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MEZOSCALE HEAT AND WATER BALANCE STRUCTURE UNDER PRESENT AND FUTURE CLIMATE CONDITIONS – CATCHMENT CASE STUDY IN SOUTHERN PART OF GERMANY

Abstract: The heat and water balance components of the Main River catchment were estimated with the use of MBC model and the results are discussed in this paper. The input data set used in this study consists of 30 years meteorological and land-use data (from 1958 to 1987). The runoff data obtained from measurement station were used for verification of the results obtained by the use of the MBC model under present climatic condition. After verification, the MBC model was run again, but this time the present climatic data were replaced by future climatic data (obtained from GCM), and additionally some scenarios of changes in land-use structure were included. The analysis showed that under future climatic conditions and without land-use changes, runoff of the Main River catchment could increase of about 30% in comparison with present conditions. The impact of land-use and climatic condition changes on heat and water balances of the catchment is discussed in the paper.

Key words: evapotranspiration, modelling, global changes, Bowen ratio.

1. Introduction

Modelling of heat and water balance components has very often a practical application, i.e. by evapotranspiration estimating in a field scale (Tanner 1960), and regional scale (Thom, Oliver 1977), by determining the water condition due to land use condition (Kirchner 1984), or even by forecasting and estimating the yield (Tanner 1981; Gurney 1988). One of the considerable limitation for this modelling is the data availability for the input data set. There are some quite precise models for heat or water balance components estimation: McNaughton and Spriggs (1985), Holtslag and De Bruin (1988), Beljaars and Holtslag (1991), but their application for larger areas is very limited because of needed input data set. In some cases it is impossible, by now, to collect input data set i.e. moisture or physical properties of soils for a large area at satisfactory resolution. Therefore, it seems, that the MBC model recently developed at Agrometeorology Department of Agricultural University of Poznań (Olejnik, Kędziora 1991; Olejnik 1996; Leśny 1998) is a compromising solution between the quality and resolution of conclusions versus the possibilities of input data set collection and appropriate consideration of physical and biological processes included into the modelling procedure. The resolution of MBC (limited only by land use data resolution) can be significantly higher than GCMs resolution, and the input data set is relatively easy to collect for larger areas. This model, or his earlier stage, has been successfully applied in different scales: in field scale (Olejnik 1988b), in catchment scale (Kędziora et al. 1989), in the regional scale (Olejnik, Kędziora 1991) and in country scale (Ryszkowski et al. 1991). Because one part of input data set is meteorological data, it is possible to include the data about climatic change due to greenhouse gases concentration increase, coming out from GCM models.

2. Methods

During the model investigations on heat and water balance components exchange, both, physical and biological factors have to be included in the models for all scales: from a field to the global scale.

Heat balance equation can be written as follows

$$Rn = LE + S + G \quad \text{or} \quad E = (Rn - S - G)/L \qquad (1)$$

where: Rn is the net radiation, LE is latent heat flux (L is evaporative heat of water and E is evapotranspiration), S is sensible heat flux and G is soil heat flux.

For the adequate long period the water balance can be written as follows:

$$P = E + H \quad \text{or} \quad E = P - H \qquad (2)$$

where: P is precipitation, E is evapotranspiration and H is runoff.

Through the evapotranspiration (E), there is a direct connection between heat and water balance of investigated area (Eq. 1.-Eq. 2). The connection between these balances plays a very important role in the complex description of energy-water conditions of the environment, and also has a practical application in models verification. For example, modeling the areal evapotranspiration on the basis of heat balance structure (Eq.1), one can compare the values of evapotranspiration obtained by the use of the model with values obtained by the hydrological measurement (as a difference between precipitation and runoff, Eq. 2). That kind of procedure was used during the MBC model creation (Olejnik 1996), and verification of some results obtained by that model (Kędziora et al. 1992).

The MBC model is based on the empirical equation which links the Bowen ratio (β) with meteorological parameters and plant development stage:

$$S/LE = \beta = f(T,D,u,s,f) \qquad (3)$$

where: S, and LE are the sensible and latent heat fluxes respectively, β is Bowen ratio, T is air temperature, D is saturation water vapour pressure deficit, u is wind speed, s is relative sunshine and f is plant development stage.

Using Equations 1 and 3 the latent heat flux density can be estimated as follows:

$$LE = -(R_n + G) / (1 + \beta) \qquad (4)$$

In the MBC model the net radiation Rn and soil heat flux are estimated with the use of standard procedures and equations described in details in the work by Olejnik, Kędziora (1991).

