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On future changes in the long-term seasonal discharges in selected basins of Slovakia

Zuzana SABOVÁ*, Silvia KOHNOVÁ

Climate change and its impact on hydrological characteristics is a research topic of increasing interest. Studies that examine historical, current or future changes in hydrological regimes are important for understanding future changes in the water balance and its components. This study analyses changes in long-term discharges in the summer and winter half-year and the baseflow index for eight selected river basins in Slovakia till 2100. For the analysis, data observed from the period 1981–2010 were used to calibrate the HBV-type rainfall-runoff TUW model. To simulate future discharges up to the 2100 horizon, two climate scenarios were used, i.e., the Dutch KNMI and the German MPI. The analysis was performed for four selected periods with a duration of 30 years. The results point to the most significant changes in the increase in long-term seasonal discharges in the winter half-year by 2100. In the future, the summer period will probably be characterised by a reduction in long-term seasonal discharges and decrease in the base flow index in all of the basins analysed.

KEY WORDS: seasonal discharges, baseflow index, the KNMI and MPI climate scenarios, the HBV model, the TUW model

Introduction

The impact of climate change on river runoff is increasingly being investigated due to changes in various factors, including the air temperature, amount of precipitation, evaporation, and evapotranspiration. These changes have resulted in an increased occurrence of extreme events, i.e., floods, droughts, heat, heavy rain, and intense cyclones. More extreme events associated with global warming could have an intense impact on changes in the hydrological cycle, thereby leading to socio-economic consequences (Vyshnevskyi and Donich, 2021; He et al., 2022; Meresa et al., 2022).
Global and regional models are essential when explaining the annual, seasonal, and daily characteristics of precipitation and air temperatures. Forecasts for climate models differ due to different parametrisation methods and the underlying network structure. This fact makes it challenging to develop accurate and reliable climate data. The differences in the results should be corrected by the so-called 'calibration' before their further use in projections of hydrological extremes in hydrology. Most hydrological models consist of physical mechanisms or empirical equations that describe basins. Rainfall-runoff models often comprise a series of equations that describe simplified hydrological processes from small to large basins (Meresa et al., 2022). Hydrological models are widely used to analyse and determine changes in hydrological environments, including modifications and improvements in different areas. Many models with various structures are applied to basins with different climatic or geographical conditions. The most significant advantage of hydrological models is that they are used to predict hydrological dynamics by combining them with climate scenarios (Yang et al., 2022). Rainfall modelling is often used in water management simulation analyses to predict the future course of floods, droughts, and climate change. It must be taken into account that, in the period simulated, the climate conditions can differ from the calibration conditions when uncertainties arise that may affect the accuracy of outputs (Sleziak et al., 2017).
Meresa and Romanowicz (2017) addressed uncertainties in projecting hydrological regimes. They pointed to increased uncertainty in hydrological models that result in further uncertainty in climate models, leading to increased risks for the adaptation, planning, and management of water resources for future extreme hydrological events. Yang et al. (2022) studied the effect of calibration conditions on the accuracy of conceptual hydrological models under different climatic conditions. Huntington (2003) studied the relationship between the average annual temperature, precipitation, and evapotranspiration in the New England region of the USA. He found that annual runoff decreased by 11–13% for the historical periods in the selected basins until 2003. Various analyses have been performed for the territory of Slovakia that were devoted to hydrological changes (Ďurigová et al., 2020), changes in water balance and soil moisture (Rončák et al., 2021), and an evaluation of

average monthly discharges (Pekárová et al., 2007; Ďurigová et al., 2019; Majerčáková et al., 2007). The impact of climate change on the Hron, Váh, and Laborec River basins using the KNMI, MPI and ALADIN-Climate climate data in the period 1961–2100 was addressed by Štefunková et al. (2013). The team focused on the impact of climate change on the territory of Slovakia using an HBV-type rainfall-runoff TUW model by Sleziak et al. (2016; 2018), who pointed out changes in simulated runoff that are related to changes in precipitation, but stressed the need to recalibrate conceptual HBV models if climate conditions change.
This study deals with an analysis of future changes in long-term seasonal discharges; it is divided into two groups, i.e., the summer half-year (April–September) and the winter half-year (October–March). Data from the KNMI and MPI climate scenarios are input in the HBV-type rainfall-runoff TUW model to predict future discharge changes up to 2100. The 30-year future periods were compared with a historical one, which forms the reference period from 1981 to 2010. An analysis of changes in the baseflow index's average annual values within the periods examined until 2100 was also carried out.

