Modelling changes in the runoff regime in Slovakia using high resolution climate scenarios

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Abstract The potential impact of climate change on river runoff and the water balance in a mountainous basin in Slovakia was evaluated using a conceptual spatially-lumped water balance model and a regional climate model (RCM). The basin is significantly affected by local climate conditions, and the need for high resolution climate studies is particularly important here. Within the framework of the Sixth Framework Program CECILIA (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment), the ALADIN-Climate regional model with a very high resolution was developed and applied to test the sensitivity of the basins to climate change. The climate characteristics, such as precipitation totals, air temperature and relative air humidity, were simulated by the ALADIN-Climate model in daily time steps with a grid spacing of 10 km. These grid climate outputs were spatially averaged over the selected basins and recalculated to monthly time steps. The conceptual water balance model was calibrated in monthly time steps with data from the 1971-2000 period and validated with data from the 1961-1970 period. Based on the outputs of the ALADIN-Climate model, possible changes in the mean monthly runoff for the time horizons of 2021-2050 and 2071-2100 were estimated. The simulated results of the long-term mean monthly runoff indicate future changes in the seasonal runoff distribution in the mountainous basins of Slovakia.

Keywords regional climate change scenario; the Hron river basin; changes in runoff

INTRODUCTION

The impact of climate change on hydrological processes is usually estimated by defining the scenarios of changes in climatic inputs to a hydrological model from the output of general circulation models (GCMs). As was also reported in the IPCC Fourth Assessment Report (IPCC, 2007), most hydrological impact studies are based on global rather than regional climate models. Two approaches are often used to construct weather series representing a changed climate (Dubrovsky *et al.*, 2000): an observed weather series is modified by the scenario parameters (Maytín *et al.*, 1995), or a weather series is produced by a weather generator whose parameters have been modified according to the scenario (Dubrovsky *et al.*, 2000).

Global Circulation Models (GCMs) can reproduce climate features on a large scale reasonably well, but their accuracy decreases when proceeding from continental to regional and local scales because of the lack of resolution. In the region of central and eastern Europe the need for high resolution studies is particularly important. This region is characterized by the northern flanks of the Alps, the long arc of the Carpathians, and smaller mountain chains and highlands in the Czech Republic, Slovakia, Romania and Bulgaria that significantly affect the local climate conditions.

The ALADIN-Climate prediction model as originally developed by an international team headed by Météo-France, and its modification for RCM purposes started in 2001 in cooperation with CHMI in Prague. ALADIN is a fully three-dimensional baroclinic system of primitive equations using a two-time-level semi-Lagrangian semi-implicit numerical integration scheme and digital filter initialization (Bubnová *et al.*, 1994; Vána, 1998). A few modifications had to be made to run the

ALADIN model in a climate mode; they mainly include changes in lower boundary condition specifications and the availability of a restart (CECILIA, 2007).

Monthly conceptual water balance models are intended to simulate selected hydrological processes, usually by conceptualizing a catchment as an assemblage of interconnected storage systems through which water passes from input as rainfall to output as streamflow at the catchment outlet; the controlling equations usually satisfy the requirements of the hydrological balance. In impact studies, the model parameter values from the representative periods are usually considered to be representative of runoff generation in the future.

Several climate change impact studies have been conducted in recent years on the territory of Slovakia. Usually, three types of climate change scenarios have been used in previous impact studies: analogue scenarios based on an analogy with warmer periods and periods with a specified variability in the climate in the past (WP and SD); regionally downscaled GCM scenarios (CCCM, GISS, GFDD3) with typical time horizons of 2010, 2030 and 2075; and incremental climate change scenarios. Additional details can also be found in the following studies on Slovak rivers: Danihlík *et al*. (2004); Halmová (2004a); Halmová & Melo (2006); Hlavčová *et al*. (2006b; 2008); Kostka & Holko (2001); Kostka (2003); Majerčáková & Takáčová, (2001); Pekárová & Szolgay, eds. (2005); Petrovič (2000); Szolgay *et al*. (2007a,b) and Takáč (2001).

