

Long-term analysis of changes in seasonal and maximum discharges of Slovak rivers in the period 1931–2020

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Abstract: Central Europe and other parts of the world have experienced numerous extreme floods and prolonged periods of very low water discharges. With the increasing length and availability of hydrological data time series, it is now possible to analyse a larger volume of data. This paper presents long-term of changes in seasonal and maximum discharges. This paper aims to comprehensively assess the hydrological regime changes of Slovak rivers, using data from 26 gauging stations based on 90 years of observation. The study's first part explores monthly flow changes within each year for selected Slovak rivers. The second part identifies changes in the maximum daily discharges, their long-term trends, and their occurrences. Additionally, we have compared the variability of the hydrological regime of the Slovak rivers with the variability of the hydrological regime of selected gauging stations on the Danube River and its tributaries, such as the Drava, Sajó, and Tisa rivers, to understand broader regional patterns. The findings show that the rivers selected exhibit relatively high intra-annual runoff variability, with various changes in the runoff regime curve based on the long-term monthly Pardé coefficient. For the Slovak region, maximum annual runoff variability is observed in the Krupinica and Plašťovce rivers (reaching a maximum of 12.1 during the period 1930–1960), while minimum annual runoff variability is observed in the Biely Váh River (2.205 for the period 1930–1960). The long-term trend analysis of the Burn index time series for maximum daily discharges over the entire period from 1930/31 to 2019/20, as well as the significance of trends during the summer-autumn and winter-spring seasons, shows that stations exhibited decreasing, stable, or increasing trends. The most significant increasing trend was observed at sixteen of the stations analyzed: at seventeen stations during the summer-autumn season and at nine stations during the winter-spring season over the period from 1930/31 to 2019/20.

Keywords: Slovak river basins; Hydrological regime; Climate change; Seasonality; *T*-year maximum daily discharge; Frequency distribution.

1 INTRODUCTION

The issue of possible changes in the hydrological regime of rivers in connection with expected climate changes is a frequently discussed topic among both experts and the lay public. The hydrological regime is determined by the climatic, hydrological, hydrogeological, and physical-geographical conditions of individual river basins. Natural water circulation is often affected or disrupted by anthropogenic activities in river basins (Oki et al., 2006). The effect of human activities on the Earth's climate and hydrological cycle has become increasingly clear since the middle of the 20th century and it has been proven that the impact of human activity and the socio-economic development of society on the process of a hydrological regime is intensifying (Blöschl, 2022; Dey and Mishra, 2017; Yu et al., 2023). Nevertheless, the considerable natural variability of climate patterns makes it difficult to assess the extent to which human activity has contributed to these changes (Abbott et al., 2019; IPCC, 2021; Trenberth et al., 2014). Climate change and human activities therefore introduce numerous uncertainties into the prediction of future water balances. Long-term analyses of hydrological runoff extremes show the increasing severity and frequency of extreme wet and dry events worldwide, which are often associated with large-scale oceanic oscillations and climate change (Li and Rodell, 2023). Studies in Europe from 1950 to 2020 show non-stationary trends in extreme floods to be influenced by climatic and socio-economic factors, with

preliminary results showing the long-term dynamics of European floods (Tilloy et al., 2023). Compound hot-dry extremes, especially hydrological extremes, pose a significant threat. The global increase in mean precipitation in the warm season contrasts with the decrease in mean runoff in these warm season, leading to increased composite hydrological hot-dry extremes at high temperatures (Min et al., 2023).

The water regime in the Carpathian region of Central Europe is significantly fluctuating within the year. The runoff seasonality of snow-dominated rivers in Central Europe is decreasing, with runoff increasing in the winter and spring, while decreasing in the summer and early autumn. This is mainly attributed to reservoirs constructed in the Alps over the past century for hydropower production (Rottler et al., 2020). Furthermore, reconstructions of hydro-climatic conditions in Europe from 1500 to 2000 using precipitation, temperature, and runoff data show good agreement between reconstructed and observed runoff, which contributes to an understanding of historical and future hydroclimatic extremes (Nasreen et al., 2021). A comparative analysis of the seasonality of hydrological characteristics in Slovakia and Austria by Parajka et al. (2009) showed that the seasonality of the selected hydrological characteristics is an important indicator of flood processes, but it can vary considerably in space. This change is more pronounced in lowland and hilly regions than in the mountains. The annual discharge maxima of European rivers have changed considerably, with the highest discharge maxima occurring in