After latent heat flux estimation, with the use of Equation1, the areal evapotranspiration was estimated (based on calculations of evapotranspiration for every land use unit). To verify the quality of the model estimation, the values of modelled areal evapotranspiration were compared with areal evapotranspiration calculated from climatological water balance equation (Eq. 2).

3. Results and Concluding Remarks

The MBC model was applied for the Main River catchment located in the southern part of Germany. The whole catchment was covered with the grid net of 0.1°x0.1° (latitude, longitude) resolution. All meteorological data, from 18 meteorological stations, were interpolated at that resolution (interpolation procedure using Fourier extension was described in detail in the work of Olejnik et al. 2000). At the same resolution, the land-use data were included in the MBC input data set. The MBC model was applied for the Main River catchment, and data from 1958 to 1987 were used. Figure 1 shows the results of heat balance structure components modelled by MBC from 1958 to 1987. As an example, in Figure 1 the courses of Bowen ratio and ratio LE/Rn were shown (these ratios were calculated for the whole catchment as the areal average, year by year from 1958 to 1987).

On the basis of long term average monthly data, the average yearly courses of heat and water balance components have been modelled. The mean annual course of heat and water balance component is shown in Figure 2.

To verify the obtained results the statistical analysis was applied. The modelled values of water balance components were compared with independent data from German Weather Service. Statistical comparison, including modelled data about runoff (precipitation minus areal evapotranspiration) versus measured runoff at Frankfurt station was carried out. This comparison was made for different periods of averaging: from one year to 30 years (Fig. 3). It is easy to see that after about 10 years the relative error in the estimation of water balance components became constant at the level of about 3%. In comparison to precipitation, the MBC model estimates the other water balance components (evapotranspiration and runoff) with the accuracy of 3% for the period longer than 10 years. For a longer period of estimation by MBC model, the obtained results are very satisfactory.

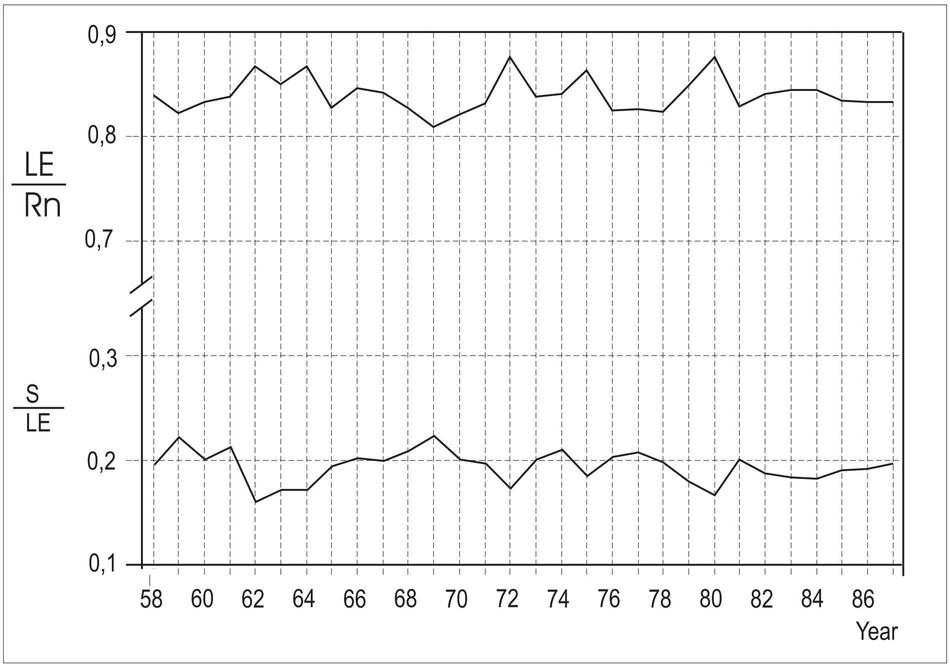

Fig.1. The course of mean annual values of heat balance components ratios (S/LE and LE/R_n) from 1958 to 1987: the areal average for the whole Main River catchment.