Material and methods

For the study, eight basins in the territory of Slovakia were selected; they differ in their area, altitude, and location (Table 1 and Fig. 1). The river basins have an area from 238.5 to 2093.7 km^2, with a mean elevation from 361.7 to 1090.1 m a.s.l., a minimum elevation from 163 to 568 m a.s.l, and a maximum elevation from 792 to 2489 m a.s.l
The data observed from the gauging stations provided by the Slovak Hydrometeorological Institute were used to create the modelled data using the HBV-type rainfall-runoff TUW model. The model´s calibration parameters simulated the daily discharges up to 2100 and the modelled data (MODEL HBV) were created (Table 2).
The HBV-type TUW model is a conceptual semi-distributed rainfall-runoff model, which was used for modelling changes in the daily discharges (Fig. 2). The basic structure of the HBV consists of three modules, i.e., snow, soil, and runoff. The HBV model has 15 parameters for the calibration. The model needs daily discharges, precipitation, the air temperature, and evapotranspiration as the input data for the calibration.

Table 1. Characteristics of the selected gauging stations

River basin / Gauging station	ID	Basin area [km^2]	Mean basin elevation [m a.s.l.]	Min. – Max. elevation [m a.s.l.]
Myjava / Jablonica	5022	238.45	361.7	206 – 792
Nitra / Nitrianska Streda	6730	2093.71	419.5	175 – 1179
Hron / Banská Bystrica	7160	1766.48	844.4	332 – 2030
Turiec / Martin	6130	827.00	716.0	403 – 1456
Poprad / Chmeľnica	8320	1262.41	878.1	510 – 2489
Váh / Liptovský Mikuláš	5550	1107.21	1090.1	568 – 2387
Laborec / Humenné	9230	1272.40	421.7	166 – 917
Topľa / Hanušovce nad Topľou	9500	1050.05	435.4	163 – 1077

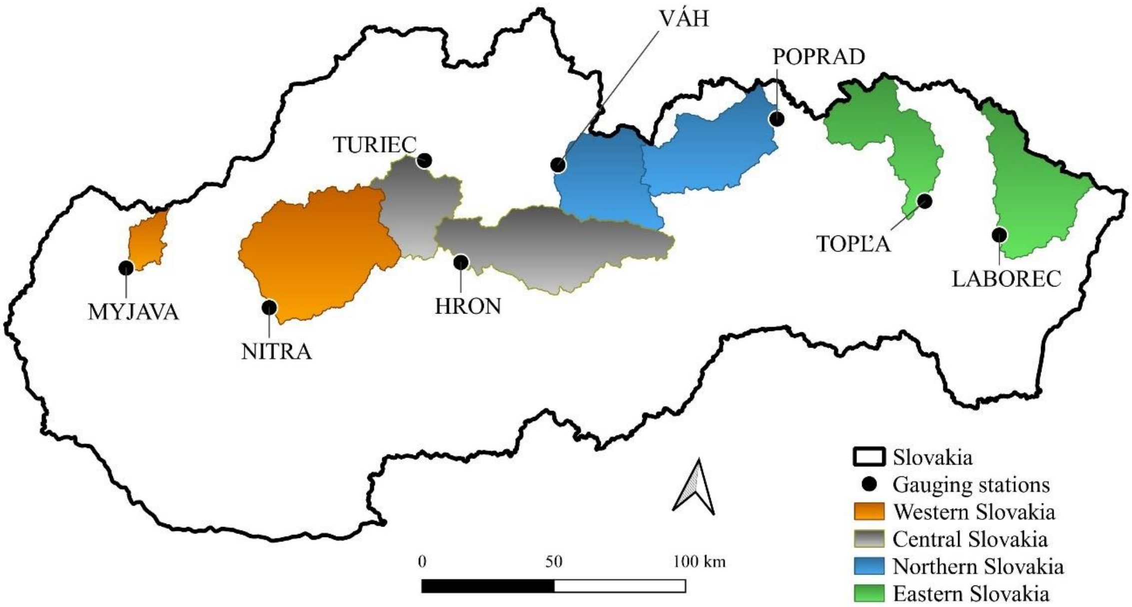

Fig. 1. Location of selected basins within the territory of Slovakia.