In this study the potential impact of climate change on river runoff in the upper Hron River basin was evaluated using a conceptual spatially-lumped water balance model. The conceptual water balance model was calibrated with data from the 1971-2000 period. The period of 1971-2000 was assumed to be the reference for impact simulations in the CECILIA (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment, CECILIA (2007) project. Changes in climate variables in the future were expressed by two different climate change scenarios developed within the framework of the CECILIA project. The climate change scenarios were constructed using the ALADIN – Climate regional model with a grid resolution of 10 km.

PILOT BASIN AND INPUT DATA

The upper Hron River basin (total catchment area of 1766 km^2) can be considered as a representative Slovak mountain basin with an environment which is unaffected by water tanks. The River's network is slightly asymmetrical with the left-hand dominated catchment areas caused by major tributaries of the Black Hron River and Slatina River. The minimum altitude of the basin is 340 meters above sea level; the maximum altitude is 2034 meters above sea level; and the average altitude is 850 meters above sea level (Fig.1). The upper Hron River lies in a cool and wet climate zone. The average annual temperature in the upper valley parts of the Hron are between 4 and 5 °C; the average annual precipitation is 800 - 900 mm; and the evapotranspiration in the upper parts of the Hron River is significantly lower than the precipitation, so we have recorded a surplus moisture.

Fig. 1 Map of the river network in the upper Hron river basin.

The monthly water balance model which was used requires at a minimum the time series data of the monthly average of precipitation [mm], the air temperature [°C] and runoff [m^3 s^{-1}]. These can be extended by data required for estimating the potential evapotranspiration. Daily precipitation data for the study area were measured in 21 rain gauge stations; daily temperature data were available from 6 climatic stations (fig.2). These measured values were subsequently converted to the monthly average data. The long-term monthly potential evapotranspiration data were calculated by the method of L.I. Zubenok (Zubenok, 1976).

Fig. 2 Rain gauge stations (red) and climatic stations (blue) for the upper Hron basin.

METHODOLOGY

a) calibration of the conceptual hydrological balance model in monthly time steps for the Hron river basin,

b) simulation of the reference mean monthly runoff series using climate data input from the reference period of 1961-1990,

c) modification of the climate input data from the reference period (precipitation totals, air temperature and relative air humidity) according to the ALADIN-Climate model outputs for the time horizons of 2021-2050 and 2071-2100,

d) simulation of the monthly runoff series using the calibrated hydrological balance model and changed input climate data,

e) comparison of the differences between the seasonal runoff distribution in the reference period and future time horizons.

DESCRIPTION OF THE HYDROLOGICAL MODEL

For estimating the changes in the seasonal runoff distribution, the conceptual hydrological balance model (Danihlík *et al.*, 2004) that was developed at the Slovak University of Technology, Department of Land and Water Resources, was used (Fig. 3). This model is a refinement of the Watbal model (Výleta *et al.*, 2009) which was chosen as a reference model for the CECILIA project (CECILIA, 2007). The inputs required for the modelling of the water balance in monthly time steps are: the mean monthly precipitation for the basin, the mean monthly discharges in the outlet of the basin, and the mean monthly potential evapotranspiration (PET). For calculating the potential evapotranspiration, various methods can be used, e.g., L.I. Zubenokova’s method (Zubenok, 1976), the Thornthwaite method (Thornthwaite, 1948; Novák, 1995), the Ivanov method (Novák, 1995) and the FAO method (Doorenbos & Pruitt, 1977). Additional climate data (the mean monthly air temperature values, the mean monthly hours of the duration of sunshine, the mean monthly values of the relative air humidity or the mean monthly values of the water vapor pressure, the mean monthly values of the wind speed, the monthly cloudiness values and the number of days with snow cover in a month) are also required. The model simplifies the river basin by dividing it into 2 nonlinear reservoirs: in the first nonlinear tank, the process of accumulation and snow melting takes place; and in the second nonlinear tank, the simulation of the hydrological balance of the catchment’s elements takes place. The underlying assumption of the model is that the individual components of the runoff from the basin depend on the actual volume of water in the basin.