One can assume that the model can be applied for the analysis of changes of heat and water balance components due to global climatic change in a local-catchment scale with the use of quite high resolution. Because the input data set partly consists of meteorological data, it is possible to run the model using new, anticipated climatological data. The results from GCM (2xCO_2) were used as new input data for MBC model. The increase of temperature (by 4°C) and the increase of precipitation (by 0.4 mm/day) for this part of Europe were assumed (Hulme et al. 1990).

In Figure 4 the results of this analysis were shown. The upper part shows the present conditions of heat and water balance of the Main River cachment. Scenario I (middle part of Fig. 4) shows the heat and water balance conditions after climatic change (data from GCM). Possible changes of land use data were not included in scenario I. It is easy to see that the increase of temperature and precipitation will result in a very significant increase of runoff: from 235 mm at present to 306 mm in about 2050 year. For this scenario the land-use conditions were assumed as at present no changes were included.

Using scenario II one can try to answer the question "how should the land use structure be changed to reduce the significant increase of runoff due to climatic

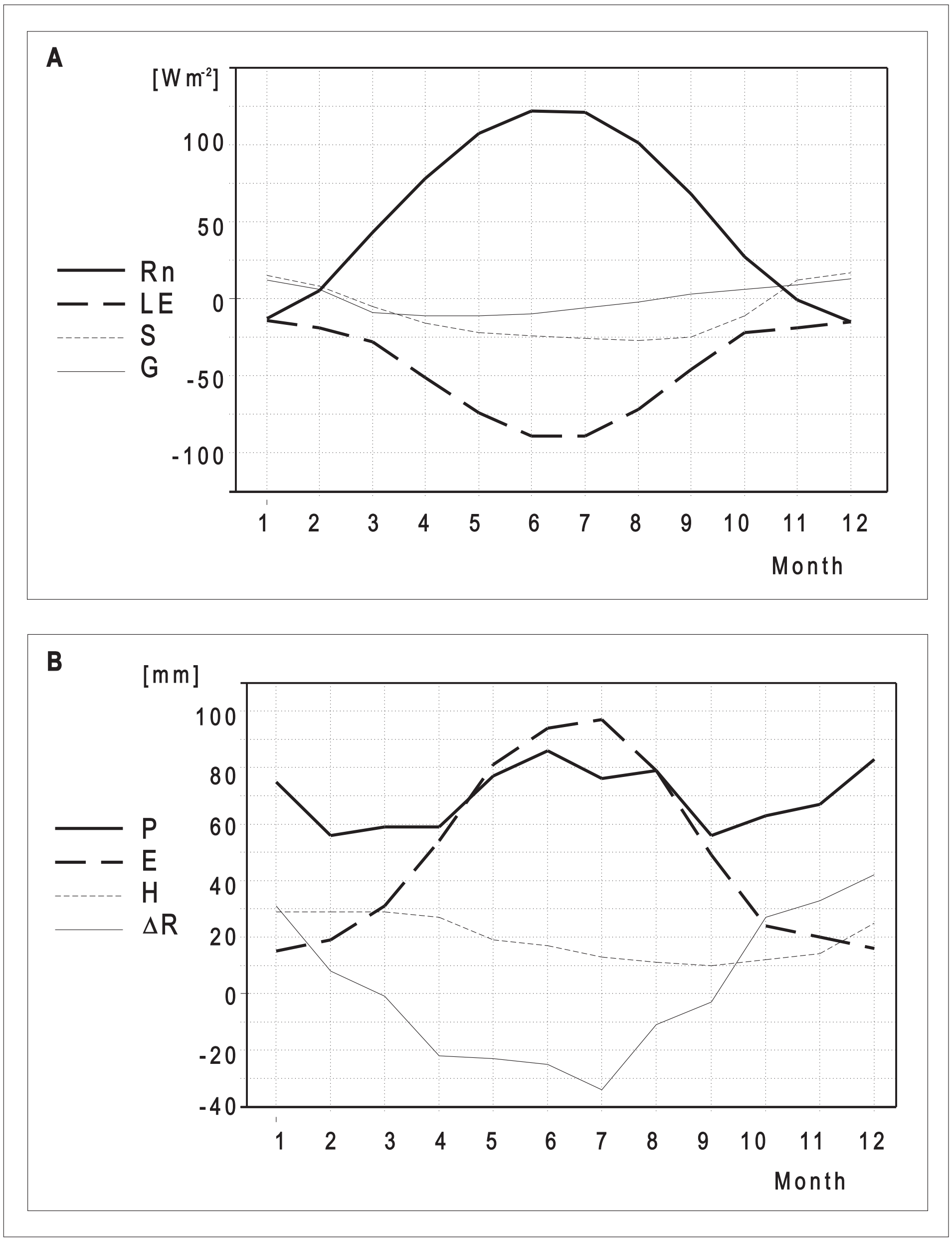

Fig.2. The average annual course of heat balance (a) and water balance (b) components in Main River catchment (averaged from 1958 to 1987).

