Assessment of Evapotranspiration Simulations in the Malše Basin

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Abstract: The application of the distributed hydrological model brings the benefits of assessment of the spatially distributed quantities which are hard to measure in the field over a larger area, e.g. evapotranspiration. The Malše River basin has been chosen for the evaluation of evapotranspiration simulation by the distributed hydrological model, SWIM (Soil and Water Integrated Model). The primary interest in this analysis was to assess the ability of the hydrological model to simulate the actual evapotranspiration on larger scales and to evaluate its dependence on the landscape characteristics such as the vegetation cover, soil type, and average precipitation amount during the simulation. Annual actual evapotranspiration in each hydrotope was evaluated in the simulation period of 1985–1998. Because of the lack of the data observed (evapotranspiration), the model was calibrated on the discharge time series. The credibility was quantified using Nash Sutcliffe efficiency which was more than 0.7. The main trends of the simulated actual evapotranspiration were evaluated and assessed as satisfactory. The differences in the soil types did not seem significant for the evapotranspiration variation, the monthly average values among soil types differing by ± 10% except histosol. On the other hand the differences in the land-use categories strongly influenced the amount of evapotranspiration (–30; +50%). It appears that the model SWIM overestimates the actual evapotranspiration in the spring and, on the other hand, underestimates that in the autumn according to the comparison with the only data available in the entire Climate Atlas of the Czech Republic.

Keywords: hydrologic modelling; evapotranspiration; SWIM model

Publicity of extreme hydrologic events has been increasing recently in consequence of the attention paid to floods and droughts by the media. At the same time, the question of possible impacts of the global climate change on the extreme events has come into the centre of interest and the effects of the change on the hydrologic regime have started to be analysed. Hydrological modelling has become a commonly used tool for estimating the role of each part of the runoff formation within the hydrological cycle and evaluating their possible changes in the future. Besides that, the application of hydrological models is useful for the simulation of quantities which are hard to measure in the field over a larger area, e.g. evapotranspiration or soil water content. Thus, the data measured in small experimental catchments in the context of geographical conditions can help to create a conception of their role in hydrological modelling in larger areas and in ungauged basins.

This article deals with the modelling of evapotranspiration in the mesoscale Malše River basin (435 km^2) using the hydrological model SWIM (Soil and Water Integrated Model). The aim of the study was to assess the abilities of the model to simulate spatially the actual evapotranspiration

Supported by the Grant Agency of the Academy of Sciences of the Czech Republic, Project No. KJB 300600602.

within the basin, which is usually not measured in the real basin. The new approach was the use of daily steps within the actual evaportanspiration simulation. The vegetation cover, soil types (resp. soil water content), and water availability are the main factors determining the rate of actual evapotranspiration. The comparison of the effect of the factors was performed to evaluate the rate of their influence on the size of actual evapotranspiration. The monthly trends of the actual evapotranspiration were analysed in relation to different types of the vegetation cover and soil type.

Hydrological model SWIM

The SWIM model (Krysanova *et al*. 1998) is a continuous-time distributed simulation watershed model, which is able to simulate both the water quantity and quality supported by GIS tools. It covers the description of hydrological processes, crop/vegetation growth, and nutrient dynamics, which allows the use of the model for the analysis of climate change and land use change impacts on hydrology and water quality on the regional scale. SWIM is based on a three-level disaggregation scheme basin – sub-basins – hydrotopes, defined in GIS GRASS according to the basin input parameters (land use, soil type, elevation model). A hydrotope can be assumed to behave in a hydrologically uniform way within the sub-basin. Meteorological data are interpolated for each subbasin. The hydrological module is based on the water balance equation in a hydrotope, taking into account the precipitation, evapotranspiration, percolation, surface and subsurface runoffs in the soil column, which is divided into several layers according to the soil type. The simulated hydrological system consists of four control volumes: the soil surface, root zone, shallow aquifer, and e deep aquifer. Water running from the soil profile recharges the shallow aquifer and then contributes to the streamflow. The water balance for the shallow aquifer takes into account the groundwater recharge, capillary action in the soil profile, groundwater return flow, and percolation to the deep aquifer (Figure 1). The snow and melting routine has been adapted for the conditions of the Czech Republic through the involvement of standard snowmelt routine based on a degree-day approach, taking into account the air temperature, with a water holding capacity of snow which delays the runoff. The benefit of the model resides in that it is allowed to adjust the computation rules in the model source code according to the specific needs.

Since the SWIM is a physically based model, it requires a large amount of detailed data. Although the model has been primarily designed for the simulation in mesoscale watersheds (from 100 up to 10 000 square kilometres) and has been primarily used for modelling in the Malše basin, it has been also tested and adopted for use in small basins. The model study has been carried out at the experimental catchment Liz on the basis of a large amount of directly measured data.

