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CLIMATE CHANGE IMPACT ASSESSMENT ON VARIOUS COMPONENTS OF THE HYDROLOGICAL REGIME OF THE MALŠE RIVER BASIN

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Climate change impacts on water cycle at regional scale have been recently very investigated and discussed issue. This study focuses on changes of not only total runoff but also others water balance components: soil water content and evapotranspiration, in a monthly step. The climate change was described using outputs of two different global circulations models, ECHAM and HadCM based on two divergent scenarios (optimistic B1 and pessimistic A2) according to the IPCC. The simulation of water cycle was processed in the mesoscale Malse basin (437 km^2) in southern Bohemia using distributed physically based hydrological model SWIM. The outputs for the time horizon 2050 were assessed in comparison with mean values from the representative period 1987–1998.

The study indicates vulnerability against predicted changes of both temperature and precipitation patterns referred to the selected scenarios. A decrease of total runoff was expected; however, hydrological balance will be different particularly in the monthly pattern within a year. The aim of this article is to describe the impact on various hydrological balance components.

KEY WORDS: Climate Change, Hydrological Modelling, Hydrological Cycle.

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Stále aktuálnější otázkou jsou dnes dopady klimatické změny na hydrologický cyklus v regionálním měřítku. Tato studie se zaměřuje na sledování změny nejen odtoku, ale také změn obsahu půdní vody a evapotranspirace, a to v měsíčním kroku v průběhu roku. Pro popis změny klimatu byly zvoleny výstupy dvou globálních modelů ECHAM a HadCM podle dvou odlišných scénářů budoucího klimatického vývoje (optimistický B1 a pesimistický A2) podle IPCC. Hydrologický cyklus byl simulován použitím distribuovaného fyzikálního hydrologického modelu SWIM, a to na středně velkém povodí jihočeské Malše (437 km^2), pro závěrový profil Pořešín. Výstupy odpovídající hypotetickému stavu v roce 2050 byly porovnávány s dlouhodobými průměrnými hodnotami z povodí za léta 1987–1998.

Ukazuje se, že středně velké povodí Malše je citlivé vůči předpovídaným změnám teplot a srážek a podle scénářů dojde k očekávanému celkovému poklesu odtoku z povodí. Tento pokles bude provázen změnami hydrologické bilance během roku, viditelné především přesunem maximálních hodnot jednotlivých prvků do jiných měsíců.

KLÍČOVÁ SLOVA: klimatická změna, hydrologické modelování, změny hydrologického cyklu.

Introduction

There is a growing consensus in the geoscience community that the Earth will experience a gradual warming in the coming decades. It is generally believed that this increase of temperature is caused by anthropogenic activity, although also natural processes have its influence. However, according to the IPCC AR4 (2007) most of the observed increase in global average temperature since the mid-20th century is very likely (with more than 90% confidence) due to the observed increase in anthropogenic greenhouse gases (GHGs) concentrations. This warming should lead to increase of temperatures in the area of the Central Europe and also to the change of precipitation pattern within a year. In the winter and spring period an increase should occur instead of decrease in summer time (*Kalvová* and *Nemešová*, 1997; *Kalvová* et al., 2002). Such changes in climate will also have a significant impact on local and regional hydrological regimes, which will in turn affect ecological, social and economical systems.

In recent years, numerous studies have investigated the impact of climate change on hydrology and water resources in many regions e.g. *Arnell* and *Reynard* (1996), *Bergström* et al. (2001), *Gao* et al. (2002), *Eckhardt* and *Ulbrich* (2003), *Stelle-Dunne* et al. (2008), *Kilsby* et al. (2007). Several impact studies have also been conducted in the Czech Republic e.g. *Kašpárek* (1998), *Košková* (2005), *Vizina* and *Horáček* (2009), *Kašpárek* and *Mrkvičková* (2009), *Horáček* et al. (2008) and in Slovakia e.g. *Danihlík* et al. (2004) or *Hlavčová* et al. (2008).

In this study the data from two global climate models (GCMs) ECHAM4 and HadCM2 are used to investigate the impact of climate change on the hydrological regime of the mountain-forested watershed of the Malše River on the Czech-Austrian border. The physically based hydrological model SWIM is applied in order to provide detailed information on changes in various components of the hydrologic cycle. Thus at first the ability of the SWIM model to simulate particular components of the hydrologic cycle was tested and then these simulated results were compared with those gained from simulations with new climatic data by GCMs.

Data and methods

Distributed modelling is considerably data demanding. Two sorts of data are required. Firstly, spatial data about basin describing the natural conditions in the basin and secondly time series of meteorological quantities. In addition, time series of the outlet discharge for the model calibration are needed. Optionally, any other measured quantities which are simulated by the model, e.g. evapotranspiration, soil water content etc. can be used for the comparison to observed conditions. However, it is very complicated to gain such data for medium-size basin.

The study area

The Malše River basin (979.1 km^2) is located in southern Bohemia and the Malše River is a right tributary of the Moldau River (in the Elbe Basin), see Fig. 1. There is a large drinking water reservoir Římov in the lower part of the basin, therefore the model was set up only for the upper part with the outlet at the gauging station Pořešín to deal with uninfluenced discharge. The catchment area takes a little more than one half of the whole basin area (436.83 km^2).

Spatial data

Four layers of spatial data are necessary for the model: map of sub-basins, digital elevation model, soil types and land cover, optionally a map of the river network. The hydrological model SWIM simulates water conditions in several layers of the soil column that is why detailed soil and hydrologic properties are required for each horizon of every soil type.

During the GIS processing the hydrotops were defined by overlaying the three input layers, the map of land use, the soil map and the map of subbasins. The subbasins and channel characteristics were derived from the DEM as well.

The Malše basin is a mountainous rather forested area with predominance of cambisols among soil types.