The basic mass balance equation in the model is written as:

$$S_i - S_{i-1} = \left[\left(R_{act(i)}\left(1-\beta\right)\right) - Rs_i - Rss_i - Ea_i - Rb\right]\Delta t \qquad (1)$$

where:

S_i, S_{i-1} - water currently stored in the basin in months i and i -1 [mm],
i - time step [month],
R_{act} - effective precipitation in the month i [mm],
β - direct runoff coefficient [–],
Rs_i - surface runoff in the month i [mm],
Rss_i - subsurface runoff in the month i [mm],
Ea_i - the basin’s average actual evapotranspiration in the month i [mm],
Rb - base flow [mm].

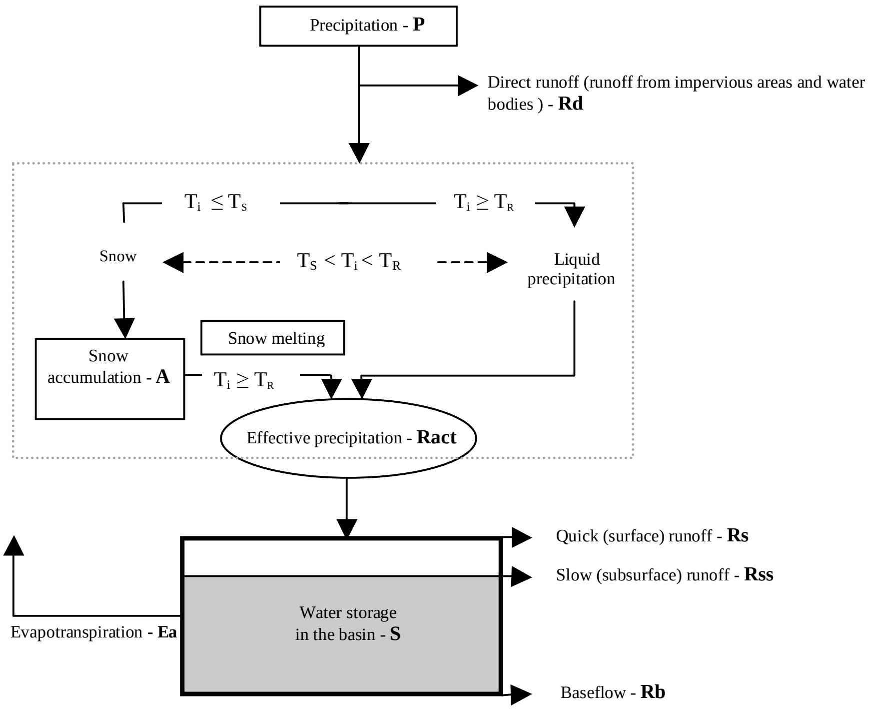

Fig. 3 Scheme of the hydrological balance model.

At the beginning of the simulation the part of the precipitation which has fallen to the impermeable surface or the water surface is extracted as direct runoff. The rest of the precipitation goes to the first snowmelt and snow accumulation nonlinear reservoir, which enables a distinction to be drawn between the solid and liquid precipitation on the basis of the threshold temperatures. In this reservoir, the effective precipitation, which further participates in the formation of runoff, is calculated as:

$$R_{act(i)} = mc_i \, (A_{i-1} + P_i) \qquad (2)$$

where:
$Ract_{(i\}}$ - effective precipitation for the basin in one month i [mm],
P_i - the basin's average measured precipitation in a month i [mm],
$A_{i\text{-}1}$ - snow accumulation in the month i-1 [mm],
mc_i - snow melting factor in the month i [–].

An important part of the model is calculating the mc factor (the snow-melting factor), which divides the observed precipitation into rain and snow. If the current air temperature in the month i is higher than the threshold temperature T_R, all the precipitation is considered to be liquid, and it will participate in the formation of runoff in this month.

$$mc_i = 1, \; if \; T_i \ge T_R \qquad (3)$$

If the current air temperature is lower than the threshold temperature Ts, all the precipitation is accumulated in the snow cover.

$$mc_i = 0, \; if \; T_i \le T_S \qquad (4)$$

In the event the current air temperature is in between Ts and T_R (T_S < Ti < T_R), a part of the liquid and a part of the accumulated precipitation is calculated according to the snow-melting factor mc:

$$mc_i = \left[\frac{T_i - T_s}{T_R - T_s}\right]^{C_{Ract}}, \; if \; T_s < T_i < T_R \tag{5}$$

where:

mc_i - snow-melting factor in the month *i* [–],
T_i - mean air temperature in the month *i* [^{o}C],
C_{Ract} - parameter for calculating the basin's average effective precipitation [–],
T_s - threshold air temperature for snow accumulation [^{o}C],
T_R - threshold air temperature for snow melting [^{o}C].