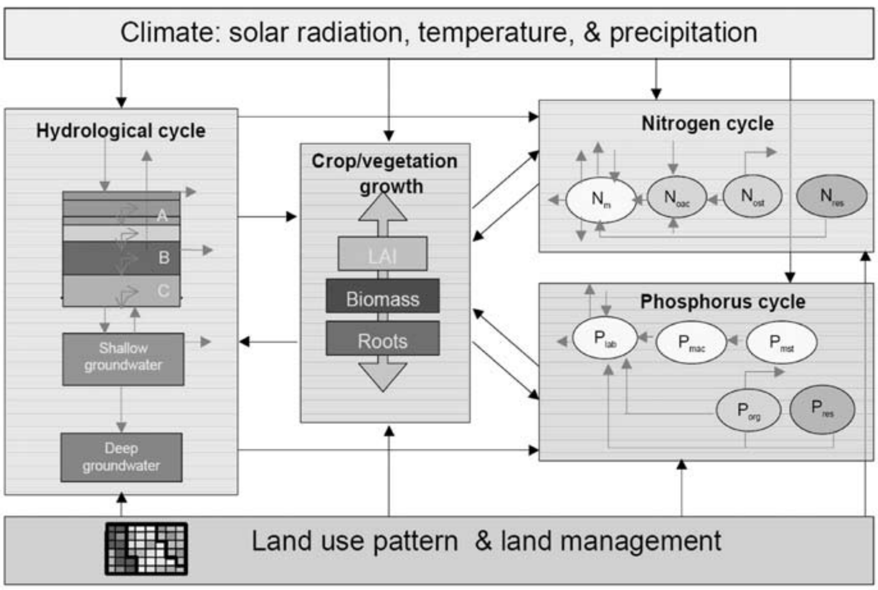

Figure 1. Flow chart of the SWIM model (Krysanova *et al.* 1998)

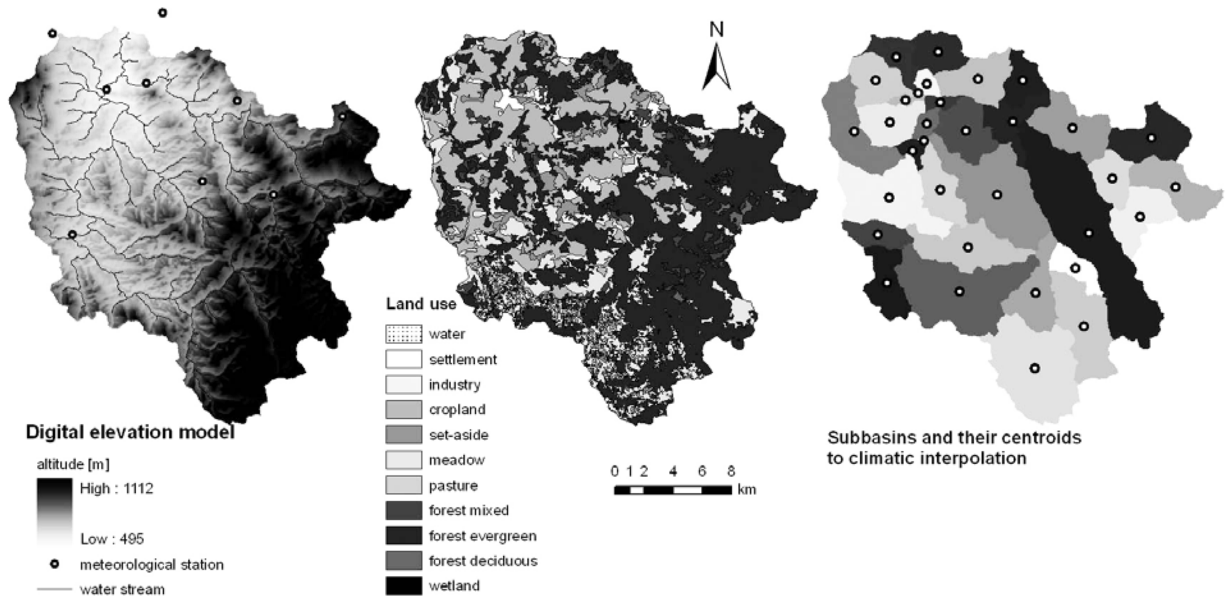

Figure 2. The Malše River basin input maps (elevation, land use, subbasins with their centroids)

Implementation of the model SWIM in the Malše basin

The model was implemented in the Malše River basin. A gauge station in Pořešín was set as the outlet. The gauge station is situated upstream of the water reservoir Římov, so that the discharge was not affected by the dam manipulations. The Malše River is located in Southern Bohemia and it rises in Austria. The catchment has an area of 435 km^2. The upper basin is covered mainly by the forests of the Novohradské hory Mts. On the contrary, there are more meadows and agricultural arable land in the lower part of the catchment. The basin has quite a low population density.

The wooded areas (mostly deciduous and mixed forests) cover about 51% of the basin, meadows comprise 22% and arable land 21% (Figure 2).

A high variability in physical characteristics has been detected within each soil type over the catchment; consequently, the soil subtypes were derived according to a field soil survey (Němečková *et al.* 2007).

Besides the spatial data describing the basin (i.e. elevation, land use, soil, subbasins with their centroids), meteorological and hydrological data (time series) are required as the input. The meteorological data series were obtained from eighteen precipitation stations in the Czech Republic and two in Austria. At five of them, the temperature (max, min, and average air temperature at two metres above the surface), radiation, and relative air humidity were measured in addition. The measured values were interpolated for the centroids of each subbasin using universal kriging concerning the altitudes of the meteorological stations and of the subbasin centroids.

The hydrotopes were defined using the SWIM/GRASS interface in accordance with the input maps of the basin characteristics. The number of these unique areas was 456. The outflow scheme and all other input files required by the model were also designed by the SWIM/GRASS interface.

During the implementation of the model in the time period of 1961–1998, the measured discharge time series in Pořešín proved not to be consistent in time. The cause of the affection seems to have been the discharge distortion during the reservoir construction. As a result, the calibration and validation of the model were carried out only in the time period of 1985–1998 (calibration 1985–1987, validation 1996–1998).