Table 2. Distribution of the time period examined concerning the use of data

Time period analysed	Group of data
1981–2010	Observed mean daily discharges Modelled mean daily discharges using the HBV-type rainfall-runoff TUW model Simulated mean daily discharges according to the KNMI climate scenario´s data Simulated mean daily discharges according to the MPI climate scenario´s data
2011–2040 2041–2070 2071–2100	Simulated mean daily discharges according to the KNMI climate scenario´s data Simulated mean daily discharges according to the MPI climate scenario´s data

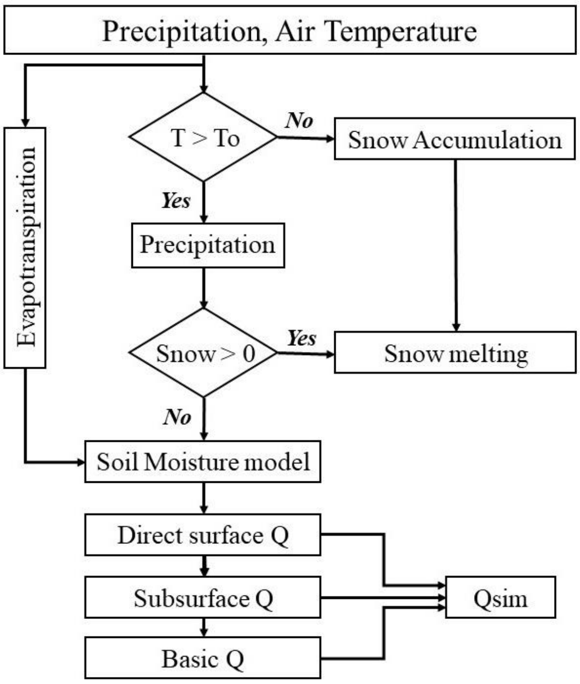

Fig. 2. Basic scheme of the HBV-type rainfall-runoff TUW model (T – air temperature, To – air temperature of melting snow, Q – runoff, Qsim – simulated discharge).

More details about the model can be found in, e.g., Výleta et al., 2020; Sleziak, 2017.

Daily precipitation and temperature data from two climate scenarios, i.e., the Dutch KNMI and the German MPI, were used to model discharges for the future periods. Both climate scenarios belong to regional circulation models that were scaled for the territory of Slovakia in a daily step with a resolution of 25x25 km. They have 190 grid points with detailed topography in and around Slovakia. Their outputs were processed for the period 1951–2100.

The period of 1981 to 2100 investigated in our study was divided into four 30-years periods to determine in which period the most significant changes in long-term seasonal discharges could be expected. The following periods were compared: 1981–2010, 2011–2040, 2041–2070, and 2071–2100. For a better representation of the changes in the discharges, the relative deviation in percentages was calculated according to the formula:

$$RO = \frac{CS - MODEL\ HBV}{MODEL\ HBV} * 100 \quad [\%] \qquad (1)$$

where:

RO – relative deviations [%];

CS – long-term seasonal discharges simulated using the KNMI/MPI climate scenarios in all the periods selected;

MODEL HBV – long-term seasonal discharges simulated using the HBV model in the period 1981–2010.

In this study, changes in the base flow index for the hydrological characteristics are analysed. This was estimated as the ratio of the 7-day minimum discharge to the average annual discharge using the Indicators of Hydrologic Alteration program. The resulting values of the base flow index were also calculated according to Equation (1) to represent the results of the work.

Results and discussion

The study compared changes up to 2100 in the long-term seasonal discharges in the summer and winter half-years and the average annual baseflow index within the simulated discharges according to the KNMI and MPI climate scenarios. The results were processed using graphic representations and in tabular form.

a) Long-term seasonal discharges in the summer and winter half-years

In the graphic processing of the seasonal discharges for the selected river basins in Slovakia, it can be seen that in the summer half-year, a decrease in long-term seasonal discharges, and in the winter half-year, an increase in long-term seasonal discharges, up to 2100 is expected (Figs. 3 and 4). The increase in discharges in the winter months may be caused due to the continuation of more intense snowmelt, e.g., in the Hron River basin in an earlier period (February–March). For the Váh and Poprad River basins, the results indicate higher values of seasonal discharges in the summer than in the winter until 2100, despite the fact that the values of the seasonal discharges in the basins will decrease in the future. The reason could be the maintenance of snow cover, increased precipitation, or snow melting in the higher areas of the basins in April and May.