The snow accumulation is calculated by the equation:

$$A_i = (1 - mc_i)(A_{i-1} + P_i) \tag{6}$$

Parameters A_i and A_{i-1} represent the snow accumulation in months *i* and *i*-1 [mm]. The quick (surface) runoff *Rs* is calculated as a function of the ratio between the current and maximum water storage in the second nonlinear (water accumulation) reservoir. It is also a function of parameter *ε* and the difference between the effective precipitation and baseflow *Rb*. The basic drain *Rb* represents the supplying of the flow from the groundwater in a minimum flow period.

If the effective precipitation in month *i* is lower than the base flow value, the surface runoff is equal to zero.

$$Rs_i = 0, \; if \; R_{act(i)} < Rb \tag{7}$$

Otherwise, the quick (surface) runoff is expressed as:

$$Rs_i = \left(\frac{S_i}{S_{\max}}\right)^{\varepsilon} (R_{act(i)} - Rb), \; if \; R_{act(i)} > Rb \tag{8}$$

where:

S_{max} - maximum water storage in the second nonlinear reservoir [mm],
S_i - current water storage in the second nonlinear reservoir in the month *i* [mm],
$Ract_{(i)}$ - effective precipitation in the month *i* [mm],
Rb - base flow [mm],
ε - a model parameter [-].

The slow (subsurface) runoff is a function of the ratio between the current and maximum water storage in the second water accumulation reservoir and parameters α and *γ*:

$$Rss_i = \alpha \left(\frac{S_i}{S_{\max}}\right)^{\gamma} \tag{9}$$

The total runoff RC is calculated as the sum of the four runoff components Rs, Rss, Rb and Rd.

$$RC_i = R_s + R_{ss} + R_d + R_b \quad (10)$$

The actual monthly evapotranspiration for the basin Ea_i is calculated as a function of the monthly potential evapotranspiration for the basin ET_i and the ratio between the current S_i and maximum water storage in the second water accumulation reservoir S_{max}. The actual monthly evapotranspiration is expressed in the form:

$$Ea_i = ET_i \left[1 - \left(1 - \frac{S_i}{S_{\max}} \right)^{Cea} \right] \quad (11)$$

where:
ET_i - the potential evapotranspiration in the month *i* [mm],
C_{ea} - a model parameter [-].

In the calibration procedure of the hydrological balance model, 11 model parameters are optimized (S_{max}, α, γ, ε, C_{Ract}, T_S, T_R, *Rb*, *Cea*, β and *Z*). The parameter *Rb* is determited manually by estimation and the parameter *Z* is an initial value of the ratio between Si and S_{max}. A genetic algorithm (GA) is built into the model to enable the calibration of the model parameters based on the input data, and several criteria (or combination of them) are used as an objective function. The basic optimization criteria are the Nash-Sutcliffe criterion (Nash & Sutcliffe, 1970), the sum of the squared differences between the logarithms of the measured and simulated values (SRLE), (Fernandez, Vogel, Sankarasubramanian, 1999), logarithm Nash-Sutcliffe criterion and multi- criterion.

MODEL CALIBRATION AND VALIDATION

The hydrological balance model was calibrated and validated for the Hron river basin based on data from the period of 1971-2000 (the calibration period) and 1961-1970 (the validation period). The results of the calibration are displayed in Figures 4 and 5.
The mean monthly precipitation for the basin, the mean monthly discharges in the basin and the mean monthly potential evapotranspiration (PET) in the basin were used as input data. For calculating the potential evapotranspiration, the Zubenokova method was chosen, and additional climate data for this purpose were collected: the mean monthly air temperature values, the mean monthly values of the relative air humidity or the mean monthly values of the water vapor pressure. The average values of the monthly precipitation totals and mean monthly air temperature were estimated by the Thiessen polygons method.