Hydrology

The hydrological characteristics of the Malše basin correspond to the fact that it is a mountainous area. The specific discharge resp. runoff coefficient is rather high (9.3 l s^{-1} km^{-2}). In the Tab. 1 the characteristics are compared with average values for the whole Elbe basin (the part in the Czech Republic).

The average annual daily discharge at the Pořešín gauging stations equals to 4.0 m^3 s^{-1}. Daily maximum discharges occur during summer after heavy rainfall. During the three biggest floods the daily discharges reached 107 m^3 s^{-1}, 90 m^3 s^{-1}, resp. 74 m^3 s^{-1}. However, the monthly maximal runoff occurs in April and is caused by snowmelt.

Runoff values of the span of 1961–1998 in a daily step were at disposal. Firstly, consistency of data series was checked by means of double mass analysis, when the runoff was plotted against precipitation in the basin. Then flow-mass integration curve showed equal slope for whole period with no evident disturbance. Twelve-years long (1987–1998) validation period, which is also the baseline for derivation of meteorological data series of climate change scenarios, was statistically verified to be representative in terms of a hydrological regime regarding whole time series. Monthly average runoffs were computed and the selected validation period was compared with the rest of dataset through profile analysis (e.g. *Anděl*, 2007). At first profile parallelism of the selected period and the

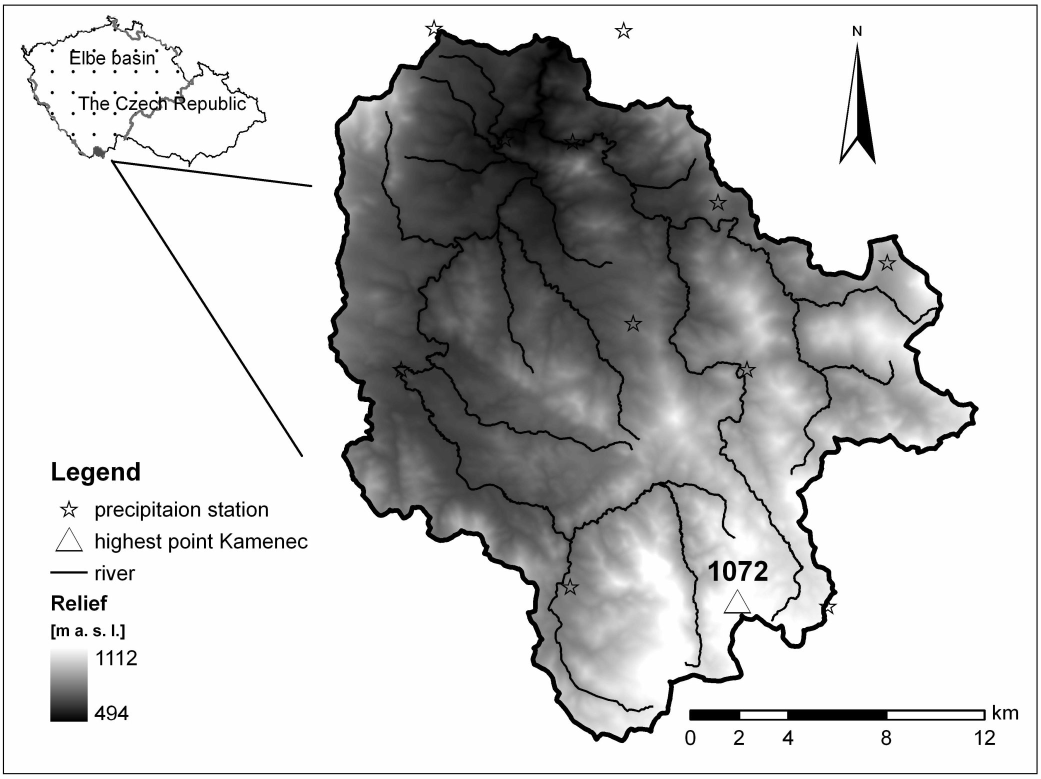

Fig. 1. Relief of the Malše River basin and its location within the Czech Republic.

T a b l e 1. Basic hydrological characteristics of the Malše and Elbe basins.

	Malše basin[1)]	Elbe basin (in the CR)[2)]
Mean annual rainfall [mm]	794	685
Depth of runoff [mm]	293	197
Runoff coefficient [%]	36.9	28.7
Specific discharge [$l\ s^{-1}\ km^{-2}$]	9.3	6.0

Source: [1)]observed 1980–1998, [2)]*Němec* and *Hladný* (2006).

rest of dataset was tested. Then homogenity of the curves of the selected period versus first third (1961–1973) and then versus second third (1974–1986) was tested. These tests resulted into the finding, that there is no point with statistically significant difference between selected period and the rest of dataset. Significance level of all tests was 95%.

Climate

The basin is located at the winward side of the Novohradské Mountains and the average annual rainfall is 794 mm. This area belongs to rather rainy region within the Elbe basin.

The climate data necessary to drive the model are precipitation, minimum, maximum and average temperature, air humidity, wind speed and solar radiation. The distributed model requires the input of meteorological data mentioned above for each sub-basin in a daily step. Therefore it was necessary to interpolate the variables over sub-basins, resp. their centroids. The interpolations of temperatures (T_{max}, T_{avg}, T_{min}) were performed by the method of universal kriging taking altitude into account. Precipitation, radiation and humidity were interpolated also by kriging but without considering altitude. This approach provided larger amount of precipitation over the basin than real values which fact might cause little overestimation of the model.

There are 9 precipitation gauging stations right within the basin and 5 not far from the basin. There is not any climate station (measuring other quantities besides precipitation) thus farther stations must be used. Actually, data from 20 measuring stations were at disposal.