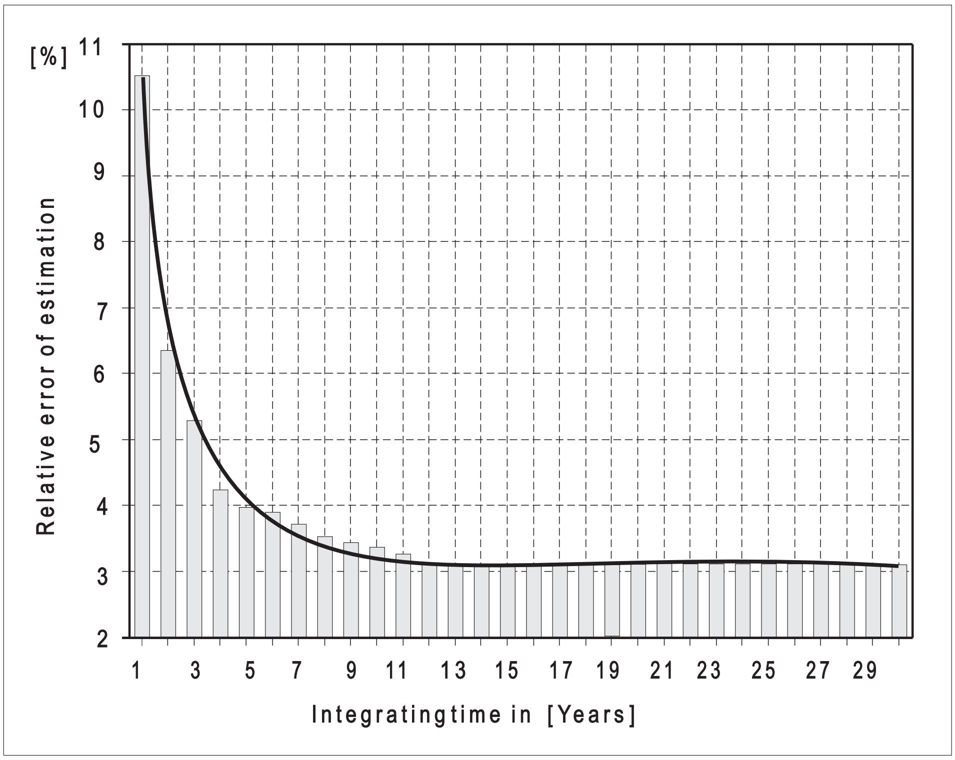

Fig.3. The relative error of evapotranspiration estimation by the use of MBC model as a function of time of integration.

changes?”. By the assumption of the climatic changes (increase of temperature and precipitation) like these mentioned above, it is still possible to keep the runoff value at the current level, but the land use structure should be significantly changed. The total forest area should be increased to more than 68% in the whole catchment – which theoretically is possible but unrealistic to be applied (Fig. 4).

The more realistic future land-use conditions were assumed in scenario III (down part of Fig. 4). The decrease of arable lands and increase of forest, water bodies and urban areas were assumed on the basis of some reports on future land-use conditions in European Community. Such changes in land use conditions will significantly decrease the runoff from scenario I without land-use changes assumption (from 306 mm- scenario I to 271 mm - scenario III).

This analysis shows a very significant influence of land-use conditions on heat and water balance conditions. One can hope the MBC model can be a very helpful tool for forecasting the water and energy conditions under new climatic, as well as land-use conditions.