For a better representation of the future changes predicted using data from the KNMI and MPI climate scenarios, Tables 3a (KNMI) and 3b (MPI) were created; they consist of the resulting values of the long-term seasonal discharges in the summer half-year for the discharges modelled by the HBV-type rainfall-runoff TUW model (MODEL HBV) and for the simulated discharges using the climate scenarios by 2100. The tables also contain the percentage changes in the simulated discharges from the discharges modelled. Blue indicates the most significant decreases, and red indicates the highest increase in long-term seasonal discharges in the summer half-year. According to the simulated discharges using the MPI climate scenario for western Slovakia, an increase in long-term seasonal discharges in the summer half-year by 23% (the Myjava River basin) and 30% (the Nitra River basin) until 2070 is expected. We can assume that this will be caused by increases in

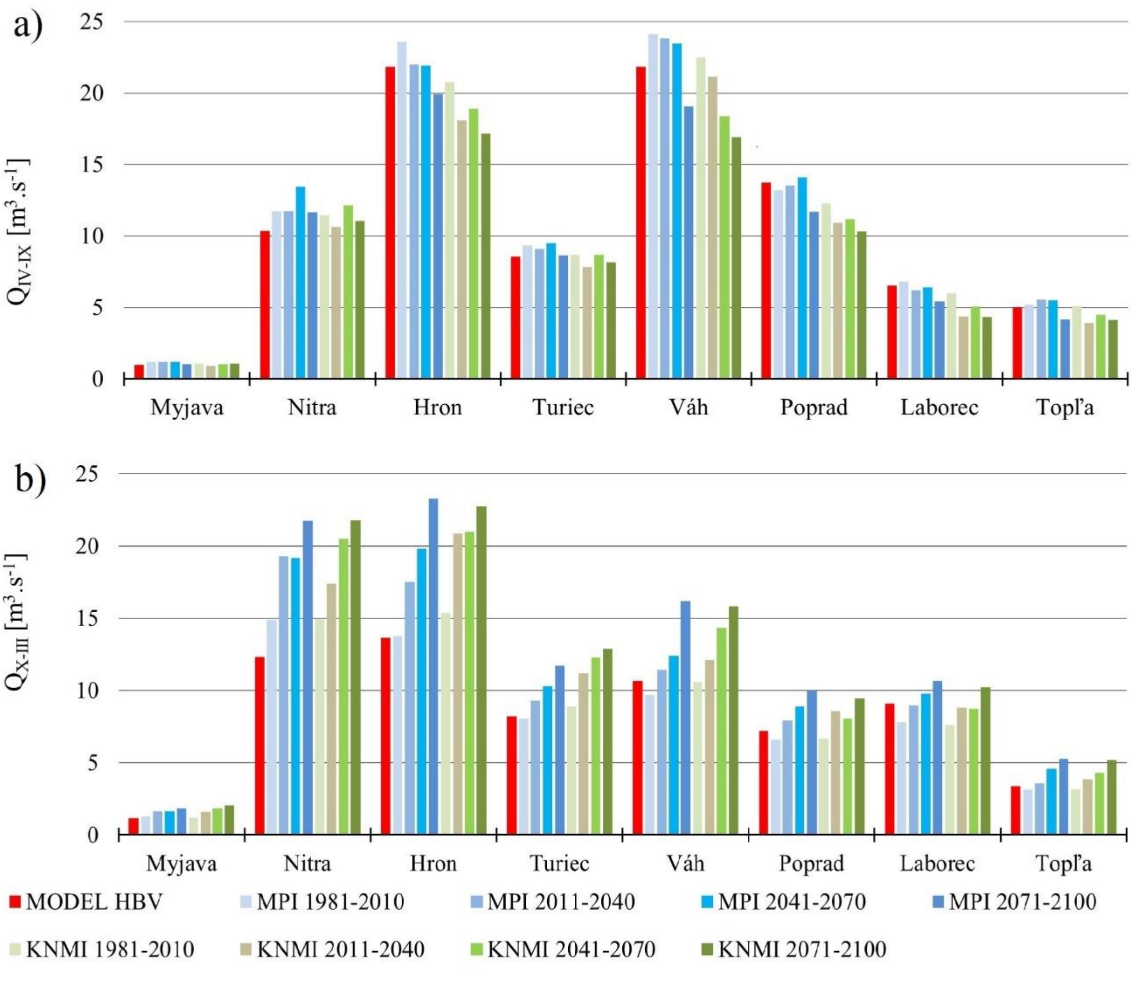

Fig. 3. Comparison of temporal changes in the long-term seasonal discharges for the discharges modelled by the HBV-type rainfall-runoff TUW model (MODEL HBV) and simulated discharges according to the KNMI and MPI climate scenarios for the selected periods analysed: a) in the summer half-year; b) in the winter half-year.