Scenarios

In this study the incremental climate change scenarios were used. The delta change scenarios are sufficient for this kind of study concentrated on the sensitivity of the Malse basin under the climate change. The scenarios used were accepted from *Kalvová* et al. (2002), whose project assessed the most suitable scenarios and models for the area of the Czech Republic according to evaluation of the relief, vertical and horizontal resolution of the models and validation by historical run of the models over the span of 1961–1990. The climate change scenarios designed for impact studies in CR were created by downscaling of outputs of the selected models ECHAM4 (*Roeckner* et al., 1996) and HadCM2 (*Johns* et al., 1997) (more in *Kalvová* et al., 2002). The scenarios discover mean monthly/annual increase/decrease of single quantities expressed in percent (precipitation, humidity, wind speed, solar radiation) or in grades in the case of temperatures.

The observed climate series from 1987 to 1998 (corresponding to validation period) were set as baseline for deriving the affected time series by climate change. These modified model input time series were prepared by adding the differences to observed time series in 20 precipitation and climate stations.

The possible climate change is described in the Special Report on Emissions Scenarios (SRES) by the IPCC in varieties (*IPCC*, 2007). Two most divergent scenarios were applied in this study, A2 as a pessimistic future development and B1 as an optimistic scenario.

The A2 scenario supposes more divided world characterized by continuously increasing population and slower and more fragmented technological changes and improvements.

The B1 scenario assumes a more integrated and global world characterized by increasing population only up to limit in 2050 and the introduction of clean and resource efficient technologies with an emphasis on global solutions to economic, social and environmental stability.

Finally, 8 variants of modified time series of meteorological quantities (2 different global circulation models, 2 scenarios in 2 degrees of climate sensitivity) were derived for the purpose of this study, which deals with the hydrological modelling under future changed conditions.

Because of this delta change method does not account for variability of meteorological inputs in daily step this study is focus only on evaluation of average change, i.e. not the extreme situations. It could be considered as a drawback and therefore the outputs from regional climatic model will be used for further studies.

The model and its calibration

SWIM model

The SWIM (Soil and Water Integrated Model) is a spatially distributed physically based hydrological model which was compiled at PIK, Germany. It is based on two previous models, SWAT and MATSALU. The model was developed especially for impact studies at regional and basin scales (*Krysanova* et al., 1998, 2005).

The spatial disaggregation of the SWIM is a three-level scheme, basin – subbasin – hydrotope. The hydrotope is a spatial unit of the same geographical properties and therefore it may be assumed as a unit of an uniform hydrological response behaviour. Hydrotopes are derived by means of GIS tools by overlaying three input layers, the map of land use, the soil map and the map of subbasins.

This physically based model includes calculations of the single hydrological processes following specific techniques: water percolation (storage routing technique, *Arnold*, 1990), surface runoff (SCS CN technique), interflow (kinematic storage model, *Sloan* et al., 1983), groundwater recharge (*Hattermann*, 2004), evapotranspiration (*Priestly*, *Taylor*, 1972; *Ritchie,* 1972), vegetation cycle (EPIC model) and river routing (Muskingum routing). All processes are calculated for each hydrotope in a daily step and then aggregated and averaged for subbasins resp. monthly values. Full description can be found in *Krysanova* et al. (2000).

This study is focused on expressing actual evapotranspiration (AET), soil water (SWIND) and water yield (WYLD):

- The evapotranspiration is represented by calculating evaporation from soils and by transpiration of plants according to *Ritchie* (1972). The plant transpiration is calculated using value of potential evapotranspiration (*Priestly*, *Taylor,* 1972) and *LAI* (leaf area index). If soil water is limited, plant water transpiration is reduced.

- Soil water content is expressed by following water balance equation:

$$SW_{(t+1)} = SW_{(t)} + PRECIP - Q -$$
$$-ET - PERC - SSF,$$

where *SW*(*t*) – the soil water content in the day *t*, *PRECIP* – the precipitation, *Q* – the surface runoff, *ET* – the evapotranspiration, *PERC* – the percolation, *SSF* – the subsurface flow.

The soil water content in the day *t* is computed for the each soil layer of the profile. The storage routing technique (*Arnold* et al., 1990) is based on the equation:

$$SW_{(t+1)} = SW_{(t)}.\exp\left(\frac{-\Delta t}{TT}\right),$$

where *SW*(*t* +1); *SW*(*t*) – the soil water contents at the beginning and the end of the day [mm], Δt – the time interval [24 h], *TT* – the travel time through layer [h].

Model calibration and validation

The SWIM model in the Malše River basin was calibrated in the daily time step using stream flow gauging station Pořešín which is located above the Římov dam. After several testing runs the period of 1980–1984 was chosen for thorough calibration, because the results of the model performance were constantly best obtained in this particular period. Different calibration periods with different length were tested in this pre-calibration phase. This specific period is probably suitable also due to the variability of weather conditions, which causes presence of both low and high discharges. The best parameter set gained from the calibration period was then used for the validation of the model to see whether this set was suitable enough to be used for further analysis.

As a calibration tool the automatic parameter estimation algorithm (PEST) was chosen. The detailed description of PEST can be found in *Doherty* (2004). The basis of the PEST algorithm is the minimization of an objective function related to the difference between model-calculated variables and observations of these variables. The advantage of this method is the automaticity of the calibration process, especially when the SWIM model has 17 parameters to be calibrated. An attempt was made to reduce the number of calibration parameters but without any significant improvement in the Nash-Sutcliffe efficiency.

The Nash-Sutcliffe index of performance was used to assess model calibration at the daily basis. Reasonable value of 0.7 was gained for the entire period of 1980–1998 using the best parameter set from the calibration period. The 12-years period of 1987–1998 was used for detailed validating of the model performance. Within this period the Nash-Sutcliffe coefficient of 0.73 was reached for daily discharges. These values were considered satisfactory because they correspond e.g. to the values obtained by *Luo* et al. (2008) and exceed those by *Kannan* et al. (2007), who had used a similar physically based model SWAT. Model performance in validation period is shown in Fig. 2. Higher values of the Nash-Sutcliffe coefficient were not reached particularly due to not precise simulation of peaks of the biggest floods and also due to an occasional overestimation of discharges, especially when low flows occur. Thus focusing on the model performance these are the areas of a future interest.

