

In the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001) it is stated that 'emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate'. This conclusion is supported by the Europe ACACIA project (Parry, 2000). In this project, it has been shown that there is a high probability that the anthropogenic climate change signal over Europe will stand out significantly from the natural long-term climate variability.

Potential consequences of an elevated atmospheric CO_2 concentration are not only higher mean temperatures, but also changes in the temporal and spatial

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distribution of precipitation accompanied by an increased risk of both heavy rainfall events and droughts. If we want to quantify the effects of these changes on hydrological processes at the catchment scale we need models relying on a physically based description of the relevant processes. The application of empirical formulae as in the study of Krüger et al. (2001) can be misleading since empirical formulae have been developed for present day climate.

The model being used in this study is the version SWAT-G (Eckhardt et al., 2002) of the 'Soil and Water Assessment Tool' SWAT (Arnold et al., 1998). SWAT was developed to assess the impacts of land use changes on water supplies, erosion and nonpoint source pollution in meso- to macroscale catchments. The model includes approaches describing how CO_2 concentration, precipitation, temperature and humidity affect plant growth, evapotranspiration, snow and runoff generation, and therefore is also used to investigate climate change effects (Fontaine et al., 2001; Stonefelt et al., 2000; Cruise et al., 1999; Rosenberg et al., 1999; Hanratty and Stefan, 1998).

However, a review of studies reporting on the impacts of elevated ambient CO_2 concentrations on stomatal conductance and leaf area reveals that the model approaches describing plant transpiration in a CO_2 enriched atmosphere have to be revised. In this paper, we provide the data to update the model in this respect and use the revised model to carry out a hydrologic climate-impact study for a central European low mountain range catchment. A comparison of the results obtained with the original and the revised model approaches shows the importance of an adequate description of the complex response of the land cover to changes in atmospheric boundary conditions.

2. Description of the model SWAT-G

SWAT-G is a conceptual distributed model operating on a daily time step. Using a distributed model, a catchment is divided into explicitly parameterised smaller areas (subbasins and hydrotopes), which are assumed to be homogeneous with respect to their hydrologic properties. In the case of SWAT-G, raster maps of a digital elevation model, land cover and soil are needed for this purpose.

SWAT-G uses both empirical and physically based approaches as the Penman–Monteith method (Monteith, 1965) for calculating the potential evapotranspiration. Therefore, SWAT-G requires observational data of precipitation, temperature, solar radiation, wind speed and dew point as input. If daily mean temperature is less than 0 °C it is assumed that precipitation falls as snow. Precipitation in fluid form is first reduced by canopy evaporation. Water reaching the ground or set free by snowmelt partially flows off as surface runoff, which is calculated by a modified curve number approach (USDA-SCS, 1972). The remaining water infiltrates the soil which can be divided into several layers. Downward flow, or percolation, occurs if field capacity of a soil layer is exceeded and if the layer below is not saturated. If the temperature in a particular layer is below the freezing point no redistribution is allowed from that layer. Lateral subsurface flow (interflow) in the soil profile is calculated simultaneously with redistribution. A kinematic storage model (Sloan and Moore, 1984) is used to predict lateral flow in each soil layer. Furthermore, soil water is diminished by evaporation from the soil surface and transpiration of plants. Percolation from the bottom of the soil profile recharges the shallow aquifer. The shallow aquifer is a linear reservoir which releases water into surface water bodies (baseflow) and by seepage to the deep aquifer.

The part of SWAT-G describing plant growth is a simplification of the EPIC crop model (Williams et al., 1984). Growth can only occur if the daily mean temperature exceeds a plant-specific base temperature. The temperature excess, counted in 'heat units', is accumulated over time. The phenological development of plants is controlled by comparing the actually accumulated heat units to the predefined heat unit sum required for maturity of the plant. Stress factors, i.e. deviations of temperature from its optimum value for growth, and differences between demand and supply of water and nutrients, restrain the growth.

Canopy evaporation is a function of potential evapotranspiration, maximum interception capacity and the ratio of actual and potential maximum leaf area index. Plant water uptake from the soil is simulated as a function of potential evapotranspiration, leaf area index and rooting depth and is limited by soil water content.

3. Stomatal conductance and leaf area in a CO_2 enriched atmosphere

In forest stands of central European low mountain ranges about 70–90% of the precipitation is evapotranspirated, mainly by canopy evaporation and plant transpiration (Wohlrab et al., 1992). These two processes, however, are determined by leaf area and stomatal conductance. Stomata are small apertures on the leaf surface whose conductance for water vapor depends on environmental conditions as atmospheric CO_2 concentration or vapor pressure deficit. We compile results of plant physiological studies showing how a climate change might influence the model parameters stomatal conductance and leaf area in order to improve the reliability of our simulations.