different decades on the continent (Kundzewicz et al., 2005). In recent decades, climatic anomalies have been detected, that have led to long-term changes in the hydro-meteorological regime and the system of the interaction of water masses with the underlying surface, especially in the channel and floodplain sections of rivers. Within the framework of the international cooperation of IHP UNESCO, Petrovič (2006), developed the water regime balance of the Danube River basin. With the same framework of international cooperation of IHP UNESCO, a monography of the flood regime of rivers in the Danube River basin was carried out (Pekárová and Miklánec, 2019). Both publications provide a good starting point for further water balance studies and the impact of climate change on the Danube water regime (Pekárová et al., 2023). A study conducted at the Bratislava station on the Danube shows that an increase in extreme events can be expected in both the summer and winter in the future (Leščešen et al., 2024).

An assessment of the impacts of climate change on river discharges and the runoff of rivers from basins has been a frequently discussed subject in recent years by Slovak experts (Danáčová et al., 2015; Škoda et al., 2016; Szolgay et al., 2007). Proposals to mitigate these consequences are contradictory; on the one hand, technical measures and, on the other hand, so-called “green measures” are being promoted. Studies in Slovakia have analysed historical, current and future changes in hydrological characteristics. They indicate an increase in the long-term seasonal runoff in the winter half-year by 2100, while a decrease in the long-term seasonal runoff and a decrease in the base flow index are expected for the summer period (Sabová and Kohnová, 2023). In addition, on assessment of mean annual discharges over different time periods highlights the need for a new reference period after 2000 to accurately calculate the design values, and to emphasize the importance of detailed analyses for precise determinations (Blaškovičová et al., 2023; Jenciova et al., 2023; Poárová et al., 2023; Šipikalová et al., 2015). These analyses provide valuable insights into the evolving hydrological regime in Slovakia that are crucial for understanding and managing the effects of climate change on water resources. Kohnová et al. (2019) also showed the need for a re-evaluation of design discharge values for future designs of water management structures from the point of view of land-use changes.

As already mentioned, almost all components of the hydrological cycle are directly or indirectly affected by changing climatic conditions and human activity, which are also reflected in the hydrological regimes of the river basins. Therefore, one of the challenges of hydrologists, and also climatologists should be to detect changes in the components of the hydrological cycle, analyse and update the relations of the components participating in the hydrological regime, as well as describe the possible consequences of their changes on the future hydrological conditions in the basin. For this reason, the European Union (EU) has created a legal framework to guide Member States in the management of water resources and the mitigation of flood risks. EU Directive 2007/60/EC on the assessment and management of flood risks mandates Member States to draw up flood risk maps and management plans (European Commission, 2007). The directive underscores the necessity of understanding hydrological extremes and their probabilities, which are critical for the formulation of robust flood risk management strategies. To fulfill these objectives, it is necessary to process long-term series of hydrological data. With the increasing availability and length of hydrological data series, analysing larger datasets has become feasible. This study seeks to address the main research question: How have the hydrological regimes of Slovak rivers changed

over the past 90 years, particularly in relation to climate variability and human activities? The primary objective is to conduct a long-term analysis of seasonality and maximum average daily river discharges (with a duration of 1 day) to identify trends and changes that may be linked to climate change or other anthropogenic influences.

This research is particularly relevant given the pressing challenges in water resource management today, including climate change, population growth, and urbanization. As regions face increased variability in precipitation and extreme weather events, understanding how river flow patterns have changed becomes essential for effective water management. The findings of this study can help inform adaptive management strategies that ensure sustainable water supply, protect ecosystems, and mitigate flood risks. Moreover, by establishing a unified methodology for estimating maximum discharges, we could contribute to developing frameworks that can be utilized in regions experiencing similar hydrological shifts. This is crucial for policymakers and water resource managers who need to make informed decisions based on reliable data and predictive models.