The accuracy of the model was evaluated for both periods – calibration and validation. The simulated and observed discharges at the outlet gauge station were compared (Figures 3 and 4). The model represented better the low flows. Some differences occurred with the high flows, especially in extreme peaks. The discrepancy could be connected with the problem of the vegetation cover evolution during the year and annual mean vegetation parametrisation within the model. The

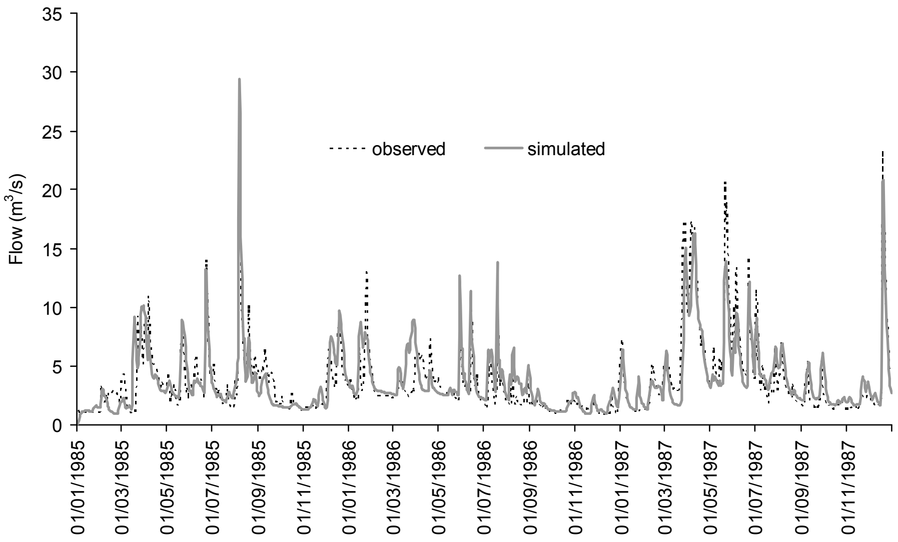

Figure 3. Observed and simulated flows during calibration period

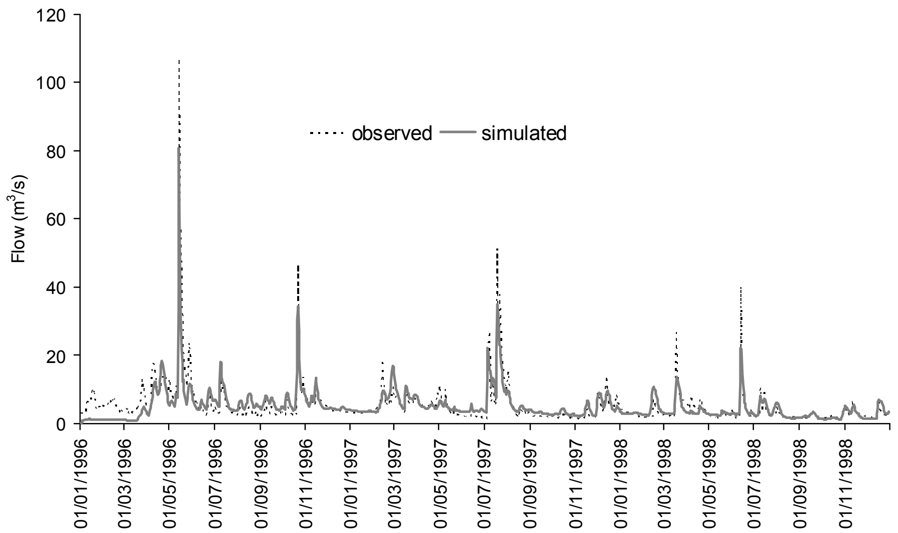

Figure 4. Observed and simulated flows during validation period

comparison was quantified using Nash Sutcliffe efficiency and water balance of the simulated and observed discharges. Nash Sutcliffe efficiency was 0.74 per calibration period and 0.72 per validation period. The decrease of the value during the validation period was not significant. The decrease of the efficiency was very likely caused by the greater difference between the measured and simulated flows during the first three months of the validation produced by the diverse initial snow accumulation and snow melting conditions. The water balance in the calibration period was +3% and in the validation period –2%. The finding indicates the balance of the simulated and observed discharges. The output of the model could be described as satisfactory.

Evapotranspiration calculation in the model

The expression of evapotranspiration in the model is based on the calculation of evaporation from soils and transpiration by plants separately, according to Ritchie (1972). The plant transpiration is calculated using the value of potential evapotranspiration and leaf area index (LAI). If the soil water content is limited, the plant water transpiration is reduced.

$$EP = \frac{EO.LAI}{3} \text{ if } 0 \leq LAI \leq 3 \quad \text{or } EP = EO \text{ if } LAI \geq 3 \qquad (1)$$

where:

EO – potential evapotranspiration (mm/d)

EP – plant transpiration (mm/d)

LAI – area of plant leaves relative to the soil surface area

The potential soil evaporation from the soil surface ESO (mm/d) is simulated by an exponential function of the leaf area index according to the equation of Richardson and Ritchie (1973):

$$ESO = EO.\exp(-0.4.LAI) \quad (2)$$

The actual evaporation from the soil surface is calculated in two stages. In the first stage, only the energy available on the surface limits the actual soil evaporation, which, in this case, is equal to the potential soil evaporation. When the accumulated soil evaporation exceeds the first-stage threshold (equal to 6 mm), the second stage begins according to the following expression:

$$ES = 3.5.(\sqrt{TST} - \sqrt{TST-1}) \quad (3)$$

where:

ES – soil evaporation from the soil surface on day t (mm/d),

TST – number of days since stage-two evaporation began.

The actual soil water evaporation is estimated on the basis of the top 30 cm of soil and snow cover, if any. If the water content in the snow cover is higher than or equal to ES, the soil evaporation comes from the snow cover. If ES exceeds the water content in the snow cover, water is removed from the upper soil layers if available.

