

Impacts of climate change on mid-European river basin hydrology

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Abstract The impact of climate change on the hydrologic regimes of medium-scale rivers in Europe is investigated in this work. The main aim is to predict hydrological changes at a medium time scale (referring to several decades) for medium-scale river catchments in Europe. A downscaling approach is used to apply GCM data for this: large-scale pressure distribution patterns were classified as a base for conditional statistics of rainfall and temperature data. These were utilized for the calibration of statistical models of local rainfall and temperature. Using appropriate interpolation methods, these data were then used as input for runoff models of medium-scale river catchments in Europe. This method was finally applied to GCM outputs representing a doubled CO₂-scenario. Using the calibration for the historical data delivers a prediction about the impact of climate changes on the local weather parameters and changes in hydrological regimes. Application of the methodology and results are illustrated on the Neckar catchment (Germany) and the Enns catchment (Austria). In both catchments changes in temperature and runoff for the 2 × CO₂-scenario simulations are observed. However, due to the shortness of simulated time-series no detailed conclusions with respect to extreme events are possible.

INTRODUCTION

This paper is about the work on the impact of climate change on the hydrologic regimes of medium-scale rivers in Europe, done during the CCHYDRO project. The main aim of the ongoing CCHYDRO project is to predict hydrological changes at a medium time scale (referring to several decades) for medium-scale river catchments in Europe. The method and some results of the project will be presented. The prediction of changes in seasonal characteristics and in extreme values was one of the main research tasks. Since the CCHYDRO project is still going on, further refinement of methodology and analysis of results will be done. However, this is not expected to produce significant changes in results and their interpretation (Bárdossy *et al.*, 1996, 1998; Diernhofer *et al.*, 1996, 1998).

METHODOLOGY

Global Climate Model output is known to be reliable only for phenomena of at least the same scale as their grid sizes. Since the grid size is actually some hundred

kilometres, a direct use of the data for small and medium-scale climate change impact forecasting is not possible. Furthermore, precipitation is an uncertain parameter of the simulations. Because of this, the first step in this work was the classification of large-scale pressure distribution patterns. In practice only objective automated classification methods could be used, due to the aim to apply this method to GCM output data.

These classifications were the base for conditional statistics of rainfall and temperature for points with historical observations. These conditional statistics were utilized for the calibration of statistical models of local rainfall and temperature. Thus a statistical linkage between large-scale pressure distributions and local weather parameters was established for points with historical observations.

Using appropriate interpolation methods, local point data were then used as input for runoff models of several medium-scale river catchments in Europe. These methods were also applied to GCM outputs representing a doubled CO₂ scenario (2 × CO₂). The calibration for the historical data delivers a prediction about the impact of climate changes on the local weather parameters. When applied to the runoff models the change of hydrological regimes of the river catchments for the GCM scenarios can be predicted.

Circulation pattern classification

In most applications subjective classification schemes such as “Großwetterlagen” (Baur *et al.*, 1944; Hess & Brezowsky, 1969) show better performance than mathematically-based automatic classification like *k*-means-clustering. Therefore, the basic idea of the fuzzy rule-based approach is to build a classification similar to the subjective classification by definition of patterns on the normalized 700 hPa surface and classify observed pressure maps according to these patterns using fuzzy rules (Bárdossy *et al.*, 1995).

For this purpose, 29 circulation patterns (CPs) have been defined manually, aiming to imitate the “Großwetterlagen” definitions. The definitions for the CPs were made on a grid of 5° width covering the area of 40°W–25°E and 35°N–70°N. Every point was assigned to one of five membership functions represented by triangular fuzzy numbers: Very High = (0.6, 1, 1)^T, Medium High = (0.5, 0.8, 1.2)^T, Medium Low = (–0.2, 0.2, 0.5)^T, Very Low = (1, 1, 0.4)^T, Undefined = constant 1. Usually the first four classes have above 2–5 points each in a pattern, the fifth class (undefined) does not influence the calculations and can be ignored. To classify daily pressure observations, the fulfilment for the observed normalized surface is calculated for each point using the membership functions, the results of the four classes are then combined by the use of *l_p*-norm, finally the overall fulfilment is calculated as the simple product of the class-fulfilment.

This delivers a single numerical value of the degree of fulfilment for each day and pattern, the pattern with the best result is chosen as CP type of the day. This way most days can be classified, only a small number have to remain as unclassified, which is treated as an additional CP. Tests on different data sets showed that this fuzzy rule-based classification performs better than other automatic classification, though not achieving the results of the original subjective “Großwetterlagen” classification.