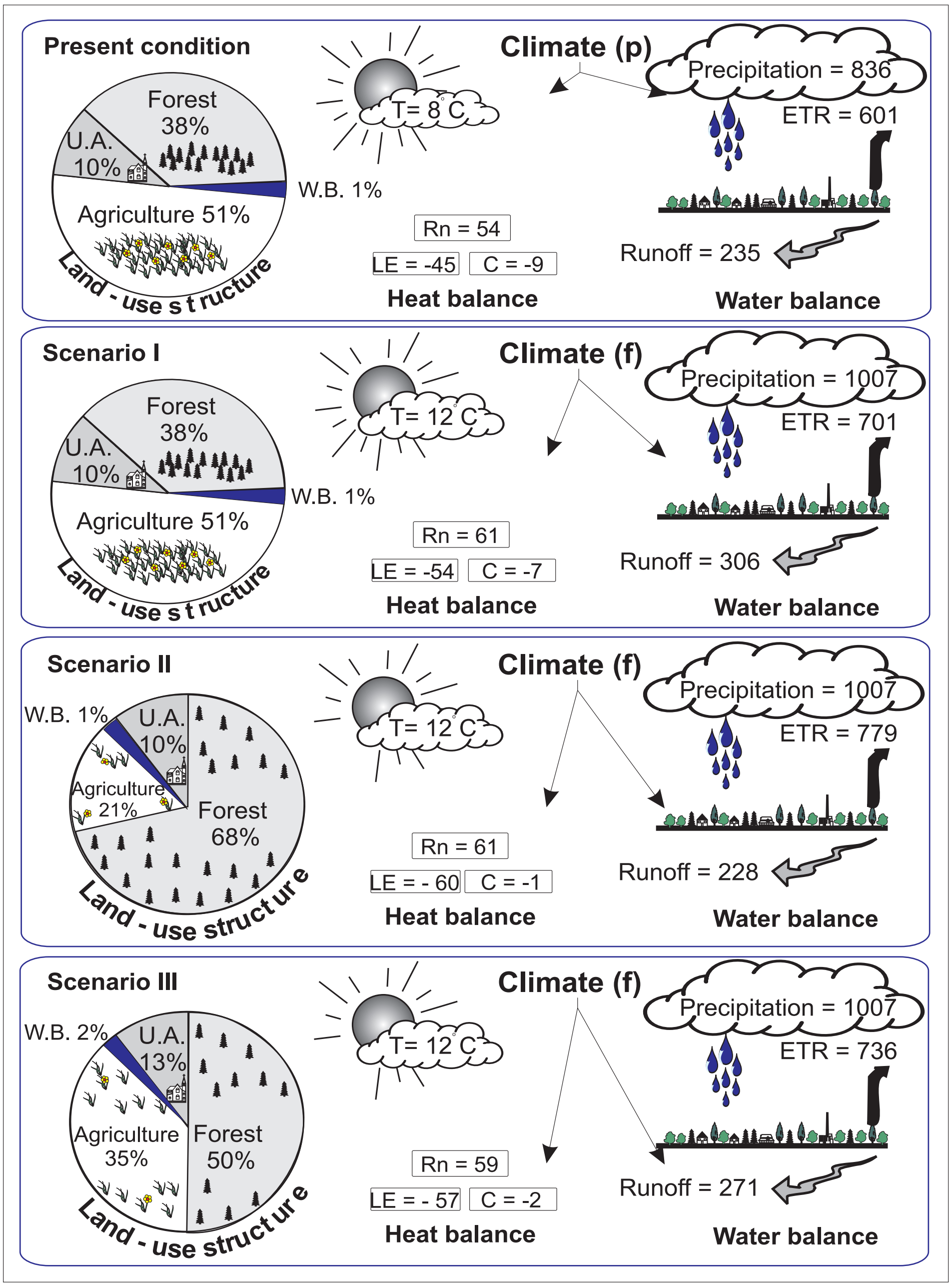

Fig.4. Mean annual values of meteorological data, heat balance and water balance component in the Main River catchment in present climatic and land-use conditions (p) as well as the future conditions (f) (scenarios I, II, and III); explanations to the figures: U.A. – urban areas, W.B. – water bodies.

As it was mentioned in the previous part of this paper, the MBC model is based on the Bowen ratio parameterisation. It is possible, using the graphical procedures of the model, to show the areal distribution the heat balance components. The use of such maps should be very helpful for land-use managers, for making decisions about future land-use changes. In the Main cachment there are areas were the land-use can be modified in a way to increase the areal evaporatranspiration which can significantly decrease the high runoff in the future.

There are no special limits in resolution increase for MBC model. The only one is the resolution of the available land-use data. Because of this, we do hope that the MBC model can find applications in making decisions about new land-use structure on catchment but also local scale due to socio-economic and climatic change aspects.

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