3.1. Stomatal conductance

Morison (1987) suggested that a doubling of the atmospheric CO_2 concentration leads to a decrease in stomatal conductance of crops by about 40%. Wand et al. (1999) reported a less pronounced effect for wild grasses, a decrease in stomatal conductance of C3 grasses by 24% and of C4 grasses by 29%. Field et al. (1995), reviewing measurements in 23 tree species, found an average decrease in stomatal conductance of 23% as a reaction to a doubling of the ambient CO_2 concentration. Saxe et al. (1998) pointed out that the decrease for coniferous forest is smaller than for deciduous forest. This was affirmed by Medlyn et al. (2001) who evaluated 13 long-term, field-based studies of the effects of elevated CO_2 concentration on European forest tree species. Their analysis indicated an average decrease of 21% in stomatal conductance in response to growth in elevated CO_2 concentration with a stronger effect on deciduous trees (−24%) than on coniferous trees (−8%). There was no evidence of adaptation which would attenuate this effect over longer periods.

Stomatal conductance also depends on vapor pressure deficit. Elevated air temperature and reduced transpiration as a consequence of the decreased stomatal conductance will increase vapor pressure deficit. Stomata will then further close to reduce water loss. In SWAT, the approach of Stockle et al. (1992) is used to account for this effect. If vapor pressure deficit exceeds a threshold value, stomatal conductance is linearly reduced. Medlyn et al. (2001) assumed a linear response to vapor pressure deficit as well which, according to their analysis, was not altered by an elevated atmospheric CO_2 concentration. We may therefore conclude that the approach used in SWAT to reduce stomatal conductance for increased vapor pressure deficit can be left unchanged.

3.2. Leaf area

Concerning wild grass, Wand et al. (1999) showed that a doubled atmospheric CO_2 concentration induces an average increase in leaf area of 15% for C3 species and of 25% for C4 species. Pritchard et al. (1999) evaluated 63 observations of total leaf area per plant and concluded that leaf area of crop species increases the most (+37%) compared to wild, nonwoody species (+15%) and tree species (+14%). Yet, Norby et al. (1999) pointed out difficulties when transferring experimental results concerning leaf area of trees to closed-canopy forest where potential growth is more restricted. Therefore, we assume a smaller increase in leaf area index of deciduous and coniferous forest (+7%) without a possibility of validation. More leaf area would increase the evapotranspiration and, hence, lead to less groundwater recharge and streamflow, while a stronger reduction of leaf growth would enhance groundwater recharge and streamflow compared to our results.

3.3. Summary and remarks

Based on Morison (1987), Wand et al. (1999), Pritchard et al. (1999) and Medlyn et al. (2001) we suppose that a doubled atmospheric CO_2 concentration changes stomatal conductance and leaf area index as indicated in Table 1. The value for the leaf area increase of pasture is the mean of the values for C3 and C4 grasses specified by Wand et al. (1999). Range land is supposed to assume a medial position between pasture and forest. We assume that for CO_2 concentrations as considered in the present study the reduction in conductance is linear (Morison and Gifford, 1983). A linear relationship is also supposed for the increase in leaf area.

It has to be pointed out that in the original version of the model SWAT (SWAT2000 and older versions)

Table 1
Assumed response in maximum stomatal conductance and leaf area index to a doubled atmospheric CO_2 concentration

Land cover	Stomatal conductance (%)	Leaf area index (%)
Deciduous forest	−24	+7
Coniferous forest	−8	+7
Pasture	−25	+20
Range land	−20	+15
Arable land	−40	+37

a doubled CO_2 concentration leads automatically to a general decrease of stomatal conductance by 40% irrespective of the land cover. In catchments that are not solely covered by arable land, the reduction of stomatal conductance therefore is overestimated. Moreover, the model does not take into account the leaf area increase. It is necessary to update the model in these aspects. We will show this in Section 6 by comparing results obtained with the original model approaches and results that were calculated with the revised assumptions concerning changes in stomatal conductance and leaf area. To this purpose, we modified the source code of the model so that stomatal conductance is no more model-internally decreased if the CO_2 concentration rises. Instead, all changes to stomatal conductance and leaf area were explicitly defined by entries in the central plant parameter database of the model, the input file 'crop.dat'.