2 METHODOLOGY

2.1 Analysis of seasonal changes of hydrological regime

An analysis and evaluation of changes in the intra-annual hydrological regime of monthly discharges in selected rivers in the Slovak region according to the Pardé's method (1947) was used. It compares the discharge in each month with the mean annual discharge and provides a series of dimensionless coefficients that show the relative fluctuations of water discharges throughout the year. By applying the Pardé method to rivers in the Slovak region, this study provides a localized analysis of an intra-annual hydrological regime, which may reveal unique patterns and insights specific to this geographic area. Analysing the seasonal distribution of river discharge also provides valuable insights for water management, environmental protection, and the adaptation to climate change. The Pardé method is a fundamental tool in hydrology for classifying and understanding river discharge regimes. The Pardé method, named after Maurice Pardé (1947), is a widely used classification system for understanding and categorizing the hydrological regimes of rivers. This method focuses on the seasonal variability of river discharges, thereby helping hydrologists and water resource managers to understand and to predict river behaviour throughout the year. The Pardé method classifies hydrological regimes based on the monthly distribution of river discharges. It compares the discharge in each month to the mean annual discharge to produce a series of dimensionless coefficients that can highlight the relative variations in water discharge over the year. The Pardé coefficient P_{ki} is defined as:

$$P_{ki} = \frac{\overline{mMQ}}{\overline{MQ}}, \quad (1)$$

where: $\overline{mMQ}$ is long-term mean monthly discharge in a single month i ($i = I, \dots, XII$), and $\overline{MQ}$ being the long-term annual discharge.

Each of these categories can be further refined based on the specific seasonal patterns and local climatic conditions. The exact classification might vary slightly depending on the regional hydrological studies and specific criteria used by researchers.

2.2 Change of annual maximum daily discharge

According to Burn (1994) the seasonality index was used to detect the effect of climate change on the hydrological regime of

maximum daily discharges in the rivers selected. Trend detection techniques, including the Mann-Kendall test and Sen's slope estimator, were applied to identify significant trends in the maximum daily discharges of the rivers selected. For a comprehensive analysis of the effect of climate change on the hydrological regime of maximum daily discharges, we have also divided the hydrological data into two seasons, which proceeded from an analysis of the hydrological regime of the rivers in the Slovak region.

The Burn seasonality-index, permits the estimation of the date of the occurrence of the extremes (high or low-discharge) in the calendar year. The result is the most probable date of the occurrence of an extreme event along with the stability-index $\bar{r}$ (expressing the probability that the event will occur on this day). D_i is defined as the date of the occurrence of the i -th event in the Julian calendar, with $D = 1$ standing for 1 January and $D = 366$ for 31 December. The results of a Burn analysis are typically graphed on an unit circle, and D is understood as the polar coordinates on the unit circle with the angle $\bar{\theta}$. The direction of the mean vector of all the events gives the mean date of the occurrence MD , and the length r of the mean vectors is the measure of the variability of the date of the occurrence. The values of $\bar{r}$ range between 0 (the events occur with equal probability on all days of the year) and 1 (all the events occur on one single day in the year).

The angle on the unit circle based on the Julian calendar day is:

$$\theta_i = D_i = \left(\frac{2\pi}{366} \right), i = 1, n \quad (2)$$

The calculation of the mean flood occurrence day (MD) follows these terms and equations:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n \cos(\theta_i), \quad \bar{y} = \frac{1}{n} \sum_{i=1}^n \sin(\theta_i), \quad (3)$$

$$\bar{\theta} = \tan^{-1} \left(\frac{\bar{y}}{\bar{x}} \right), \quad \text{for } x \geq 0 \text{ and} \quad (4)$$

$$\bar{\theta} = \tan^{-1} \left(\frac{\bar{y}}{\bar{x}} \right) + \pi, \quad \text{for } x < 0 \quad (5)$$

$$MD = \bar{\theta} \frac{366}{2\pi}. \quad (6)$$

Finally, the seasonality vector is calculated as:

$$\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2}. \quad (7)$$

Note that MD should be regarded as a probability statement and not be misinterpreted as a true or exact predicted value/prediction.