The potential evapotranspiration is estimated using the method by Priestley and Taylor (1972) or Penman and Monteith (Monteith 1965), according to the data availability. The first method requires only solar radiation, air temperature, and elevation as inputs. The latter requires solar radiation, air temperature, wind speed, and relative humidity as inputs. In this study, the Penman-Monteith method was used.

The SWIM model provides a simulation of the vegetation growth in a year using the EPIC method according to Williams *et al.* (1984). In this approach, the LAI is simulated as a function of the heat unit and biomass in a year (Krysanova *et al.* 1998).

Evapotranspiration simulations

The actual evapotranspiration over the basin was evaluated after the calibration and validation of the model SWIM. The simulations were carried out in daily steps for each hydrotope, thus the values of the actual evapotranspiration were obtained in daily steps in the smallest homogenous areas – hydrotopes in a five-year time period. The hydrotopes were created by overlaying the three map layers mentioned (subbasins, land-use, soil types). All possible combinations of these geographical elements were created in this way. The actual evapotranspiration was simulated in 456 hydrotopes in total. Then the average monthly values for each soil and land-use type were calculated.

A new routine was designed to transform the model outputs from the text formats into the GIS format for visualisation of the simulated maps of actual evapotranspiration. The routine enabled us to convert text files into shape files (ArcView) directly. Statistical evaluation was performed by Statistica software, which provides the processing of the huge amount of data obtained during the simulation experiments.

RESULTS AND DISCUSSION

Figures 5 and 7 show the comparison of the maps of the land use, soil types, and average annual precipitation in the subbasin with the annual average actual evapotranspiration in mm of water column. The objective of the analysis was to find out the measure of interdependence of the actual evapotranspiration on the basic attributes of the hydrotopes entering the model (land use, soil type, and average precipitation) under specific conditions of the selected mesoscale basin, and to verify the spatial correspondence between them. The results of the comparison were represented as percentages of the total amounts of hydrotopes belonging to the specified categories of land use, soil type, and precipitation area (Figures 6 and 8).

According to the general presumption, the amount of evapotranspiration is substantially affected by the land cover type (Figures 5 and 6). The results prove that the actual evapotranspiration rises with the density of the vegetation cover. Maximal values are reached in wooded areas, as expected. Unexpected results were indicated on wetlands, where 100% of the hydrotopes reached a lower value of actual evapotranspiration (category 401–500 mm) in comparison with the value for forests (prevailing category 501–600 mm). The findings do not correspond with the presumption of sufficient soil water for the evapotranspiration demand in the wetlands. The discrepancy is very likely connected to the definition of the LAI (leaf area index) in the model parameter file describing the vegetation parameters of the land-use catego-

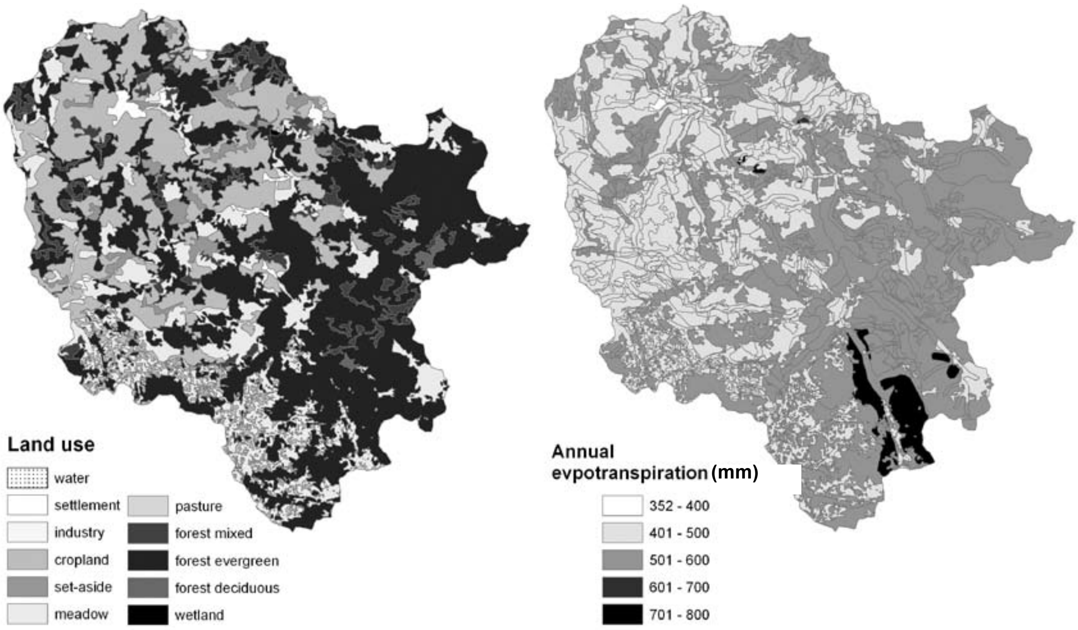

Figure 5. Comparison of the map of the average annual evapotranspiration (mm) with the map of land use

ries. That means that the wetlands are described as the vegetation cover with a low LAI, similar to pastures and meadows. This reality does not represent the real situation in this basin.

The evaluation of the results, taking into account the soil type category in the basin, indicates an interesting contradiction in comparison with the analysis presented above. The highest amount of actual evapotranspiration is produced by the soil type Histosols, where the wetlands mainly could be expected. The chart (Figure 8) shows that the actual evapotranspiration from Cambisols and Fluvisols will be lower than the actual evapotranspiration from the rest of the soil types in general. However, it is necessary to take into account the main influence of the vegetation cover and the uncertainties connected to its precise parameter definition within the specific basin.