4. Description of the catchment and of its representation in the model

The effects of a climate change are investigated for the Dill catchment which is situated in the southeast of the Rhenish Massif in Germany. The coordinates of the catchment outlet (streamgauge Aßlar) are 50°35′N, 8°28′E. The catchment area measures 693 km^2 with an elevation range from 155 to 694 m a.s.l. and mean slope steepness of 14%. In the model, the catchment is subdivided into 48 subbasins. Within these subbasins, 764 hydrotopes are defined. Hydrotopes are characterised by unique combinations of land cover and soil and are assumed to be homogenous with respect to their hydrologic properties.

Land cover is dominated by forest. Thirty percent of the catchment area is covered by deciduous forest, 26% by coniferous forest, 22% by pasture, 9% by range land, 8% by settlement, and 5% by arable land. On the slopes and hilltops, the soil consists mainly of shallow cambisols over a bedrock of schist and greywacke. This hard rock base has to be passed by the percolating water before it can recharge the groundwater. In the catchment model it is represented by an additional layer of high bulk density and low hydraulic conductivity underneath the corresponding soils. In the valleys, gley- and fluvisols are also found although in only a few percent of the area.

The meteorological input data was obtained from the Deutsche Wetterdienst (German Meteorological Service). Daily precipitation was observed at nine locations within the catchment (Fig. 1). It was regionalised using Thiessen polygons. Furthermore, the model needs daily temperature and monthly means of wind speed, radiation and dew point. These meteorological variables were measured at only one station, respectively: temperature, wind speed and dew point at the synoptic site of Dillenburg (50°44′N, 8°17′E), and radiation in Gießen (50°34′N, 8°41′E). Mean annual cycles of the gradients describing the changes of precipitation and temperature with elevation were calculated and used to linearly correct the observed daily precipitation and temperature values for the elevation difference between observation wards and the considered catchment part, respectively. Mean annual air temperature is 6.4 °C. Mean annual precipitation amounts to 955 mm.

The parameterisation of the catchment model is partially based on a literature review (e.g. McCuen, 1998, for roughness coefficients and curve numbers, and Breuer et al., 2003, for plant parameters). Furthermore, models of three subbasins of the Dill catchment were automatically calibrated. Two of these calibrations are described by Eckhardt and Arnold (2001) and Eckhardt et al. (2003), where the calibration technique and the results of calibration and validation are presented. Only streamflow measurements are available for model calibration and validation. Comparing measured and calculated monthly streamflow at the outlet of the Dill catchment over 30 hydrologic years from 1966 to 1995 (Fig. 2),

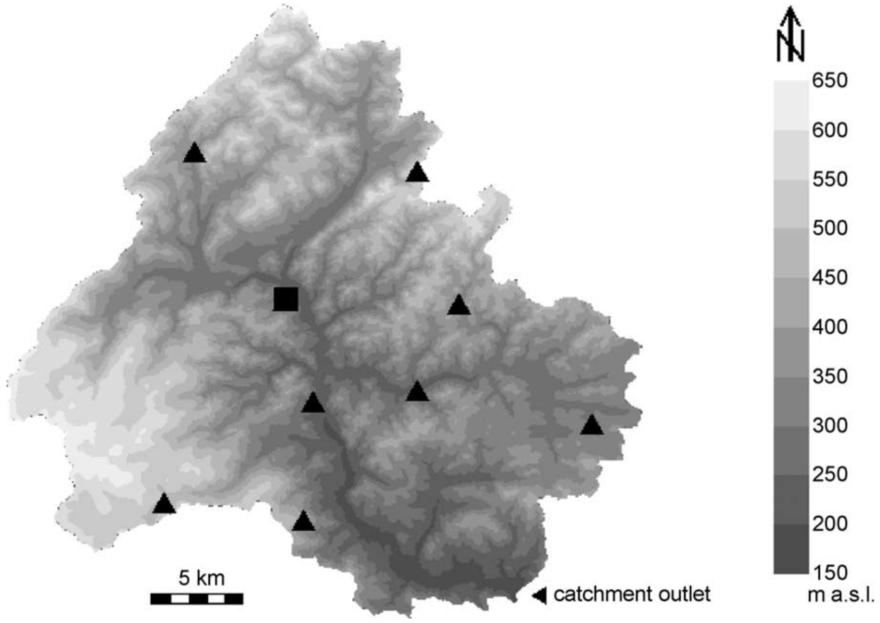

Fig. 1. Topographic map of the Dill catchment. The square marks the site where precipitation, temperature, wind speed and dew point were logged, the triangles mark those sites where only precipitation was measured. The synoptic site of Gießen where the solar radiation has been observed lies outside the display window.

a model efficiency (Nash and Sutcliffe, 1970) of 0.93 is obtained. Streamflow consists mainly of interflow. Only 14% of the calculated streamflow are baseflow or groundwater discharging into the stream, respectively.