The annual course is simulated very accurately, both maximum and minimum occur in the same months, in April, resp. October. The match of observed and simulated (SWIM) monthly runoff is shown in Fig. 3 and in Tab. 2. The simulations in May seem to be only problematic and disturb the simulated annual course. However, characteristics concerning the total runoff are overestimated by 10 % (e.g. mean daily discharge observed 4 $m^3 s^{-1}$ vs. simulated 4.41 $m^3 s^{-1}$). In spite of that, the absolute maximum daily discharges are underestimated by circa 30 %.

Results

The validated hydrological model was then used for simulation of future climate conditions using results from two distinctive GCMs ECHAM4 and HadCM2. The intention was to focus on particular parts of hydrologic cycle and therefore the need for thorough analysis of the cycle has emerged. Further attention was only paid to the validation period of 1987–1998.

Mean areal precipitation within the Malše River basin was determined by kriging interpolation method to be equal to 830 mm per a year within a desired period of 1987–1998. The average amount of yearly evaporated water volume simulated by the model SWIM is 536 mm, which corresponds to the values of 500–550 mm presented by ČHMÚ in the

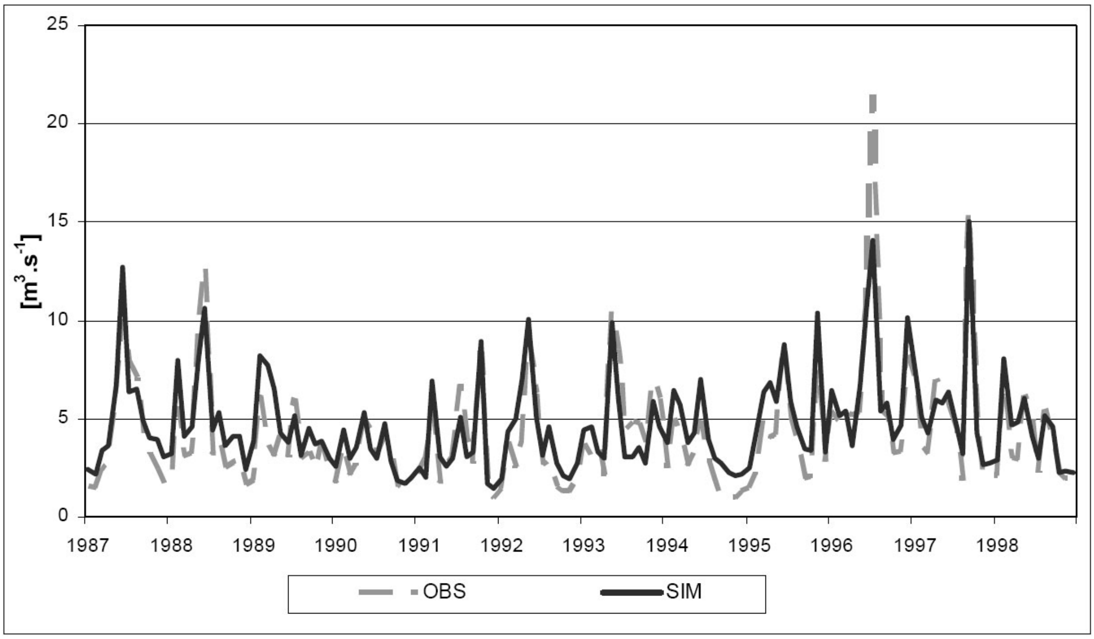

Fig. 2. Model discharge performance in validation period 1987–1998 compared with observed discharge at the gauging station Pořešín.

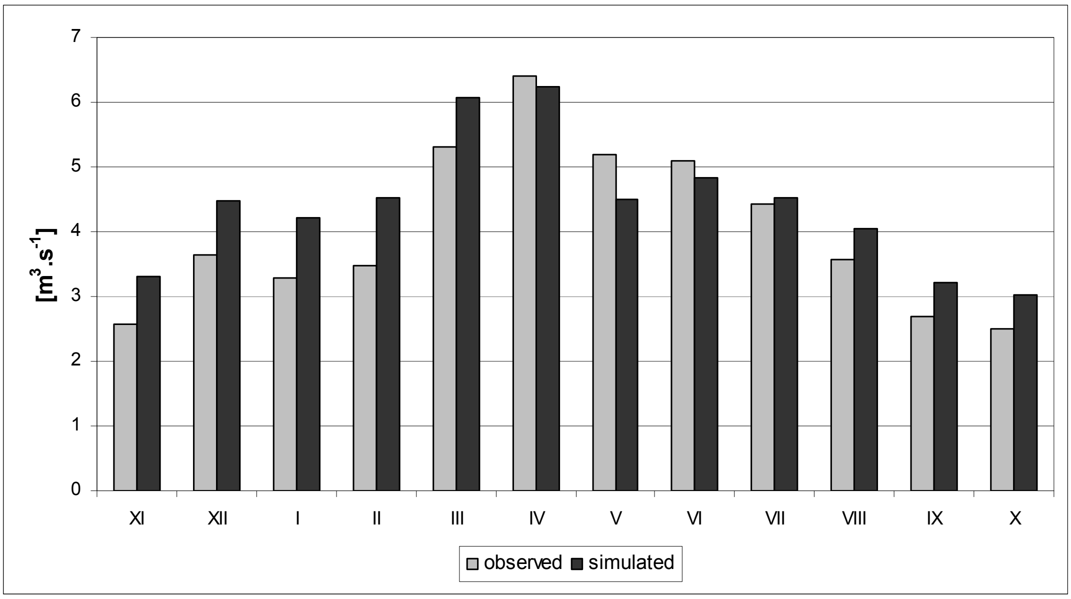

Fig. 3. Simulated and observed average monthly runoff at the gauging station Pořešín in 1961–1998.