The evaluation of the dependence of the actual evapotranspiration on the water regime of the basin was performed based on the average annual precipitation data series. (Figure 9) The variability of the precipitation spatial distribution was not great; nevertheless, the trend of the correspondence between the precipitation and actual evapotranspiration is evident within the meaning of positive correlation (Figure 10). It is unexpected that the area of the highest evapotranspiration (category

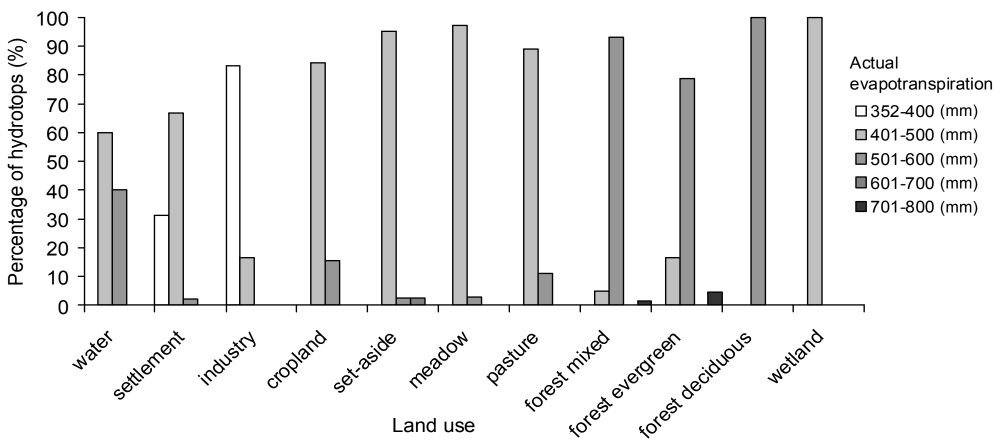

Figure 6. Percentage of hydrotopes in each type of land use in categories of the annual average evapotranspiration

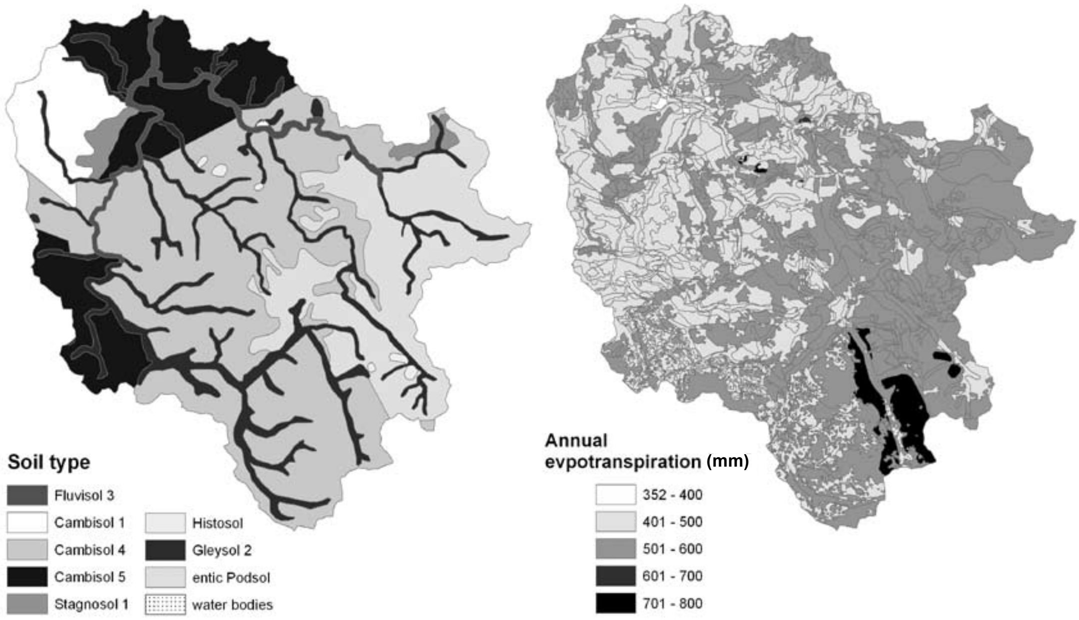

Figure 7. Comparison of the map of the average annual evapotranspiration (mm) with the map of soil types

701–800 mm) should not overlap the area of the highest precipitation. This effect can probably be explained by the local diversity of the terrain.

Additionally, the annual course of the actual evapotranspiration was evaluated. The monthly average actual evapotranspiration in each soil and land-use type was computed and compared with the average monthly actual evapotranspiration in the whole basin (Figures 11 and 12, and Table 1).

The pictures show that the average evapotranspiration kept similar trends for all the soil types during the year whereas visible differences existed in the case of the land-use. The highest values in the charts correspond to the net evaporation from the water surface. The difference between the trends variation in both charts is probably connected to different elements of evapotranspiration (transpiration and evaporation). Transpiration is mainly determined by the vegetation cover whereas evaporation by the soil type. Different physical characteristics of the soil types seem not to be significant for the variations in evapotranspiration, the monthly average values between the soil types differ by ± 10% except histosol. The greater variations of the trends in the picture concerning the land-use (–30; +50%) correspond well to the different evolution of the individual vegetation types during the year (Figure 12).