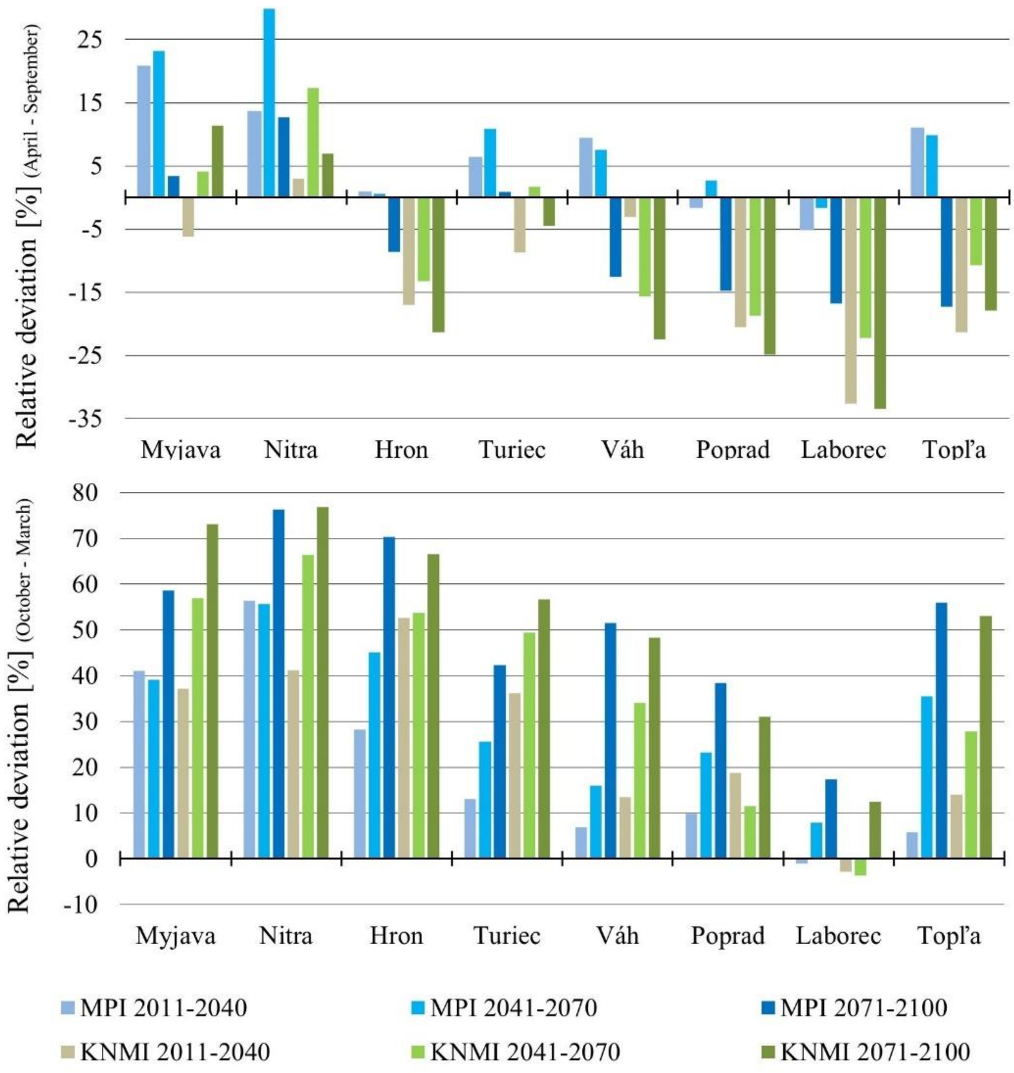

Fig. 4. *Graphic representation of the relative deviations of the simulated long-term seasonal discharges of the KNMI and MPI climate scenarios from the modelled long-term seasonal discharges of the HBV-type rainfall-runoff TUW model for the summer half-year.*

Table 3a. **Resulting values of the long-term seasonal discharges by 2100 in the summer half-year [$m^3 s^{-1}$] and their relative deviations [%] of the simulated discharges according to the KNMI climate scenario**

River basin	MODEL HBV	KNMI					
	1981–2010	2011–2040		2041–2070		2071–2100	
	[$m^3 s^{-1}$]	[$m^3 s^{-1}$]	[%]	[$m^3 s^{-1}$]	[%]	[$m^3 s^{-1}$]	[%]
Myjava	0.98	0.92	**-6.18**	1.02	4.15	1.09	**11.34**
Nitra	10.34	10.65	3.00	12.13	**17.31**	11.05	6.89
Hron	21.82	18.10	-17.03	18.92	-13.30	17.15	**-21.37**
Turiec	8.56	7.81	**-8.69**	8.70	**1.71**	8.17	-4.50
Váh	21.82	21.16	-3.02	18.39	-15.70	16.92	**-22.45**
Poprad	13.72	10.90	-20.53	11.16	-18.70	10.31	**-24.84**
Laborec	6.51	4.39	-32.64	5.06	-22.24	4.34	**-33.42**
Topľa	5.01	3.94	**-21.35**	4.48	-10.69	4.12	-17.86