Regional analysis of air movement

Although the CP-type classification describes the large-scale pattern, the regional atmospheric processes which are influenced by the CP type with a certain time lag are disregarded. In an alternative approach regional air movement is estimated from the large grid by identifying regional gradients in the pressure distribution (Diernhofer *et al.*, 1998) and linking this information (additionally with CP types) with local observations. Based on the geopotential heights available for different pressure levels at a few grid points around the basin, the air mass movement is analysed under consideration of the seasonality.

Precipitation and temperature models

A major problem in mathematical description of precipitation is the spatial and temporal intermittence. Dry days occur with high probability and on rainy days a continuous distribution describes the rainfall amounts at a selected location. Therefore, random variables with mixed distributions are required to describe daily precipitation. Because multivariate processes can much more easily be modelled if they are normally distributed, we model the amount of precipitation $Z(t, u)$ for a time t and location u by a transformed normal distributed function $W(t, u)$:

$$Z(t, u) = \begin{cases} 0 & \text{if } W(t, u) \leq 0 \\ W^{5/3}(t, u) & \text{if } W(t, u) > 0 \end{cases} \quad (1)$$

The major problem in fitting this model is that observations are related to $Z(t, u)$ not $W(t, u)$, therefore a simple calculation of the parameters of $W(t, u)$ is not possible but some more complex estimation procedures have to be utilized (Bárdossy & Plate, 1992).

Using local observations at locations u_i the parameters mean $w_j(u_i)$ and variance $\sigma_j(u_i)$ defining the normal distribution $W(t, u_i)$ are modelled conditionally for each CP type j . To model an annual cycle of these parameters they are not calculated as fixed values but represented by a Fourier series. Also temporal and spatial correlation is estimated. To ensure a positive definite spatial correlation matrix, the spatial correlation is represented by a translation invariant function depending only on the distance between two locations.

In contrast to precipitation, daily mean temperature is much less variable in space and much of its variability can be explained from topography. The clear annual cycle has to be taken into account. For this purpose the average elevation of the 700 hPa surface is used as main driving factor of a statistical temperature model. Further factors are the temperatures of previous days, the actual CP type and the areal precipitation considered as an indicator. Including these factors the temperature is modelled as an AR(1) model (Bárdossy *et al.*, 1996).

These two models are utilized for local data. To get areal data for the hydrological model the results are interpolated using kriging with height as external drift.

Runoff model

The rainfall–runoff model (Nachtnebel *et al.*, 1993) is a conceptual model with some similarities to the HBV-model (Bergström & Forsman, 1979). It is used to simulate the runoff process in a natural catchment based on data for precipitation and air temperature. The model computes snow accumulation, snowmelt, actual evapotranspiration, storage in soil moisture and groundwater and time delay for runoff in reservoirs and rivers in the catchment.

It is a conceptual model, meaning that it is based on some considerations of the physical structure and process in the catchment. This structure is based on hydrological knowledge and has been verified during development and testing of the model. The model is basically a lumped model treating each subcatchment as one unit. Within each subcatchment the sub-basin is structured in zones with similar hydrologic and meteorological characteristics. These zones are usually defined by elevation and soil characteristics.

The basic structure of the model comprises a snow layer model, a soil layer model and a runoff model part. The input of precipitation and temperature affect the first two layers and the interaction of these by snowmelt. The runoff is calculated with a scheme of three linear storages which represent the parts of runoff: direct runoff, interflow and base flow. The soil layer and the snow layer are added on top of the storage schemes. Each subcatchment is replaced by a homogeneous vertical soil column. Parameters of this column are averaged values estimated from soil maps, topographic data and land use information considering the distribution of the zones in each subcatchment. The calculations are formulated in the state space with a single-step memory.

The snow model considers snow transport caused by wind and topography by lognormal distribution of snowfall within each zone. The density is related to air temperature and precipitation measurements. The consolidation of snow is modelled by melting and refreezing, calibrated on the basis of observations. The snowmelt is described by a modified degree day technique and storage capacity depends on snow density.

The soil layer is mainly described by a characteristic thickness, its state described by water content and soil temperature. Potential evapotranspiration is calculated using Thornthwaite's equation, actual evapotranspiration is computed considering soil moisture, precipitation and snow cover. The flow to the runoff part is calculated considering soil moisture.

The model needs calibration for a catchment before application. The structure is fixed, but contains a number of free parameters (soil field capacity, recession constants for runoff, etc.) to be calibrated iteratively and some confined parameters (catchment area etc.) to be calculated from maps and other sources. A period of at least five years of observed data should be used for calibration. A calibration and optimization tool has been implemented in the model to perform this work.