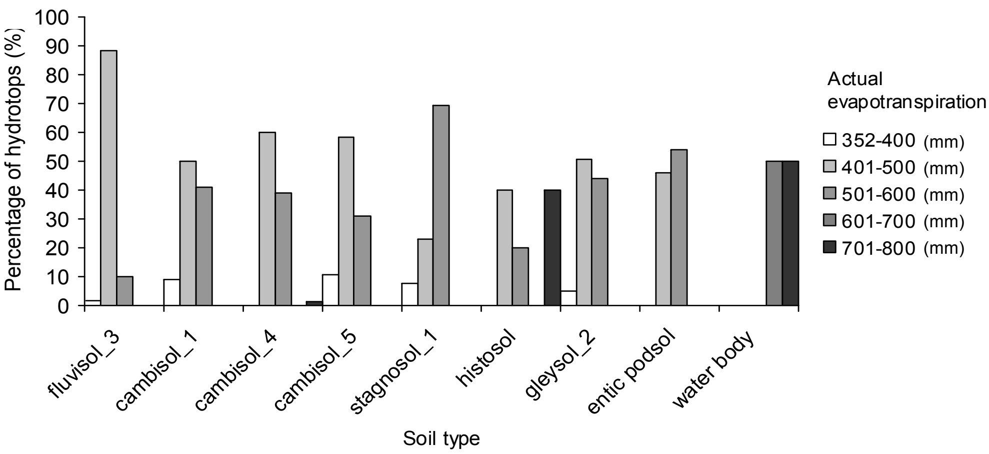

Figure 8. Percentage of hydrotopes of each soil in categories of the annual average evapotranspiration

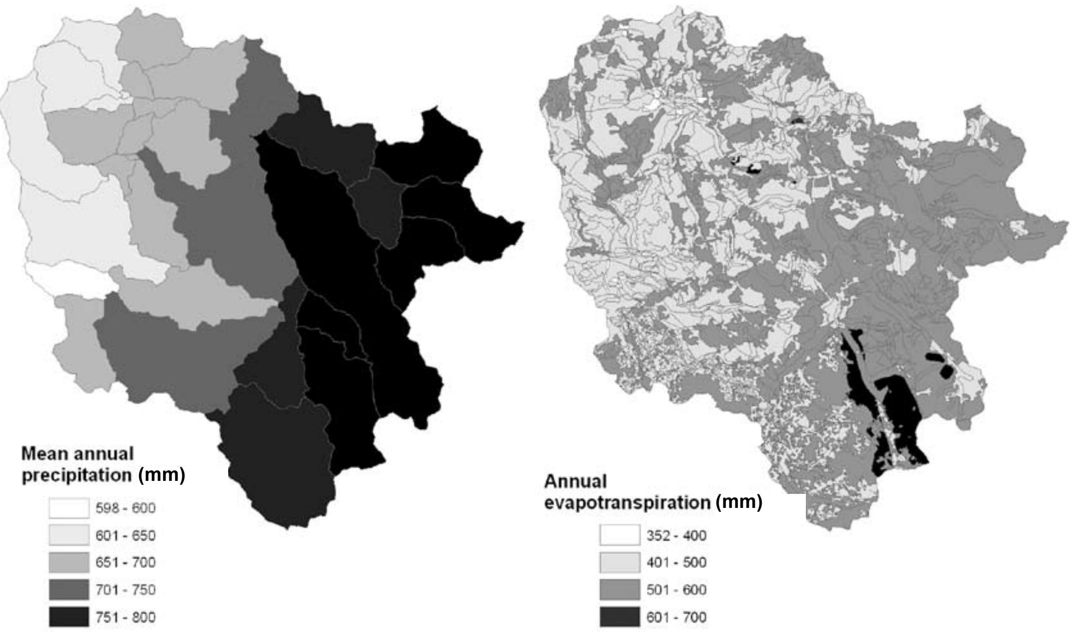

Figure 9. Comparison of the map of the average annual evapotranspiration (mm) in hydrotops with the map of mean annual precipitation in subbasins (mm)

The ratio of the actual evapotranspiration, precipitation and, runoff was investigated within the subbasin of the Malše basin where extreme amounts of actual evapotranspiration have occurred. The pictures show the annual cycle of the precipitation, runoff and actual evapotranspiration within the subbasin with the presence of hydrotops with maximal (Figure 13), minimal (Figure 14) and, for comparison, the average (Figure 15) actual evapotranspiration. The trend in the simulated annual course of actual evapotranpiration was almost the same in both the extreme and the average cases; they differed only in the total amounts. It is evident that evapotranspiration substantially exceeds the runoff rate mainly in the summer season. The actual evapotranspiration prevailed over the precipitation in April. This indicates that the actual evapotranspiration demand was then very likely covered by the soil water and groundwater reserves.

Unfortunately, no directly measured data were available of the potential or actual evapotranspiration for a detailed comparison of the simulated and observed values in the Malše basin. The model outputs were compared with the data of the entire Climate Atlas of the Czech Republic (CHMI 2007),

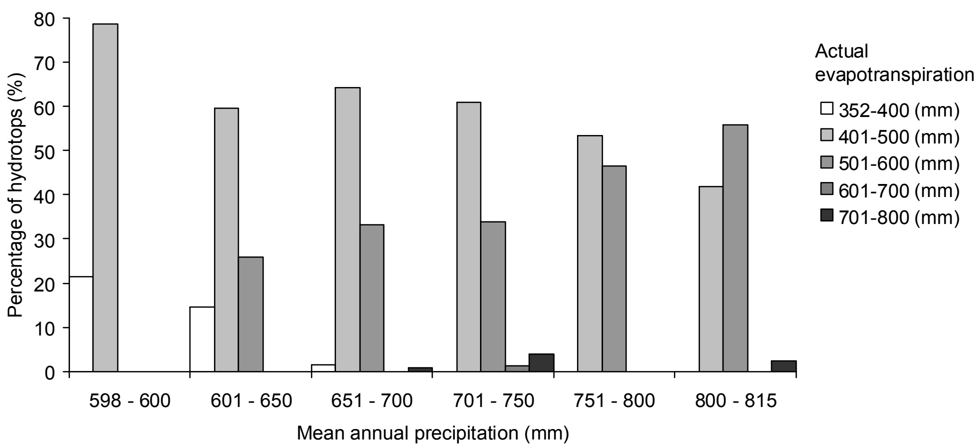

Figure 10. Percentage of hydrotopes corresponding to each category of the annual average precipitation evapotranspiration in categories of the annual average evapotranspiration