T a b l e 2. The comparison of the observed and simulated hydrological characteristics at the gauging station Poresin, derived from the period 1980 – 1998.

Poresin	Observed	Simulated by SWIM
Mean daily discharge [m^3 s^{-1}]	4.01	4.41
Mean annual runoff [m^3]	126672291	138691934
Depth of runoff [mm]	293	320
Specific discharge [l s^{-1} km^{-2}]	9.3	10.2

Climate Atlas of the Czech Republic as an annual average for this region (*ČHMÚ*, 2007). The rest of the water from rainfalls flows directly to the streams as a direct runoff or percolates to the groundwater and then forms ground water flow. The rate of the direct runoff is estimated to be equal to 170 mm annually with the highest values in the spring period. The remaining amount of water is percolated and recharges the groundwater (represented by shallow and deep aquifers). The annual behaviour of the hydrologic cycle components is depicted in the Fig. 4.

The picture indicates that owing to the lack of evapotranspiration during the winter period the *soil water index* (SWIND), which is the ratio of the soil water content to the field capacity of the soil, is increasing in spite of the fact that *water yield* (WYLD) is also higher during this period. On the contrary, evapotransipration rates in the summer are significantly higher and the SWIND is therefore descending.

B1 scenario

Focusing on the B1 scenario the values of the mean monthly *water yield* (WYLD), which represents the sum of surface, subsurface and groundwater flows, are significantly lower in the entire period (see Fig. 5). The higher differences can be observed in April, August and September in both GCMs. The decrease could reach nearly up to 50 % of the present value; however, the average decrease is circa 20 %. During the winter time the fall of WYLD is less evident, especially in December when the values are nearly the same as observed. The descent is far more obvious using the climate scenarios with the high climatic sensitivity to uncertainties. The results from ECHAM4 and HadCM2 GCMs broadly correspond together with the greatest variance in April.

Soil water index (SWIND) has nearly the same values from the mid-winter to the mid-spring period otherwise the values are lower due to higher temperature and lack of precipitation over the warmer part of the year. The average changes in monthly values are depicted in the Tab. 3. The yearly performance shows that in the summer and autumn period the values of the SWIND are decreasing and this deficit is recharged during winter and spring, when the amount of precipitation is higher. The average decrease for the summer and autumn period is 5.2 % in the case of low climatic sensitivity and 9.2 % in the case of high sensitivity. Performances of both GCMs correspond together very accurately.

The values of *actual evapotranspiration* (AET) are higher in the case of both GCMs during entire year except the winter period, which is probably caused by recharging the water in the soil and thus the amount of water available to evapotranspiration lowers. The average annual increase is equal to 15 mm for the low and 27 mm for high climatic sensitivity. The biggest difference in monthly values

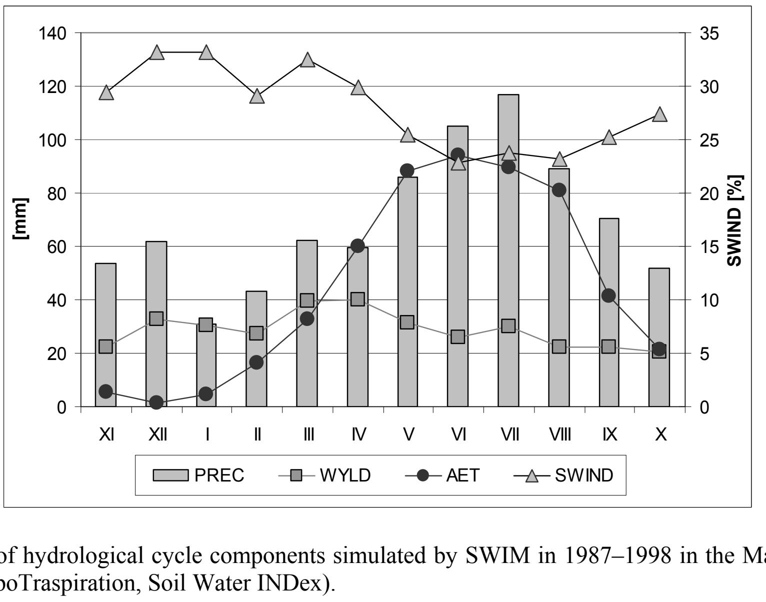

Fig. 4. Monthly averages of hydrological cycle components simulated by SWIM in 1987–1998 in the Malše basin (PRECipitaion, Water YieLD, Actual EvapoTraspiration, Soil Water INDex).

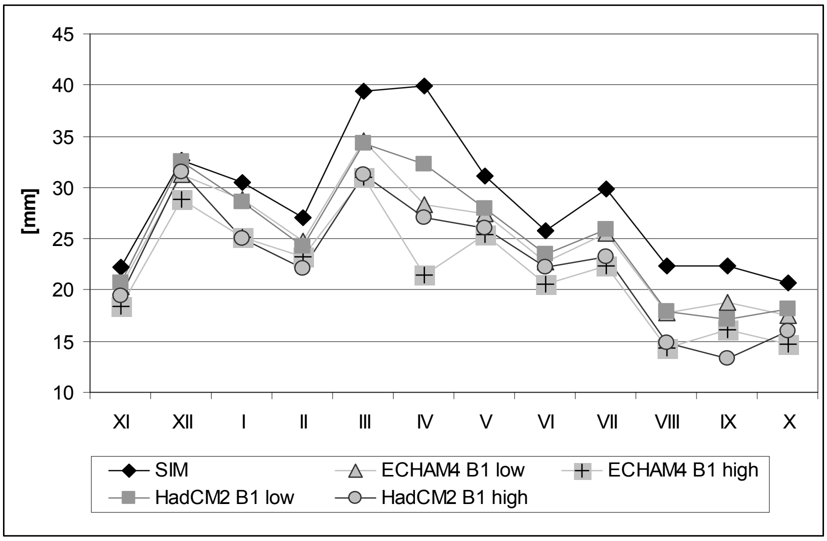

Fig. 5. Simulated average monthly water yield in the Malše River basin using B1 scenario by models ECHAM4 and HadCM2, comparison with the simulation of the reference period 1987–1998.