APPLICATION TO THE UPPER NECKAR CATCHMENT (GERMANY)

Precipitation and temperature

The upper Neckar catchment is located in southwest Germany between the Black Forest and Schwäbische Alb. It has an elevation from 245 to 1030 m, and an area of

about 3995 km². Data of 288 precipitation gauges, 46 of them located directly in the area, and 43 temperature gauges are available and have been used for this work.

The above described methods have been applied to this basin. For validation purposes observed data have been compared to data simulated by these downscaling techniques showing good results. Observed precipitation distributions are preserved within the simulation and temperature observations are well reproduced.

Time series of precipitation and temperature based on GCM produced 1 × CO₂ and 2 × CO₂ scenarios have been obtained and compared. Precipitation displays no really significant changes in the upper Neckar catchment. A small decrease of about 2% is observed in precipitation for yearly mean and most seasons, a small increase in late summer, but no significant changes in seasonality or distributions. For temperature an increase of 0.9°C for the annual mean temperature for the whole catchment is observed. The increase is spatially homogenous, but monthly values show significant differences, varying from an increase of only 0.3°C in May to 1.4°C in November. Looking at these data for single locations the changes are similar everywhere, local changes varying only ±0.1°C from area mean values (Fig. 1). The number of days below freezing point is reduced significantly in the whole area.

Runoff

The hydrological model was calibrated and applied to the Horb catchment, a sub-catchment of the upper Neckar catchment with an area of 1118 km², highest altitudes of 1040 m and highest precipitation of 1800 mm. For the establishment of the scenarios the previously obtained time series for temperature and precipitation were used as input to the hydrological model.

A significant decrease in the mean daily runoff between the simulated past and the 1 × CO₂ scenario as well as between the 1 × CO₂ and the 2 × CO₂ scenarios was observed. The standard deviation for the mean daily runoff decreased too (Table 1).

The mean maximum daily runoff for both scenarios was found to be higher than the simulated past. For the 2 × CO₂ scenario a decrease resulted compared to the

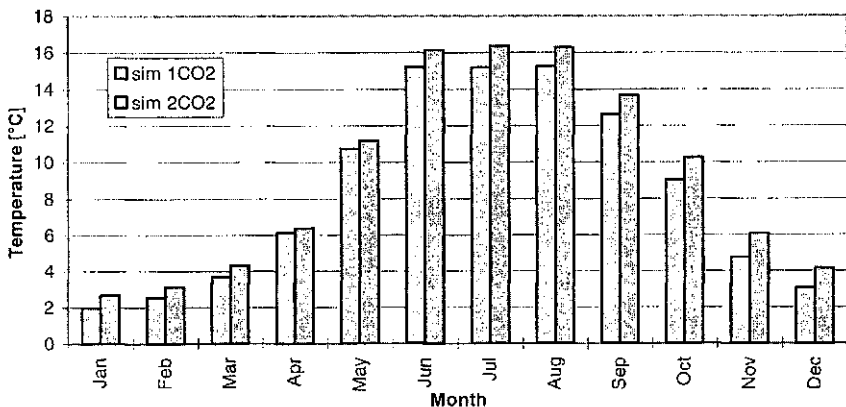


Fig. 1 Mean monthly temperature in the upper Neckar catchment.

Table 1 Changes in the mean daily runoff in the upper Neckar catchment (Horb).

	Mean daily runoff ($\text{m}^3 \text{s}^{-1}$)	Standard deviation ($\text{m}^3 \text{s}^{-1}$)
Simulated (historical data)	19.66	15.74
GCM: $1 \times \text{CO}_2$	19.19	13.43
GCM: $2 \times \text{CO}_2$	17.41	12.08

$1 \times \text{CO}_2$ scenario. However, it has to be mentioned, that the applied hydrological model does not seem to be suitable for application to extreme events in the upper Neckar catchment. Even during the calibration, the maxima were not simulated correctly. Due to this underestimation in the maxima, the simulated maxima for the scenarios should be treated very carefully.