5. Climate change scenarios

To define the climate scenarios we follow the approach to adjust observed time-series of daily climate for a baseline period by estimated differences between GCM simulations of current and future climate.

We use climate change scenarios from the Europe ACACIA project (Parry, 2000) whose results entered into the IPCC Third Assessment Report (IPCC, 2001). The scenarios are based on different assumptions concerning future greenhouse gas emissions (Nakicenovic et al., 2000) and climate sensitivity (= long-term change in global mean surface temperature following a doubling of atmospheric equivalent CO_2 concentration). Using simulations with five GCMs, four different climate change scenarios referring to a baseline period from 1961 to 1990 were generated. We consider projections for the period from 2070 to 2099 that were calculated for the scenarios termed B1-low and A2-high. These scenarios are the two extremes of the four ACACIA scenarios thus

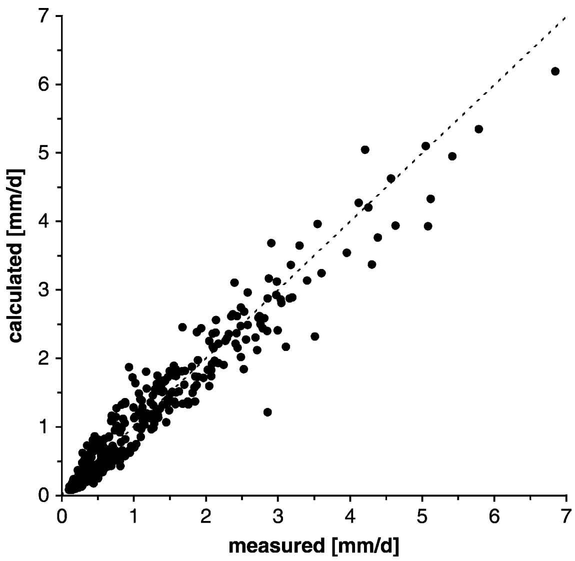

Fig. 2. Scatter plot of measured and calculated monthly means of the streamflow at the outlet of the Dill catchment during the baseline period.

indicating the range of potential responses to climate change.

Scenario B1-low is based on the assumption that the atmospheric CO_2 concentration increases by about 50% until 2080. 'low' stands for a climate sensitivity of 1.5 °C. In scenario A2-high, the CO_2 concentration approximately doubles until 2080. 'high' indicates a climate sensitivity of 4.5 °C. We use mean winter and summer temperature and precipitation changes that were calculated for a grid box of 2.50° × 3.75° located around 50.0°N/7.5°E. By interpolation with a sinusoidal function complete annual cycles of monthly mean changes were generated (Table 2). Note that in scenario B1-low the precipitation changes do not exceed a model-based estimate of natural climate variability by more than two standard deviations and, therefore, are considered to be zero.

For want of meteorological input data before 1965, the baseline period of the model simulations is slightly shifted against the baseline period of the climate change scenarios. The simulations start with January 1965. Ten months (January 1965 to October 1965) serve as 'warm-up' period for the model. The baseline period of the simulations covers the subsequent thirty hydrologic years beginning in November 1965 and ending in October 1995.

Table 2
Monthly means of temperature and precipitation changes for the ACACIA scenarios B1-low and A2-high (grid box located around 50.0°N/7.5°E, time-slice 2070–2099)

Month	Temperature change (°C)		Precipitation change (%)	
	B1-low	A2-high	B1-low	A2-high
J	+1.51	+4.94	±0	+13
F	+1.49	+4.88	±0	+11
M	+1.45	+4.78	±0	+8
A	+1.40	+4.65	±0	+3
M	+1.35	+4.51	±0	−6
J	+1.31	+4.42	±0	−19
J	+1.30	+4.38	±0	−23
A	+1.31	+4.42	±0	−19
S	+1.35	+4.51	±0	−6
O	+1.40	+4.65	±0	+3
N	+1.45	+4.78	±0	+8
D	+1.49	+4.88	±0	+11

6. Results

6.1. Baseline period

Fig. 3 shows the mean annual cycles of observed and simulated streamflow at the catchment outlet over the hydrologic years from 1966 to 1995. Streamflow is lowest at the end of summer and highest in December. In March, snowmelt causes a secondary maximum. These characteristics are well reproduced by the model. The difference between the measured and calculated mean annual streamflow amounts to only 3% (measured: 437 mm/a, calculated: 425 mm/a).