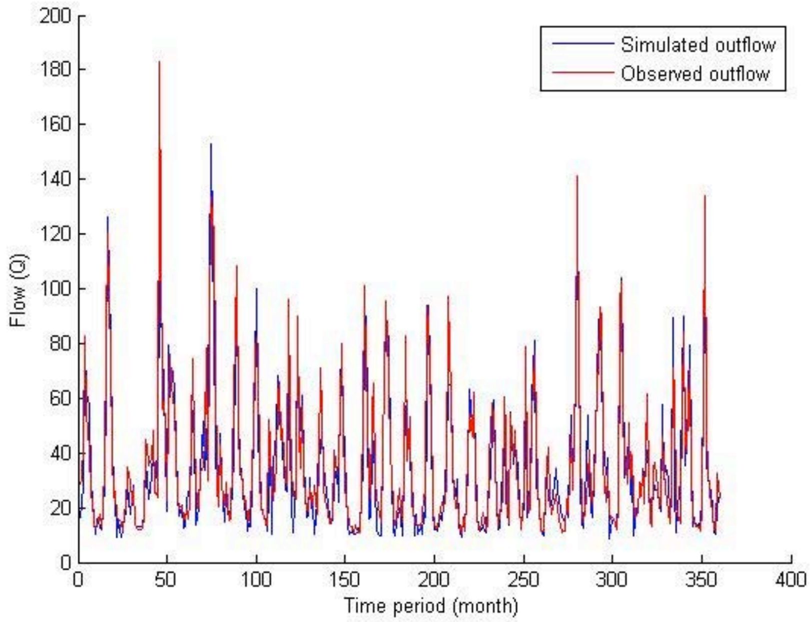

Fig. 4 Comparison of the time series of the observed and model simulated flows (upper Hron river basin, from 1971 to 2000).

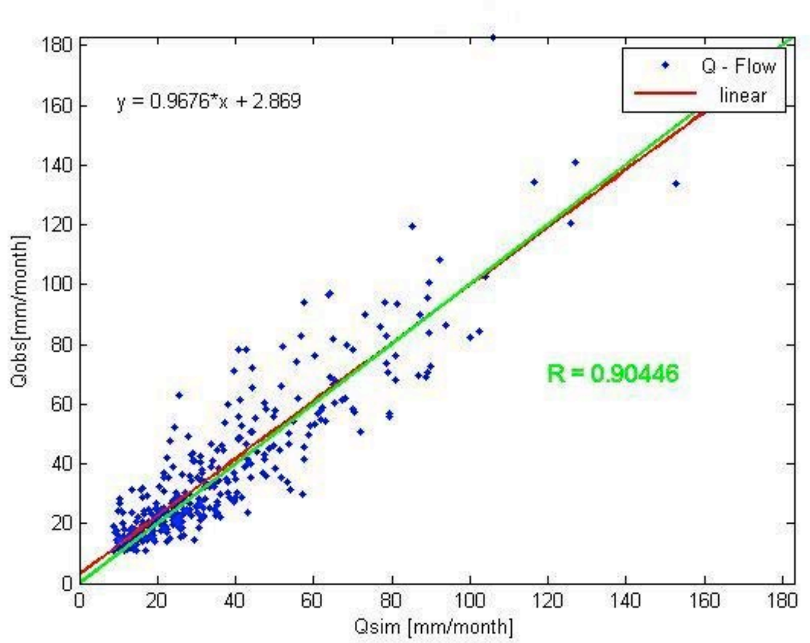

Fig. 5 Linear regression between the observed and simulated flows and correlation coefficients (upper Hron river basin, from 1971 to 2000).

CLIMATE CHANGE SCENARIOS

The climate characteristics, such as precipitation totals, air temperature and relative air humidity, were simulated by the ALADIN-Climate model in daily time steps with a grid resolution of 10 km. These grid climate outputs were spatially averaged over the Hron river basin and recalculated to monthly time steps.

Changes in the monthly precipitation totals, mean monthly air temperature and relative air humidity were considered for each month as differences between the long-term mean monthly outputs from the ALADIN-Climate model run (uncorrected outputs) in the reference period of 1961-1990 and the future time horizons of 2021-2050 and 2071-2100.

The grid points of the ALADIN-Climate model outputs with a resolution of 10 km in Slovakia and the Hron river basin are shown in Fig. 6.