T a b l e 3. Simulated percentage change in monthly sums of Soil Water Index by two GCMs using both A2 and B1 scenarios in comparison with the simulated values for reference period 1987–1998 in the Malše basin (normal font for same values or decrease up to 5 %, bold font for decrease from 5 to 15 %, and bold italic font for bigger drop.)

	ECHAM4 B1 low	ECHAM4 B1 high	HadCM2 B1 low	HadCM2 B1 high	ECHAM4 A2 low	ECHAM4 A2 high	HadCM2 A2 low	HadCM2 A2 high
November	–2.4	**–5.6**	–2.5	**–5.9**	–3.9	**–8.0**	–3.5	**–8.4**
December	–0.2	–1.4	0.1	–0.6	–1.2	–2.4	–0.1	–1.3
January	–1.3	–2.5	–1.3	–2.9	–2.0	–3.1	–1.8	–3.5
February	–0.8	–1.3	–1.1	–1.8	–1.1	–2.0	–1.5	–2.2
March	–1.2	–2.8	–1.2	–2.3	–1.9	–3.7	–1.5	–3.0
April	**–5.7**	**–9.8**	–3.2	–4.9	**–7.5**	**–11.0**	–3.8	**–5.7**
May	–4.9	–7.5	–3.0	–4.0	**–6.3**	**–8.8**	–3.4	–4.5
June	–3.0	–2.6	–2.8	–2.5	–3.4	–2.2	–2.7	–2.2
July	–3.9	**–5.4**	–4.2	**–5.7**	**–5.0**	**–6.6**	–4.7	**–6.8**
August	**–7.1**	**–13.9**	**–7.6**	**–14.3**	**–9.8**	***–18.7***	**–9.8**	***–18.9***
September	**–6.1**	**–12.4**	**–9.4**	***–19.2***	**–8.4**	***–16.9***	**–12.5**	***–25.9***
October	–4.4	**–9.4**	**–6.4**	**–13.9**	**–6.4**	**–12.7**	**–8.8**	***–19.2***

occurs in August when the AET rate is 4 mm higher for low and 9 mm for high sensitivity scenarios. The absolute change in average monthly actual evapotranspiration is showed in the Tab. 4.

As for the B1 scenarios, the average annual *stream flow* rates show a decrease of 12 % for the low sensitivity and 22 % for the high climatic sensitivity. Mean monthly discharges obtained by the simulations based on both GCMs are represented in the Fig. 6. The pattern of the average monthly flows remains the same as the present one but the significance of spring maximum is decreasing. As the figure shows the discharges are lower than observed during the whole year. The main decrease takes place from March to October with a maximum in April ranging from 19 up to 45 %. This could be caused by the fact that more winter precipitation will be in a form of a rain so the snow accumulation will be smaller and thus the spring discharges from the snowmelt will also decrease. The overall lowest decrease is represented by ECHAM4 GCM B1 low scenario because in this case the climate change is less recognizable in the meteorological datasets. The results for stream flow rates correspond to the results of WYLD which are also lower for the entire year. The lowered WYLD is also caused by the fall in groundwater flow, which has dropped by 10 % for low sensitivity and by 29 % for high sensitivity on average. This process is also well documented in the percolation and groundwater recharge rates, which are uniformly beneath the observed values in the case of all

T a b l e 4. Simulated change in absolute of monthly sums of actual evapotranspiration in mm by two GCMs using both A2 and B1 scenarios, as against the simulated values for reference period 1987–1998 in the Malše basin (normal font represents change up to 2 mm, bold font represents increase from 2 to 5 mm, and bold italic font 5–15 mm).

	ECHAM4 B1 low	ECHAM4 B1 high	HadCM2 B1 low	HadCM2 B1 high	ECHAM4 A2 low	ECHAM4 A2 high	HadCM2 A2 low	HadCM2 A2 high
November	–0.2	0.0	–0.5	–0.6	–0.2	0.2	–0.6	–0.6
December	–0.1	–0.1	–0.3	–0.3	–0.1	0.0	–0.3	–0.4
January	–0.5	–0.5	–0.5	–0.6	–0.6	–0.5	–0.6	–0.6
February	1.1	**2.7**	0.3	0.7	1.6	**3.6**	0.4	1.0
March	**3.2**	***5.2***	**2.0**	**2.3**	**3.6**	***6.5***	**2.1**	**2.7**
April	**2.8**	***5.3***	1.9	**2.9**	**3.5**	***7.1***	**2.2**	**3.8**
May	0.9	–1.9	1.8	1.2	–0.1	–3.9	1.6	0.7
June	1.1	0.7	**2.7**	**3.7**	0.5	0.7	**3.0**	**4.5**
July	1.6	**4.6**	**2.1**	***5.0***	1.9	***7.1***	**3.0**	***7.2***
August	**4.4**	***9.2***	**4.3**	***8.6***	***5.6***	***12.1***	***5.7***	***11.1***
September	0.6	1.1	**2.3**	**4.7**	0.6	1.2	**3.2**	***6.0***
October	0.5	1.4	–0.3	0.0	0.8	1.8	–0.2	0.0