6.2. Scenario B1-low

There are different, partially counteracting effects: On the one hand, the temperature rise increases the potential evapotranspiration, and the leaf area increase allows for more interception and transpiration. On the other hand, the reduction of stomatal conductance decreases the transpiration. Therefore, mean groundwater recharge and streamflow only slightly decrease by 3 and 4%, respectively (Table 3).

As a result of the temperature rise, snowfall is reduced. Because more winter precipitation falls as rain, groundwater recharge and streamflow in January and February increase, while the secondary maximum of groundwater recharge and streamflow caused by snowmelt in March disappears (Figs. 4 and 5). The growing season begins about one week earlier than in

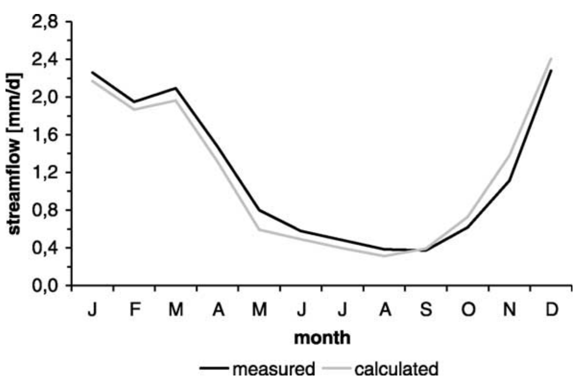

Fig. 3. Mean annual cycle of streamflow, measured at the outlet of the Dill catchment and calculated with the model SWAT-G.

Table 3
Calculated mean groundwater recharge and streamflow in the baseline period and the scenarios

	Groundwater recharge	Streamflow
Baseline period	184 mm/a	425 mm/a
Scenario B1-low	179 mm/a (−3.0%)	408 mm/a (−4.1%)
Scenario A2-high	171 mm/a (−7.5%)	396 mm/a (−6.9%)

the baseline period (Fig. 6). This further contributes to an earlier recession of groundwater recharge and streamflow in spring. The increase of groundwater recharge and streamflow in fall is delayed because of the enhanced desiccation of the soil during summer.

If we do not use the revised model but the original model approaches describing plant growth and transpiration in a CO_2 enriched atmosphere as implemented in SWAT2000 and older model versions, the observed effects are weaker. The overestimated reduction of stomatal conductance does compensate too much for the effect of the temperature rise so that the mean groundwater recharge and streamflow decrease by only 0.3 and 1.5%, respectively.

6.3. Scenario A2-high

The same effects as in scenario B1-low are observed, yet intensified by the greater temperature rise and the changes in precipitation. Not only is snowfall reduced in favour of rain but also the total amount of winter precipitation increases. Therefore, winter (DJF) streamflow is enhanced by more than 10% (Fig. 5). In spring, the decreased snowmelt, the temperature rise and the earlier beginning of the growing season reduce groundwater recharge (Fig. 4) and streamflow (Fig. 5). In summer (JJA), both enhanced potential evapotranspiration together with decreased precipitation reduce groundwater recharge and streamflow by more than 50%. Due to the enhanced soil moisture deficit in summer, groundwater recharge remains reduced throughout fall. Again, as in scenario B1-low, these effects are underestimated if the model approaches for the reduction of stomatal conductance and the increase of leaf area index are not revised. In this case, mean groundwater recharge and streamflow decrease by only about 2.5%.

There is now a more pronounced effect on plant growth as well. Due to the temperature rise by about 4.7 °C, the growing season begins about a month earlier than in the baseline period (Fig. 6). In the baseline period and in scenario B1-low leaf area index attains its maximum in July, in scenario A2-high already in June.

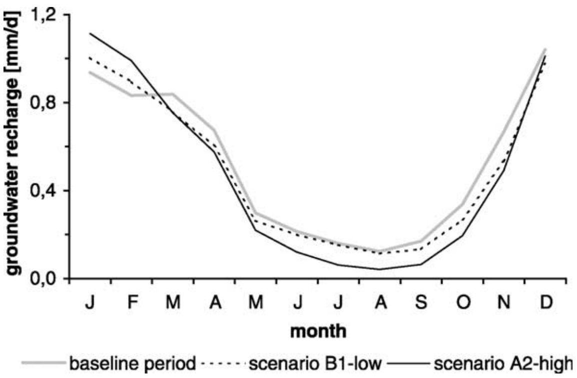

Fig. 4. Calculated mean annual cycle of groundwater recharge in the baseline period and in the scenarios.