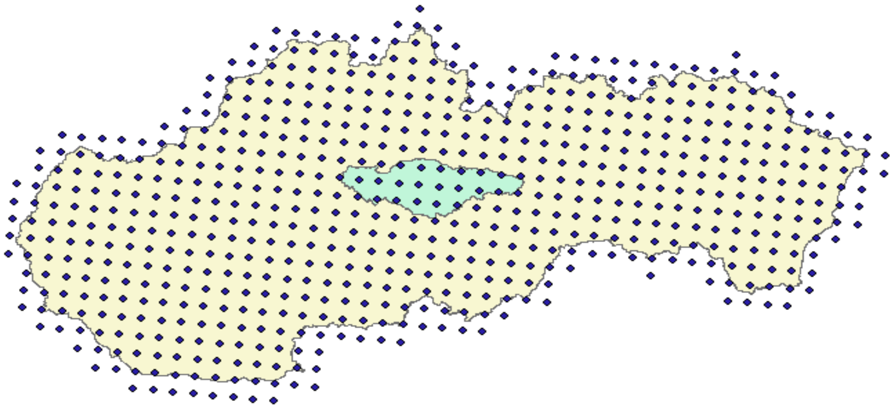

Fig. 6 ALADIN-Climate grid spacing with 10 km resolution in Slovakia and the upper Hron river basin.

Precipitation

The long-term mean monthly precipitation totals in the time horizons of 1961-1990 (measured), 2021-2050 and 2071-2100 are presented in Fig. 7.

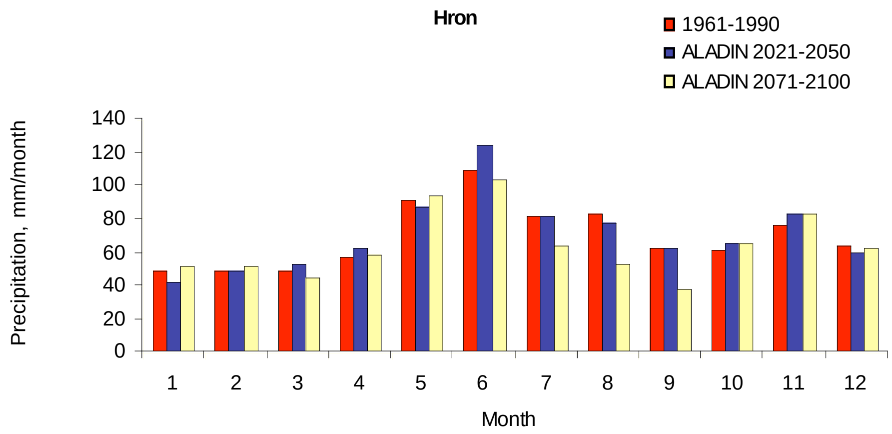

Fig. 7 Long-term mean monthly precipitation totals in mm/month in the reference period of 1961-1990 and in the time horizons of 2021-2050 and 2071-2100 in the Hron river basin.

Air temperature

The values of the long-term mean monthly air temperature in the time horizons of 1961-1990 (measured), 2021-2050 and 2071-2100 are presented in Fig. 8.

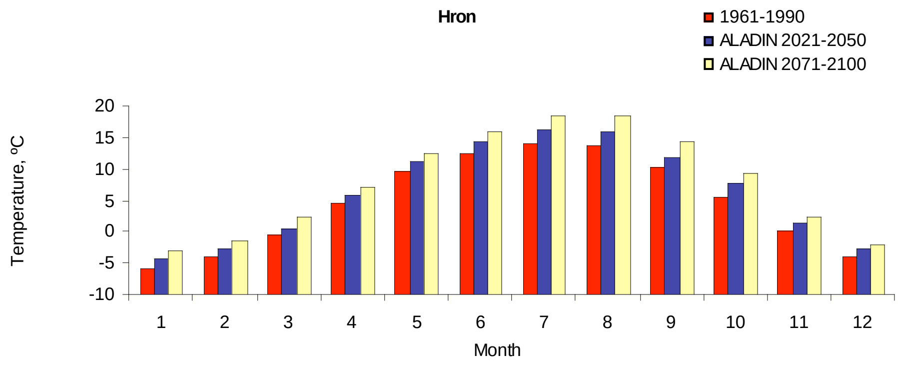

Fig. 8. Long-term mean monthly air temperature in °C in the reference period of 1961-1990 and in the time horizons of 2021-2050 and 2071-2100 in the Hron river basin.