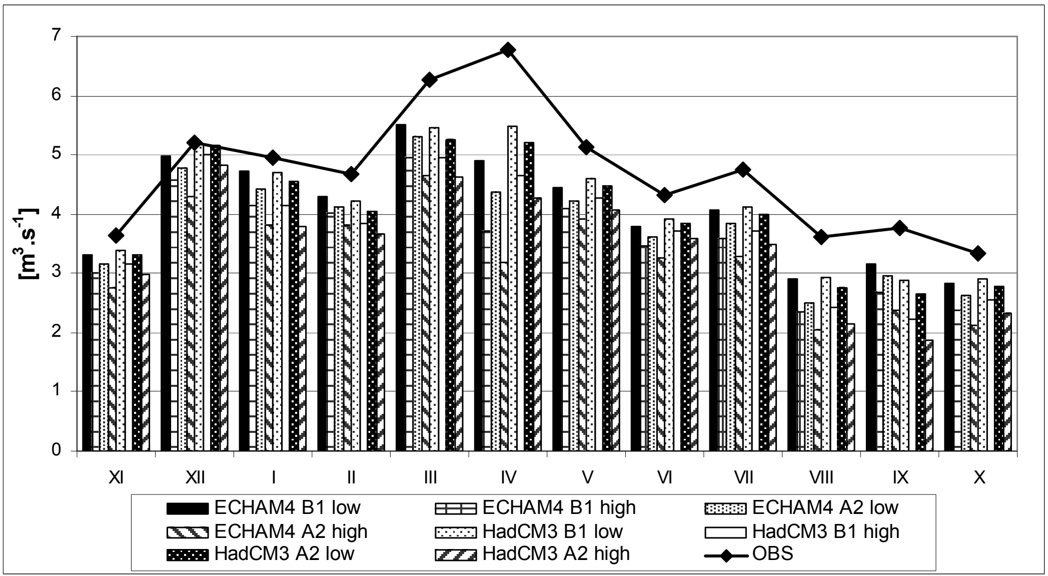

Fig. 6. Modelled average monthly discharges using both A2 and B1 scenarios by models ECHAM4 and HadCM2 at the Pořešín gauging station compared with long term simulated values from 1987 – 1998.

possible variations of B1 climatic scenario. Very similar pattern of processes was also observed by *Eckhardt* et al. (2003) in the case of the Dill catchment in Germany.

A2 scenario

The similar effects of the climate change as in the scenario B1 are in the case of A2 scenario observed, yet intensified by the greater temperature rise and the changes in precipitation.

Mean monthly *water yield* is significantly different compared to the present-day scenarios (see Fig. 7). Water yield decreases in the spring and summer time according to a precipitation decrease and from the late autumn to winter the values are getting close to observed ones but more frequently do not exceed them. The average annual WYLD drops by 15 % for the low climatic sensitivity and 35 % for high. Only in the case of December and the A2 scenario with low climatic sensitivity the values of WYLD are close to observed. The largest decrease in monthly water yield occurs during the month of April, August and September which can reach up to 25/50 % referring to low/high climatic sensitivity. This water yield pattern corresponds to a translocation of precipitation from summer to winter period. The sensitivity of water yield to precipitation pattern was also well documented by *Ficklin* et al. (2009).

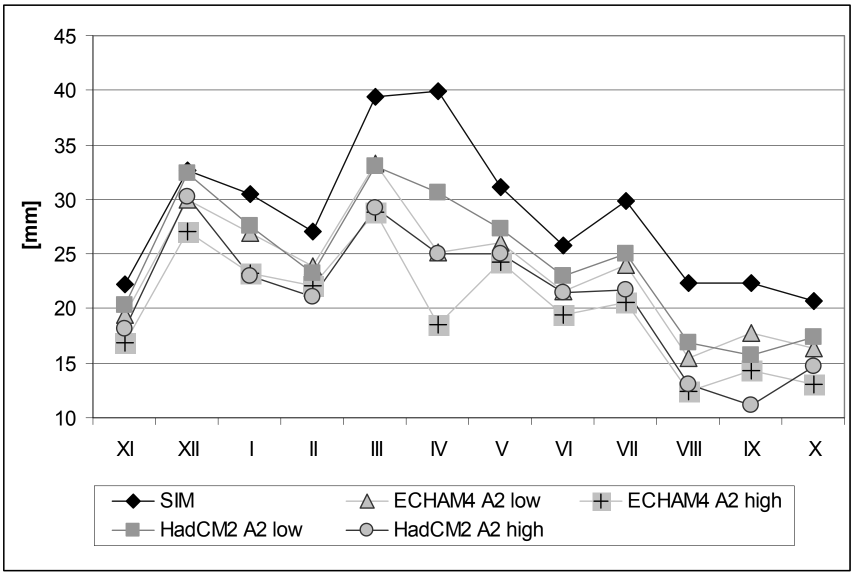

Fig. 7. Simulated average monthly water yield in the Malše River basin using A2 scenario by models ECHAM4 and HadCM2, comparison with the simulation of the reference period 1987–1998.

The *soil water index* has the same pattern as observed but the fall of water volume in the soil during summer and autumn is significantly higher. The average decrease in this period of the year is from 6.8 % to 11.9 % (low and high sensitivity). Values of each month can be found in the Tab. 3. This behaviour corresponds to translocation of precipitation within a year and thus the water level in the soil is falling down during the dry and warm period of the year and subsequently is recharged by winter rainfall.

Average monthly values of *actual evapotranspiration* are above observed values for the majority of the year except the winter period (see Tab. 4). In the winter period the process of groundwater recharge is probably dominating so the available water for evapotraspiration is limited. The annual average increase of the evapotranspiration rates is 18 mm for low climatic sensitivity and 35 mm for high sensitivity. The results of both GCMs correspond to each other, which is probably caused by the fact that in temperatures the GCMs vary less than in the case of expected change of rainfall patterns.