7. Discussion

The climate change scenarios were constructed taking into account uncertainty concerning future greenhouse gas emissions, climate sensitivity and

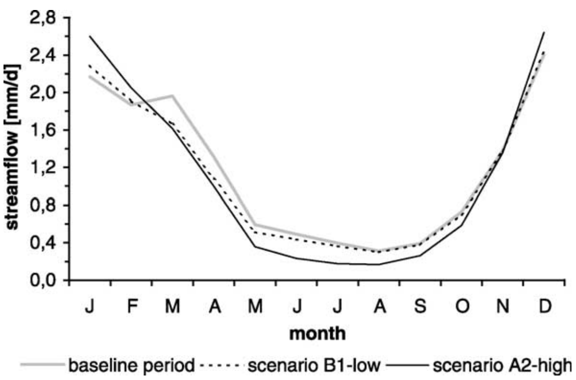

Fig. 5. Calculated mean annual cycle of streamflow in the baseline period and in the scenarios.

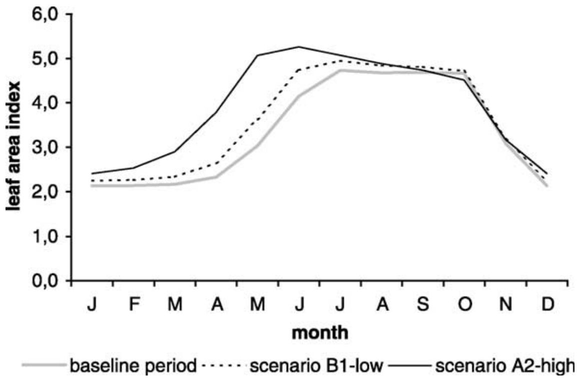

Fig. 6. Calculated mean annual cycle of leaf area index in the baseline period and in the scenarios.

regional climate change response (Parry, 2000). However, other sources of potential errors remain. For example, information on possible changes in the intensity and frequency of precipitation and temperature extremes as well as specifications concerning the other meteorological input variables (wind speed, radiation and dew point) is lacking. We also could not take into account that there are feedbacks between atmosphere and land surface. However, our results are basically confirmed by other studies (see Parry, 2000, for a review).

Rainfall and temperature were modified on a monthly basis for a weak (B1-low) and a high (A2-high) degree of climate modification. In both cases, the effects on annual mean groundwater recharge and streamflow are relatively small. Changes in the intra-annual variability are more pronounced. Except for the month of March, the streamflow changes in scenario B1-low are similar to the differences between the calculated and measured streamflow in the baseline period. Hence, they are uncertain. The changes in scenario A2-high, however, are more significant. Due to the warming, a smaller proportion of the winter precipitation will fall as snow. The spring snowmelt peak therefore is reduced while the flood risk in winter will probably increase. In summer, groundwater recharge and streamflow are potentially reduced by more than 50% (scenario A2-high). Actually, the contribution of sewage plant runoff to total streamflow at the outlet of the Dill catchment amounts to about 17% during dry-weather periods (estimation using ATV, 1995). If streamflow decreases, an increased relative contribution of sewage plant runoff could lead to water quality problems. Furthermore, groundwater withdrawals and hydro-power generation could be negatively affected.

Elevated ambient CO_2 concentrations stimulate the plant growth. Biomass increases and the growing season begins earlier. However, the risk of desiccation injuries increases as well. Changes in land use could additionally affect the catchment water balance. These impacts, however, can only be studied in more comprehensive, integrative research projects.

8. Conclusions

We carried out a regional climate impact study for a European catchment and thereby evaluated the sensitivity of an eco-hydrologic model for the assumed response of plants to elevated CO_2 levels. Using the model SWAT in its original form, the decrease in transpiration induced by an increased atmospheric CO_2 concentration will be overestimated because stomatal conductance is reduced too much and because no leaf area increase is simulated. If the results of recent plant physiological studies are taken into account, more pronounced decreases of groundwater recharge and streamflow are predicted. The present study thus shows the importance of an adequate description of the complex response of the land cover to changes in atmospheric boundary conditions.

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