Relative air humidity

The values of the long-term mean monthly relative air humidity in the time horizons of 1961-1990 (measured), 2021-2050 and 2071-2100 are presented in Fig. 9.

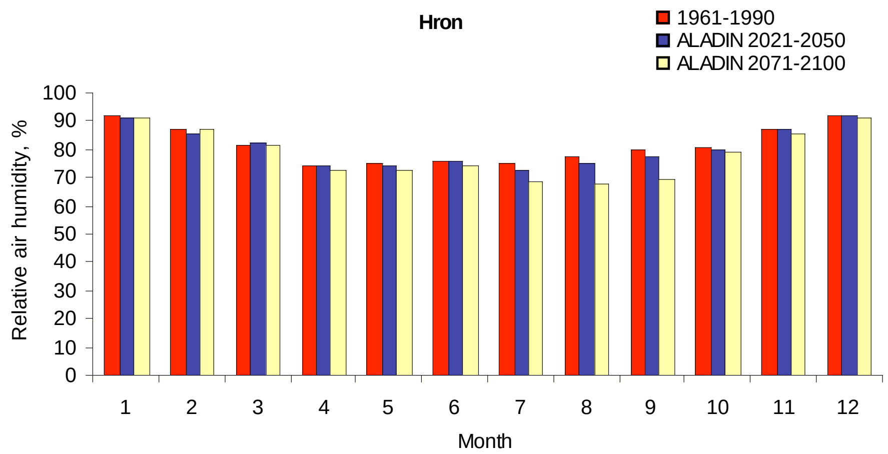

Fig. 9 Long-term mean monthly relative air humidity in % in the reference period of 1961-1990 and in the time horizons of 2021 -2050 and 2071-2100 in the Hron river basin.

RESULTS

The monthly runoff series were simulated using a hydrological balance model with the changed input climate data, and the differences in the seasonal runoff distribution in the reference and future time horizons were estimated and compared.
The values of the long-term mean monthly runoff in the time horizons of 1961-1990, 2021-2050 and 2071-2100 are presented in Fig. 10; the differences in the long-term mean monthly runoff for the future time horizons in comparison with the reference period are presented in Fig. 11.

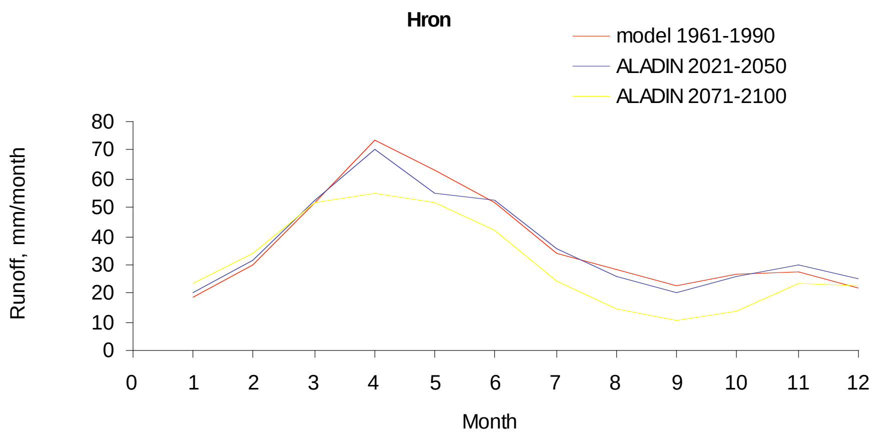

Fig. 10 Long-term mean monthly runoff in mm/month in the reference period of 1961-1990 and in the time horizons of 2021-2050 and 2071-2100 in the Hron river basin.