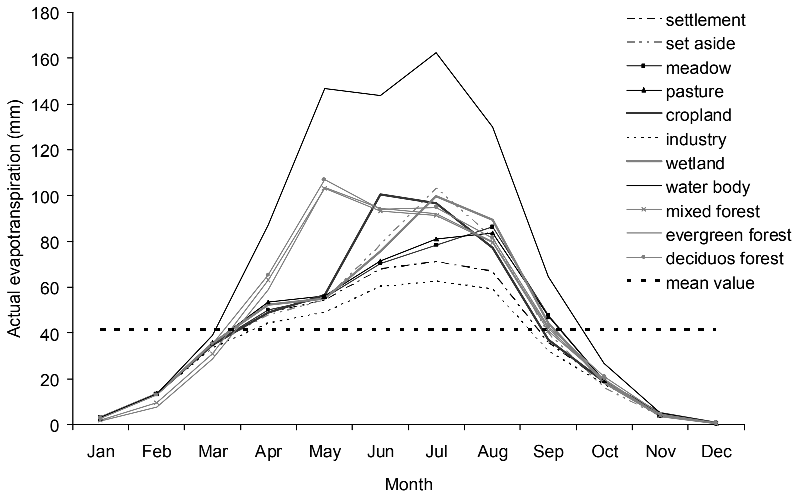

Figure 11. Annual course of actual evapotranspiration in different land use types

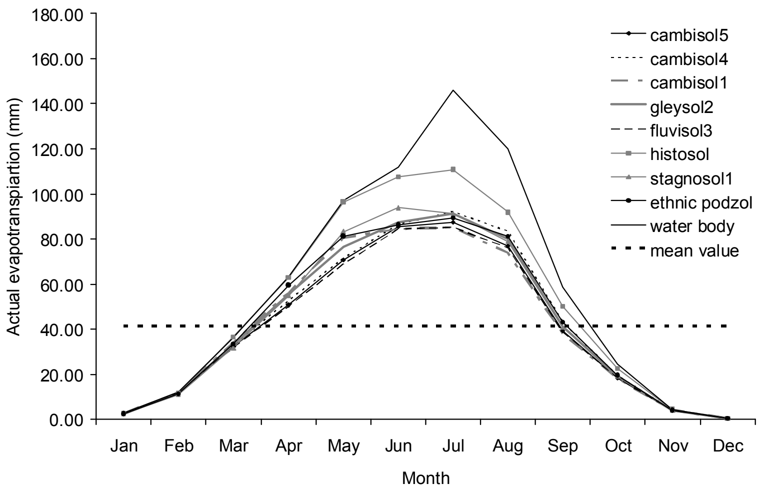

Figure 12. Annual course of actual evapotranspiration in different soil types

namely with the average annual and seasonal reference evapotranspiration (evapotranspiration value of a hypothetical crop, that closely matches the standard grass cover) at least (Table 2, Figure 16). It is a rough data, i.e. average values describing larger areas of Southern Bohemia. The differences are possibly caused by the different definitions of the real vegetation type and the hypothetical grass cover under the ideal moisture conditions. The simulations were executed for a five-year-long time period only. On the contrary, the CHMI presents long-term values.

It appears that the model SWIM overestimates the actual evapotranspiration in the spring and, on the other hand, underestimates it in the autumn.

Table 1. Comparison of the results of the actual evapotranspiration simulations with the data given in the Climate Atlas of the Czech Republic (CHMI 2007) (in mm)

	Simulated actual evapotranspiration	Reference evapotranspiration CHMI
Spring (III, IV, V)	199.4	175
Summer (VI, VII, VIII)	277.2	275
Autumn (IX, X, XI)	32.9	100
Annual	489.5	550

Table 2. Average month values of actual evapotranspiration (in mm) for different categories of land use and soil types in the basin

Land use	Mean monthly evapotranspiration	Soil type	Mean monthly evapotranspiration
Settlement	34.89	Cambisol 5	39.97
Set aside	39.64	Cambisol 4	41.79
Meadow	38.59	Cambisol 1	40.63
Pasture	39.75	Gleysol 2	41.97
Cropland	41.03	Fluvisol 3	39.23
Industry	31.68	Histosol	50.38
Wetland	40.95	Stagnosol 1	42.65
Water body	69.35	Entic Podsol	42.87
Mixed forest	44.96	Water body	56.81
Evergreen forest	44.64		
Deciduous forest	46.88		
Average in the basin	41.52		41.52

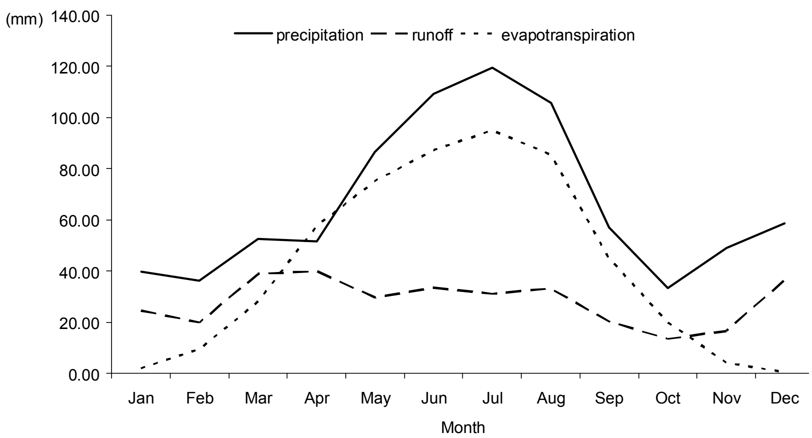

Figure 13. Runoff, precipitation, and evapotranspiration in the subbasin (No. 29), where the hydrotop of the highest evapotranspiration is located