Table 3b. **Resulting values of the long-term seasonal discharges by 2100 in the summer half-year [$m^3 s^{-1}$] and their relative deviations [%] of the simulated discharges according to the MPI climate scenario**

River basin	MODEL HBV	MPI					
	1981–2010	2011–2040		2041–2070		2071–2100	
	[$m^3 s^{-1}$]	[$m^3 s^{-1}$]	[%]	[$m^3 s^{-1}$]	[%]	[$m^3 s^{-1}$]	[%]
Myjava	0.98	1.18	20.67	1.20	**23.15**	1.01	3.43
Nitra	10.34	11.75	13.59	13.43	**29.89**	11.66	12.71
Hron	21.82	21.99	0.79	21.94	0.54	19.94	**-8.61**
Turiec	8.56	9.09	6.26	9.48	**10.86**	8.63	0.84
Váh	21.82	23.85	9.31	23.47	7.55	19.08	**-12.57**
Poprad	13.72	13.52	-1.49	14.09	**2.65**	11.70	**-14.72**
Laborec	6.51	6.18	-5.04	6.40	-1.67	5.42	**-16.80**
Topľa	5.01	5.56	**10.93**	5.50	9.84	4.15	**-17.25**

convective and long-term cyclonic events in the summer season.

According to the KNMI climate scenario, simulated discharges for the territory of central Slovakia mainly indicate a decrease in the value of long-term seasonal discharges in the summer half-year until the year 2100 (by 21% in the Hron River basin), with the exception being the period from 2041 to 2070 in the Turiec River basin, when the resulting values of the hydrological characteristics are expected to grow. According to the simulated discharges of the MPI climate scenario, an increase in the long-term seasonal discharges of the summer half-year in central Slovakia is expected to reach 11% in the Turiec River basin.

Northern Slovakia is characterised by high altitudes since the High Tatra mountains are in the territory. Changeable weather in the summer half-year there can also affect the size of the discharges in the respective basins. According to the study presented, a decrease in long-term seasonal discharges in the Poprad and Váh River basins in the summer half-year is expected to occur by approximately 23–25% until 2100 according to the simulated discharges of the KNMI climate scenario. Also, according to the data from the MPI climate scenario, a decrease of approximately 13–14%, compared to the modelled data from the HBV-type rainfall-runoff TUW model, can be observed.

The most significant decreases are recorded in the Laborec and Topľa River basins, which are located in eastern Slovakia. More precisely, this is the highest decrease in long-term seasonal discharges in the summer half-year, according to the simulated discharges of the KNMI climate scenario (a decrease of 21–33%). Simulated discharges of the MPI climate scenario predict a decrease in long-term seasonal discharges by up to 17% in the summer half-year by 2100.

The long-term seasonal discharges for the winter half-year indicate changes utterly different from those in the summer half-year in the future. These are mainly significant increases in the long-term seasonal discharges of the winter half-year according to the simulated discharges of the KNMI and MPI climate scenarios (Tables 4a and 4b). The exception is the Laborec River basin in 2011–2040, where only a slight decrease in long-term seasonal discharge values is expected from October to March, according to both climate scenarios.

For the river basins of western Slovakia, the highest increase in long-term seasonal discharges in the winter half-year is by 73–77% according to the simulated discharges of the KNMI climate scenario and by 59–77% according to the simulated discharges of the MPI climate scenario. Part of central Slovakia is characterised by approximately the same values of the changes in the long-term seasonal discharges of the winter half-year as in western Slovakia by 2100. In the basins of northern Slovakia, the expected change in long-term seasonal discharges in the winter half-year until 2100 is an increase in the values of the long-term seasonal discharges of the winter half-year by 31–48% for the simulated discharges of the KNMI climate scenario and by 38–52% for the simulated discharges according to the MPI climate scenario. For eastern Slovakia, the predictions for the selected basins differ. Simulated discharges of the KNMI and MPI climate scenarios also indicate a decrease in long-term seasonal discharges in the winter half-year by 1–4% by 2040–2070; the results indicate they will increase again by 2100. Minor changes in the long-term seasonal discharges from the winter half-year are expected in the Laborec River basin.