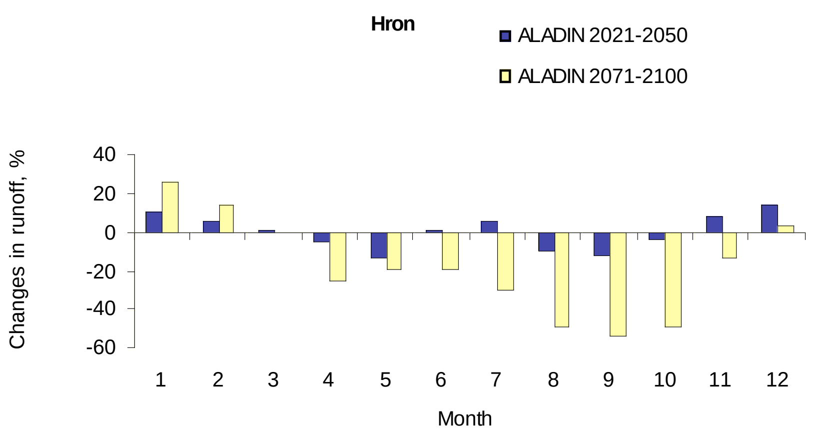

Fig. 11 Percentage changes in the long-term mean monthly runoff in the time horizons of 2021-2050 and 2071-2100 in comparison with the reference period of 1961-1990 in the Hron river basin.

The results presented of modelling the long-term mean monthly runoff indicate future changes in the seasonal runoff distribution in the upper Hron river basin. According to the ALADIN-Climate runs, an increase in the long-term mean monthly runoff can be expected from November/December to February/March. The highest relative increase in mean monthly runoff in comparison with the reference period can be assumed to be in January, i.e., +11% (+2 mm/month) in 2021-2050 and +27% (+5 mm/month) from 2071-2100. This increase could be caused by an increase in the air temperature during winter and a shift in the snow-melting period from the spring months to the winter period. A decline in the long-term mean monthly runoff may occur from April to October/November. The most extreme relative decrease in monthly runoff could occur in May from 2021-2050, i.e., -12.5% (-8 mm/month) and in August/September from 2071-2100, i.e., -53% (-12 mm/month).

In 2021-2050 there could be a slight increase in runoff in June/July, i.e., +6 % (+2 mm/month). This increase may be caused by an increase in precipitation from 2021-2050 in comparison with the period of 1961-1990 (which generally was considered a dry period). The decrease in runoff in August/September from 2021-2050 and 2071-2100 would mainly be caused by an increase in air temperature (+2.2ºC from 2021-2050 and +4.9ºC from 2071-2100).

It could generally be concluded for both of the time horizons investigated that during the winter and early spring periods, an increase in the long-term mean monthly runoff could be assumed. The period of an increase in runoff could occur from November/December to February/March. This increase could be caused by an increase in air temperature and a shift of the snow-melting period from the spring months to the winter period. A period of decrease in runoff could occur from May to October/November. The increase in winter runoff and the decrease in summer runoff are expected to be more extreme for the later time horizon (Tab. 1 and Fig. 12).

Table 1. Comparison of the mean runoff coefficient (runoff depth/ precipitation depth) in the reference period 1961-1990 and in the future time horizons.

Time horizon	Runoff coefficient
1961-1990	0.53
2021-2050	0.52
2071-2100	0.47

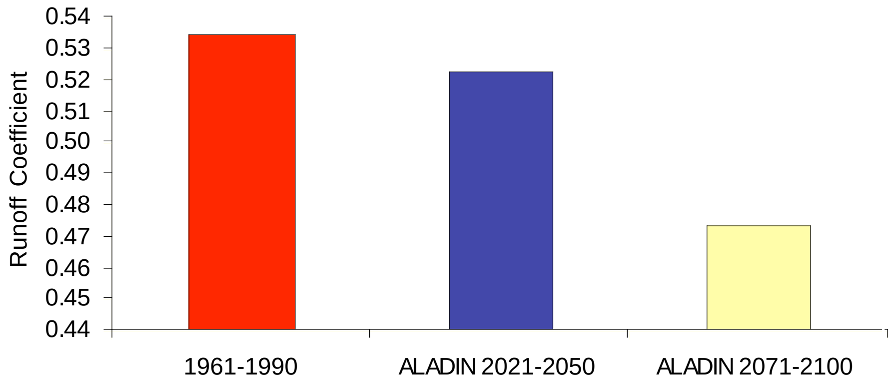

Fig. 12. Comparison of the mean runoff coefficient (runoff depth/ precipitation depth) in the reference period 1961-1990 and in the future time horizons.

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