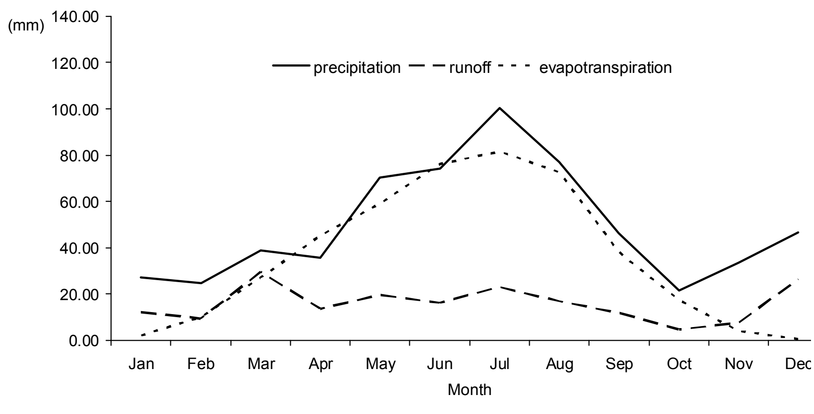

Figure 14. Runoff, precipitation and evapotranspiration in the subbasin (No. 7), where the hydrotop of the lowest evapotranspiration is located

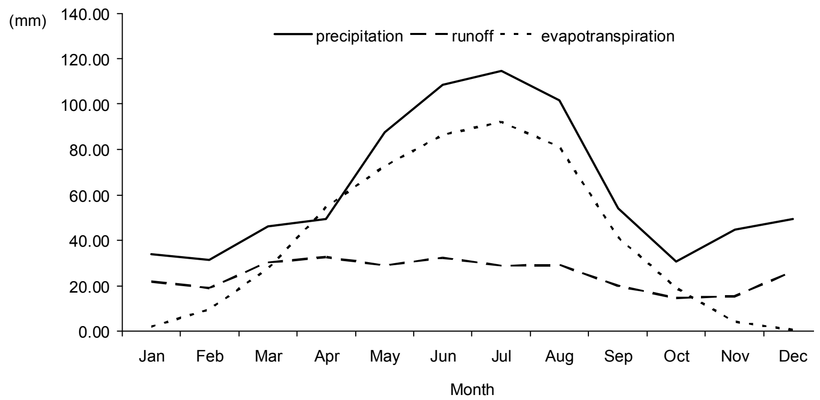

Figure 15. Runoff, precipitation and evapotranspiration in the subbasin (No. 28), where the hydrotop of the average evapotranspiration is located

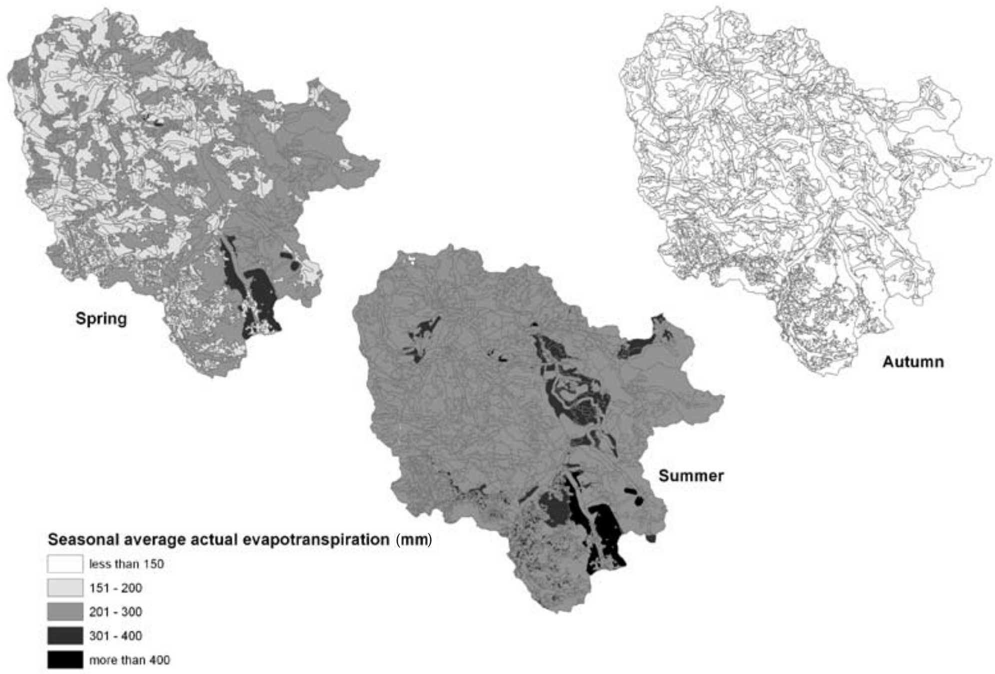

Figure 16. Average actual evapotranspiration (mm) in different seasons

CONCLUSION

The SWIM model can be used as a tool for the spatial simulations of the actual evapotranspiration over the river basins. It has been proved by comparing its data with those of the CHMI that the simulated values are realistic and satisfactory from the long-term point of view despite the overestimated values in the autumn period.

The assumptions about the influence of the individual geographic attributes (land cover, soil types, precipitation) on the spatial distribution of the actual evapotranspiration have been verified and evaluated except for the wetlands located on Histosols.

The next stage of the research will be extended by the acquisition of the field measured data during a field survey and by its integration into the SWIM model implementation.

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