The results of the summer and winter periods examined differ significantly, and the most notable changes can be expected in the winter half-year. The long-term seasonal discharges can be affected by several extremes throughout the year. Snowmelt floods occur regularly in the spring. In the summer, there are strong storms or prolonged droughts. In recent years, there have also been periods without any precipitation in the winter. In Sabová and Kohnová (2022), the authors analysed average monthly discharges in the territory of Slovakia. Their results showed that in eastern Slovakia, the highest

decrease in average monthly discharges is expected in the summer. On the other hand, the most significant increases in the winter in average monthly discharges are expected for the Nitra, Hron and Topľa River basins.
For the Hron and Váh River basins, decreasing trends in the average monthly discharges in the summer have already been identified in the historical period of 1963–2016 (Ďurigová et al., 2019). Majerčáková et al. (2007) detected the development of maximum discharges in the Poprad River basin for the territory of northern Slovakia. The result of the work confirmed the sensitivity of the basin with regard to the changes in climate.

b) Average annual baseflow index

The baseflow index is a hydrological characteristic that represents the continuous contribution of groundwater to river discharges. From the point of view of future changes, gradual decreases in the values of the base flow index for the selected river basins until 2100 in Slovakia are evident (Table 5). The most extreme changes in base flow decreases are expected in the Myjava, Nitra, and Laborec River basins (a decrease of 43%). The exceptions are the basins of northern Slovakia, that is, the Poprad and Váh River basins, which indicate positive changes in the values in the baseflow indices. For example, according to the simulated discharges from the MPI climate scenario data, an increase in the baseflow index is expected by 38% in the Poprad River basin from 2041 to 2070 (Fig. 5). The simulated discharges of the KNMI climate scenario in most cases assume higher values of the changes in the hydrological characteristics of the baseflow index, in comparison to the MPI climate scenario. The consequences of a decrease in the base flow index in almost all the basins except for the mountainous ones indicate that the basins will be more prone to drying out in the summer and autumn months.

Table 4a. Resulting values of the long-term seasonal discharges by 2100 in the winter half-year [$m^3 s^{-1}$] and their relative deviations [%] of the simulated discharges according to the KNMI climate scenario

River basin	MODEL HBV	KNMI					
	1981–2010	2011–2040		2041–2070		2071–2100	
	[$m^3 s^{-1}$]	[$m^3 s^{-1}$]	[%]	[$m^3 s^{-1}$]	[%]	[$m^3 s^{-1}$]	[%]
Myjava	1.17	1.61	37.10	1.84	56.94	2.03	**73.09**
Nitra	12.32	17.40	41.19	20.51	66.42	21.80	**76.89**
Hron	13.66	20.84	52.57	20.99	53.67	22.75	**66.53**
Turiec	8.22	11.20	36.23	12.28	49.40	12.87	**56.61**
Váh	10.69	12.13	13.48	14.34	34.15	15.85	**48.24**
Poprad	7.21	8.57	18.83	8.04	11.49	9.45	**31.04**
Laborec	9.09	8.82	-2.88	8.75	-3.72	10.22	**12.47**
Topľa	3.38	3.86	13.97	4.32	27.76	5.18	**53.06**

Table 4b. Resulting values of long-term seasonal discharges by 2100 in the winter half-year [$m^3 s^{-1}$] and their relative deviations [%] of simulated discharges according to the MPI climate scenario

River basin	MODEL HBV	KNMI					
	1981–2010	2011–2040		2041–2070		2071–2100	
	[$m^3 s^{-1}$]	[$m^3 s^{-1}$]	[%]	[$m^3 s^{-1}$]	[%]	[$m^3 s^{-1}$]	[%]
Myjava	1.17	1.66	41.12	1.63	39.06	1.86	**58.54**
Nitra	12.32	19.27	56.39	19.18	55.66	21.73	**76.35**
Hron	13.66	17.51	28.18	19.82	45.07	23.26	**70.26**
Turiec	8.22	9.30	13.11	10.32	25.52	11.70	**42.34**
Váh	10.69	11.43	6.98	12.40	15.98	16.19	**51.50**
Poprad	7.21	7.92	9.84	8.89	23.18	9.98	**38.38**
Laborec	9.09	9.00	-0.99	9.80	7.88	10.66	**17.35**
Topľa	3.38	3.58	5.81	4.58	35.47	5.27	**55.90**

Table 5. **The course of changes in the baseflow indices [–] and their relative deviations [%] for the selected river basins in Slovakia according to the simulated discharges of the KNMI and MPI climate scenarios by 2100**