Nonparametric tests are more suitable for the detection of trends in hydrological time series, which are usually irregular, and with many extremes (Burn and Elnur, 2002; Hamed, 2008; Gilbert, 1987; Yue et al., 2003). The Mann-Kendall trend test (Kendall, 1975; Mann, 1945) is one of the most widely used distribution-free tests of trends in time series. The test performs two types of statistical analyses: 1) it notes the presence of a monotonic increasing or decreasing trend, while 2) the slope of a linear trend is estimated with the nonparametric Sen's method (Sen, 1968), while the variance of the residuals should be constant over time. Distribution-free tests have the advantage that their power and significance are not affected by the actual distribution of the data. This contrasts with a parametric trend test, such as the regression coefficient test, which assumes that the data follow a Normal distribution and that the power of which can be greatly reduced in the case of skewed data (Yue et al., 2002). The Mann-Kendall trend test has therefore been widely used for testing trends, such as the temperature, rainfall, river

discharges, and water quality time series, in many natural time series that deviate significantly from the Normal distribution. The Mann-Kendall test estimates the gradients between each datum and all the subsequent data in a sequence and tests the null hypothesis based on the standardized sum of the number of positive gradients minus the sum of the number of negative gradients. This test is the result of the development of the nonparametric trend test first proposed by Mann (1945). This test was further studied by Kendall (1975) and improved by Hirsch et al. (1982, 1984), who allowed the consideration of seasonality. The MAKESENS 2-tailed test is used for four different α significance levels. The significance level of test α is a number selected from the interval from 0 to 1 or 100% (the smaller the better, but $\alpha = 0.05$ or 5%) is most often used. A significance level of 0.05 means that there is a 5% probability that the values of x_i are from a random distribution, and with that probability we would make an error in rejecting H_0 (the null hypothesis) of no trend. A significance level of 0.001 means that the existence of a monotonic trend is very likely.

We evaluated the significance of the trend in our study at selected significant levels or levels of the significance of a trend):

*** if the trend is at $\alpha = 0.001$ – the validity of H_0 is improbable;

** if the trend is at $\alpha = 0.01$ – there is a 1% error in rejecting H_0 ;

* if the trend is at $\alpha = 0.05$ – there is a 5% error in rejecting H_0 ;

+ if the trend is at $\alpha = 0.1$ – there is a 10% error in rejecting H_0 .

In the context of the Mann-Kendall test, this implies that we cannot reliably claim that there is a significant trend in the time series, and therefore we cannot reject the null hypothesis H_0 , which assumes that no trend exists. The most important trend is assigned three stars (***); with the gradual decrease in importance, the number of stars also decreases. Statistically, we can evaluate the significance of a trend using the Z value. A positive Z value indicates an upward (growing) trend, while a negative value indicates a decreasing trend. If the absolute value of Z is less than the significance level, there is no trend. The Mann-Kendall (as well as the Spearman (1904)) tests for trends assess a sequence of data and assume a null hypothesis that there is no trend in the sequence.

The Spearman test determines the difference between the actual position of each datum in the sequence and its position in the sequence when it is sorted in ascending order; and tests the null hypothesis based on the standardized sum of these differences. To estimate the true slope b of an existing trend (as change per year) the Sen's nonparametric method can be used.

3 STUDY AREA AND DATA USED

Around 96% of the Slovak territory belongs to the Black Sea drainage area. On the territory of Slovakia, the Black Sea drainage area covers part of the basin of a European water way, i.e. the Danube with its tributaries (the Morava, Vah, Hron, and Ipľ), while the basins of Slaná, Bodva, Hornád, and Bodrog belong to the drainage area of the Tisa River. The Baltic Sea drainage area (4%) is represented by the basins of the Poprad and Dunajec rivers. This first part of the study is especially focused on maximum discharges. The mean daily discharges were used as input data. The location of the twenty-six selected rivers and gauge stations in the Slovak region is presented in Fig. 1. Table 1 lists the selected rivers, gauging stations, catchments, measurement periods, and basic hydrological characteristics calculated for the periods analysed.