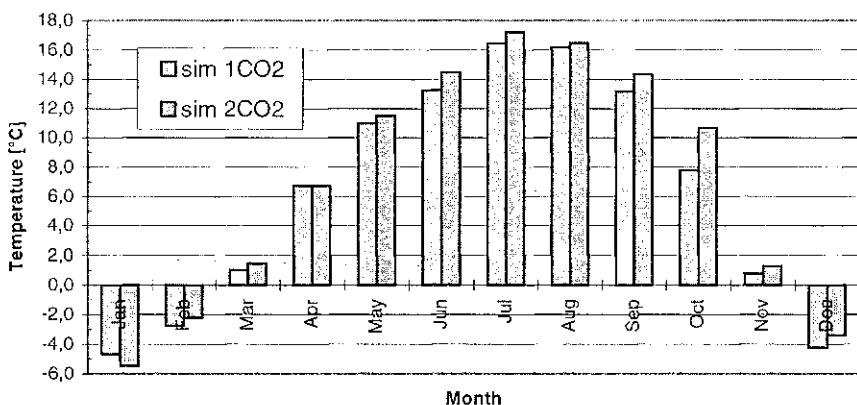
APPLICATION TO THE ENNS CATCHMENT (AUSTRIA)

Precipitation and temperature

The above described methodology was applied on the Enns basin, an alpine area of about 2400 km^2 in central Austria. Within the study area 11 temperature and 10 precipitation gauges were considered at elevations from 700 to 3100 m above sea level.

For validation purposes observed temperature and precipitation time series were compared to those obtained from the explained downscaling techniques. The results indicate that temperature observations were well reproduced by the simulated data. In cases of precipitation the empirical distribution was well preserved by the simulated precipitation series at all stations.

Based on the GCM produced $2 \times \text{CO}_2$ scenarios time series of precipitation and temperature were obtained reflecting climate change. The results on temperature showed a significant increase in the monthly means amounting up to 2.5°C within the whole catchment (Fig. 2). Further the number of days below freezing point decreased in winter. Precipitation time series reflecting climate change indicated small increases

**Fig. 2** Mean monthly temperature under $2 \times \text{CO}_2$ at station Radstadt (Enns).

in the rainfall probability and amount during the winter period (October–March) while no significant changes were detected in the summer period (April–September).

Runoff

The obtained time series of temperature and precipitation for the scenarios were used as input for the hydrological model. Increase in temperature caused a reduction of days with mean temperature below the freezing point. Snow accumulation in winter decreased and higher discharge could be expected (Fig. 3). So low flow periods were shifted from the winter months to late summer and the beginning of autumn. Evapotranspiration slightly increased while infiltration into soil was reduced and ended up in lower groundwater resources. For the yearly mean runoff no significant changes were observed (Table 2).

It is difficult to derive detailed conclusions with respect to flood frequency changes. In general, it can be said that an increase in the variance of the hydrological input will result in an increase of the respective model output and therefore the frequency of flood events might be increased. But the simulated period of about twenty years is too short to draw any specific conclusions (Hebenstreit, 1995; Nachtnebel *et al.*, 1996; Nachtnebel, 1998).

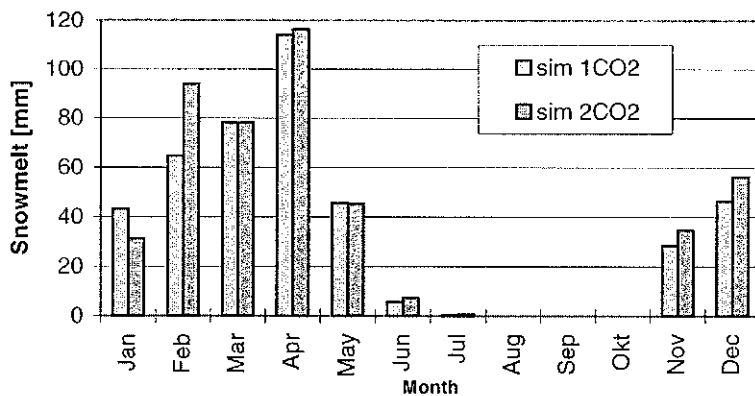


Fig. 3 Seasonality of snowmelt (Enns).

Table 2 Changes in the mean daily runoff in the upper Enns catchment (Liezen).

	Mean daily runoff ($\text{m}^3 \text{s}^{-1}$)	Standard deviation ($\text{m}^3 \text{s}^{-1}$)
Simulated (historical data)	57.30	37.80
GCM: $2 \times \text{CO}_2$	57.00	42.30

CONCLUSIONS

In both catchments an increase in temperature for a $2 \times \text{CO}_2$ scenario is observed but there are no significant changes in precipitation. The mean runoff is expected to

decrease in the Neckar catchment, while the Enns catchment shows changes in runoff due to the shifting of melting periods.

The applied methodology is suitable for gaining an insight into local climate impact but it was not possible to derive detailed conclusions with respect to extreme events due to the shortness of time series and because, in the Neckar catchment, the extreme behaviour was not simulated well by the applied hydrological model.

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