River basin	MODEL HBV	KNMI						MPI					
	1981–2010	2011–2040		2041–2070		2071–2100		2011–2040		2041–2070		2071–2100	
	[–]	[–]	[%]	[–]	[%]	[–]	[%]	[–]	[%]	[–]	[%]	[–]	[%]
Myjava	0.17	0.14	-18	0.11	-34	0.10	**-42**	0.13	-24	0.13	-19	0.10	**-42**
Nitra	0.30	0.23	-23	0.21	-31	0.18	**-40**	0.24	-22	0.23	-22	0.21	**-30**
Hron	0.33	0.32	-4	0.30	-8	0.28	**-15**	0.32	-3	0.32	-2	0.29	**-11**
Turiec	0.38	0.34	-9	0.32	-15	0.28	**-27**	0.35	-6	0.37	-2	0.29	**-23**
Poprad	0.24	0.25	4	0.29	**24**	0.28	21	0.24	3	0.33	**38**	0.30	27
Váh	0.42	0.46	8	0.48	13	0.48	**14**	0.38	**-10**	0.45	8	0.47	**12**
Laborec	0.20	0.16	-20	0.14	-31	0.11	**-43**	0.17	-15	0.17	-16	0.12	**-38**
Topľa	0.30	0.26	-11	0.25	-14	0.21	**-29**	0.26	-13	0.27	-8	0.24	**-20**

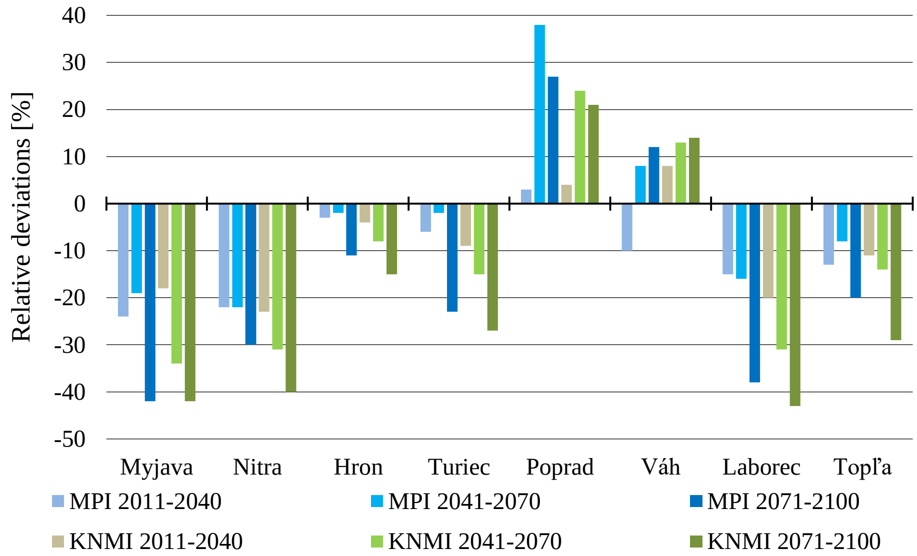

Fig. 5. Graphic representation of the relative deviations of the simulated baseflow index of the KNMI and MPI climate scenarios by 2100 from the modelled average annual discharges of the HBV-type rainfall-runoff TUW model.

Conclusion

The study is aimed at analysing changes in the long-term seasonal discharges from the winter and summer half-years up to 2100 using simulated discharges according to the KNMI and MPI climate scenarios. Four groups of basins in Slovakia were created, which were divided in terms of their location. The results for the periods predict the most significant changes for the future in the period 2071–2100 in the winter half-year, when increases in the long-term seasonal discharges of up to 77% are expected (Nitra River basin). The summer half-year shows lower increases in the values of the long-term seasonal discharges. Compared to the winter period, the results indicate that a decrease in the long-term seasonal discharges will also occur more often. The winter half-year is different for Slovakia with respect to the morphological and climatological diversity of the basins (mountain and lowland basins). The winter half-year is different for Slovakia in terms of snowfall because a lack of snow cover occasionally appears in lowland areas; on the other hand, northern Slovakia is affected by heavy snow showers on a yearly basis, which increase the discharges in the water courses. From a general point of view, the survey results indicate a decrease in the summer period and a significant increase in the values of the long-term seasonal discharges in the winter period.

The results of the analyses for the baseflow index indicate decreasing values in the future in most cases of the selected basins, which will have an adverse effect on their hydrological regimes; the best forecasts in terms of the baseflow index were recorded in the basins of northern Slovakia (the Poprad and Váh River basin), where data predictions from climate scenarios indicate an increase in the baseflow index. When using the climate scenarios, it was found that the simulated discharges under the KNMI climate scenario predicted more extreme changes than those under the MPI climate scenario.

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Ing. Zuzana Sabová (*corresponding author, e-mail: zuzana.sabova@stuba.sk)
Prof. Ing. Silvia Kohnová, PhD.
Department of Land and Water Resources Management
Faculty of Civil Engineering
Slovak University of Technology in Bratislava
Radlinského 11
811 07 Bratislava
Slovak Republic