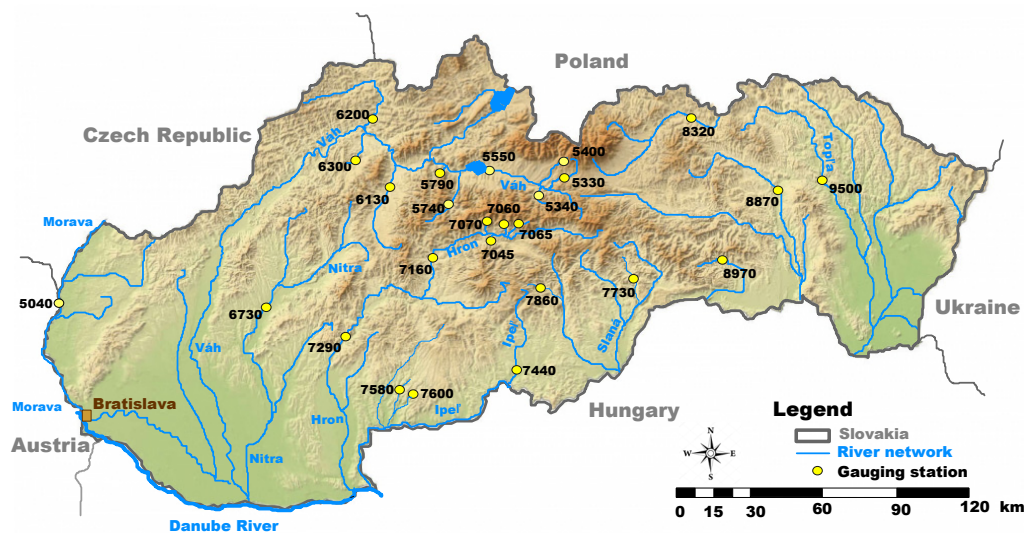


Fig. 1. Location of the twenty-six rivers selected in the Slovak region.

Table 1. List of twenty-six selected rivers in the Slovak region, and the Danube River and its tributaries, including the Drava, Sajó, and Tisa rivers, with basic characteristics and long-term mean discharge – Q_{ma} , long-term mean runoff – R_{ma} .

ID SK	Gauge station	River	Period	Area [km ²]	Q_{ma} [m ³ s ⁻¹]	R_{ma} [mm]	G. station Altitude [m a.s.l.]
5040	Moravský Svätý Ján	Morava	1930–2020	24129.3	105.1	137	146
5330	Východná	Biely Váh	1930–2020	105.64	1.58	472	730.65
5340	Kráľova Lehota	Boca Váh	1930–2020	116.6	2.01	544	655.08
5400	Podbanské	Belá	1930–2020	93.49	3.53	1191	922.7
5550	Liptovský Mikuláš	Váh	1930–2020	1107.21	20.47	583	568
5740	Podsúchá	Revúca	1930–2020	217.95	4.82	697	558.31
5790	Lubochňa	Lubochňanka	1930–2020	118.48	2.37	631	442.71
6130	Martin	Turiec	1930–2020	827	10.17	388	389.88
6200	Kysucké Nové Mesto	Kysuca	1930–2020	955.09	16.15	533	346
6300	Poluvsie	Rajčanka	1930–2020	243.6	3.53	457	393.03
6730	Nitrianska Streda	Nitra	1930–2020	2093.71	14.49	218	158.3
7045	Hronec	Čierny Hron	1930–2020	239.41	2.85	375	480.48
7060	Bystrá	Bystrianka	1930–2020	36.01	0.92	806	574.54
7065	Mýto pod Ďumbierom	Štiavnička	1930–2020	47.1	1.05	703	616.75
7070	Dolná Lehota	Vajskovský potok	1930–2020	53.02	1.36	809	495.28
7160	Banská Bystrica	Hron	1930–2020	1766.48	25.78	460	334
7290	Brehy	Hron	1930–2020	3821.38	46.22	381	195
7440	Holiša	Ipel'	1930–2020	685.26	3.03	139	172
7580	Plášťovce	Krupinica	1930–2020	302.79	1.76	183	139
7600	Plášťovce	Litava	1930–2020	214.42	1.09	160	142.02
7730	Štítnik	Štítnik	1930–2020	129.63	1.36	331	284.95
7860	Lehota nad Rimavicou	Rimavica	1930–2020	148.95	1.5	318	263.65
8320	Chmeľnica	Poprad	1930–2020	1262.41	15.51	387	507.44
8870	Košické Olšany	Torysa	1930–2020	1298.3	7.73	188	185.88
8970	Nížný Medzev	Bodva	1940–2020	90.15	0.78	273	310.24
9500	Hanušovce	Topľa	1930–2020	1050.05	8.04	241	160.4
ID							
D01	Hofkirchen	Danube	1900–2022	47496	633.1	420	299.6
26HU	Szeged	Tisza	1930–2022	138408	817.79	186	73.7
30HU	Felsőzsolca	Sajo (Slaná)	1930–2022	6440	29.34	144	107.2
44HR	Donji Miholjac	Drava	1926–2022	37306	530.1	448	88.57