The average monthly *stream flow* pattern modify as a consequence of the changes in the particular components of the hydrologic cycle as it was stated above. The process that is observed in the case of B1 scenario is for A2 amplified by more intensive temperature rise and precipitation translocation (see Fig. 6). Thus, the April maximum of stream flow has vanished and represents the largest decrease in stream flow rate ranging from 23 % to 53 % depending on the sensitivity used. Totally, the average annual stream flow has dropped by 15 % in the case of HadCM2 A2 low scenario and by 30 % in the case of ECHAM4 A2 high scenario. It is obvious that the April decrease is more profound in the case of ECHAM4 GCMs, which seems to be caused by input meteorological datasets.

According to the results watershed-wide averages of water yield decrease significantly for the majority of months. In the winter time period (November–January) only a slight decreases or even equal values are observed. The average decrease in WYLD values is 20 % for B1 scenario and 25 % for A2 scenario. The rates of actual evapotranspiration are higher for the entire year except the winter. The increase is higher in the case of A2 scenario. The soil water index representing the volume of water in the soil drops from 5 % to 9 % on average. However, in the winter period the descent is less evident. As a result of these alternations the discharges are lower for every single month. In general, the decrease is most obvious during spring period, especially in April. The average monthly discharge decreases by 12/22 % in the case of B1 scenario and low/high climatic sensitivity. Taking the A2 scenario into consideration the fall of the average monthly discharges is 15 % for low and 30 % for high climatic sensitivity. However, it is important to be aware of the model tendency to overestimate the simulated results, thus the final discharges could even be lower.

Discussion and conclusions

This study illustrates changes in water resources related to potential climate change based on the SWIM model simulation in the area of the Malše River basin. The results in this study indicate that the hydrological system in the study area is very sensitive to climatic variations on a monthly basis. The main process that will modify the hydrological cycle is uniform temperature increase and the translocation of certain amount of summer precipitation to winter period.

The hydrological model SWIM appears to be the suitable tool for simulating hydrological cycle within the Malše River basin. It was proved when the value of 0.70 of the Nash-Sutcliffe efficiency was gained for the validation period taking daily discharges into an account. Nevertheless, there is still an area of peak and, on the other hand, very low discharges to be improved in order to gain more precise simulations. However, a slight overestimation of discharges can be partially explained by the chosen interpolation method for precipitation. The average year sum of precipitation gained by kriging equals to 830 mm but to 794 mm using Thiessen polygons. Additionally, according to *Kalvová* et al. (2002) both GCMs overrate yearly sums of the precipitation, especially in the winter. Despite this fact, both GCMs are eligible to be used for the Czech Republic. Certainly, this overestimation of discharges might have an effect on the climate change simulations, in the way that even the results from the simulations could be overestimated. The uncertainty of the simulated results, especially its tendency to be overestimated, is increasing with the decreasing amount of precipitation. Thus the results from the rainy period of the year are more reliable than those from dry period. Possible underestimation of future discharges would only be possible in the case of the peaks. Generally, as the model performs, rather lower values of the future discharges might be expected compared to the simulated ones.

As the results of simulations show, the most significant change in the discharges takes place in spring period. Due to a precipitation translocation to the winter period and increasing temperature the snowpack is expected to be lower and thus the spring discharges drop significantly. Similar pattern was also presented by *Danihlík* et al. (2004) and *Hlavčová* et al. (2008) for the Hron basin in Slovakia. The major difference is in the increase in winter discharges, which is in the case of Slovakia more obvious. The same results were presented by *Košková* et al. (2005) using same climatological scenarios but Sacramento SAC-SMA hydrological model in the Bílina River basin. The fact that the winter discharges in the case of the Malše River either remain at the same level or slightly decrease was unexpected, especially when increases were observed in other studies. It arouses e.g. the question how accurately can the GCMs represent the climate change in the watersheds, where the significant amount of rainfall is caused by the strong orographic effect as it is in the case of the Malše River. This fact might cause the results presented by *Kalvová* et al. (2002) that the decrease in the Malše River basin is more obvious than in the case of any other watershed used in the study.

It has to be noted that the scenarios used in this study were able only to estimate mean monthly changes in rainfall intensity and temperature. It is necessary to understand more about the both spatial and time distribution of rain, so that further interest should be focused also on this area but more in detail. And therefore the outcomes for the GCMs must be associated with the certain uncertainty. Nevertheless, the results obtained from two different GCMs are close enough to assume that at least the orientation of the future development is correct. The main difference between ECHAM4 and HadCM2 occurs in the case of April discharge when ECHAM4 predicts deeper decrease. On the contrary, the discharges simulated by HadCM2 GCM are generally lower in the autumn. The vulnerability and sensitivity of the basin was proved by using the global models outputs, next research will be concentrate on using outputs of regional models.

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List of symbols

AET – actual evapotranspiration,
CHMI – Czech Hydrometeorological Institute,
DEM – Digital Elevation Model,
ECHAM4 – The fourth-generation atmospheric general circulation model, developed at the Max Planck Institute,
EPIC – Erosion Productivity Impact Calculator,
GCM – Global Circulation Model, atmospheric model,
GHG – greenhouse gases,
GIS – Geographical Information System,
HadCM2 – The second generation Hadley Centre coupled circulation model,
IPCC – Intergovernmental Panel on Climate Change,

IPCC AR4 – Fourth assessment report of IPCC,
PEST – Model-independent parameter estimation algorithm,
PIK – Potsdam Institute for Climate Impact Research,
PREC – Precipitation,
SCS CN – Soil Conservation Service Curve Number method,
SRES – Special Report on Emissions Scenarios,
SWAT – Soil and Water Assessment Tool, hydrological model,
SWIND – Soil Water Index,
SWIM – Soil Water Integrated Model,
WYLD – Water yield (the sum of surface, subsurface and groundwater flows).

Data sources
Spatial data:

land use – CORINE land cover database, European Environmental Agency (ww.eea.europa.eu)

DEM – SRTM project, National Geospatial Intelligence Agency

Soil map and characteristics – Czech University of Life Science

Time series: Czech Hydrometeorological Institute

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