For the processing of the discharge data series, the hydrological (water) year was used in this work. In Slovakia, the hydrological year is calculated from 1 November of the current year to 31 October of the following year (OTN ŽP 3113-1:04). A hydrological year is a twelve-month period usually chosen so that precipitation falling in that period can participate in the runoff process in the same period. For a complex analysis of the effect of the climate change on the hydrological regime of the maximum daily discharges, we also divided the hydrological data into two seasons: summer-autumn (SA: 1 May – 31 October) and winter-spring (WS: 1 November – 30 April). When analysing a hydrological series, it is required that the given series is homogeneous and stationary, since the mathematical statistics methods were derived for independent random variables and for series of the results of experiments performed under the same conditions, where the previous results do not affect the results of the next experiment. Therefore, we also selected stations where no significant changes occurred that would affect the water volume or the hydrological discharge regime.

4 RESULTS

4.1 The changes in the intra-annual hydrological regime of monthly discharges

The Pardé method shows monthly discharge developments by comparing different runoff periods. Twelve monthly Pardé coefficients (P_k) were used to construct the so-called regime curves.

Their course is essentially determined by the monthly water balances in the catchments, as well as by intra-annual storage effects like snow accumulation and melt. Originally distinguished a multitude of types of discharge regimes that will not be discussed in detail here. The dependence between the long-term maximum monthly Pardé coefficients (P_{kmax}), and altitude is illustrated in Figure 2. Based on the long-term maximum Pardé coefficient (P_{kmax}) classification, the Slovak rivers analysed have either a moderately variable discharge regime or a highly variable discharge regime. According to P_{kmax} , a moderately variable discharge regime ranges from 1.5 to 2.0, while a highly variable discharge regime ranges from 2.0 to 3.0 (Table 2).

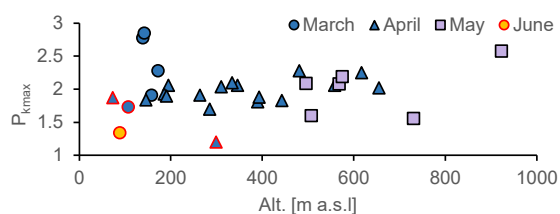


Fig. 2. The maximum seasonality strength P_{kmax} and altitude for selected rivers in the Slovak region, the Danube River and its tributaries, including the Drava, Sajó, and Tisa rivers over the entire period 1930/31–2019/20 (foreign rivers - points with red frame).

Based on the occurrence of maximum long-term Pardé coefficient (P_{kmax}) for the entire period of 1930/31–2019/20 was analysed, the runoff regime. The analysis of the runoff regime of the selected rivers in the Slovak region, i.e., the Danube River and its tributaries, including the Drava, Sajó, and Tisa rivers, shows that the long-term maxima of the Pardé coefficients (P_{kmax}) occur in the spring month of April, respectively in June (Drava River). Figure 3a illustrates the occurrence of the monthly long-term coefficient P_{kmax} for the selected rivers in the Slovak region for the entire period 1930/31–2019/20.

The maximum long-term monthly coefficient P_{kmax} for the selected gauging stations of the Danube River shows similar months of occurrences. Next, the changes in the occurrences based on the maximum long-term Pardé coefficient (P_{kmax}) for the three 30-year periods (1930–1960, 1961–1990, and 1991–2020) were analysed. The analysis shows changes in the occurrence of the monthly maxima of P_{kmax} . Based on the maximum long-term Pardé coefficient (P_{kmax}) the changes in the occurrence of the long-term maximum monthly discharges are also illustrated in Figure 3a. The analysis also shows the changes in the maximum runoff seasonality strength. The changes in the maximum seasonality strength P_{kmax} , for the selected rivers are illustrated in Figure 3b).

More detailed changes in the regime curves based on the Pardé coefficient P_k during the periods analysed are illustrated in Figure 4. The maximum runoff is set one month earlier in the period 1991–2020 than in the periods 1930–1960 and 1961–1990 for the Morava River, the Kysuca River, and the Danube River. On the one hand, the last two 30-year periods, the maximum runoff is set one month earlier on the Topľa River. On the other hand, the maximum runoff is set one month later in the periods 1961–1990 and 1991–2020 than in the period 1930–1960 for the Sajó River (Felsőzsolca). The runoff regime of the Štiavnička River shows a greater slope of the regime curve at the start of the season of increased runoff during the last two 30-year periods.

The intra-annual variability of the selected rivers was also calculated and analysed using the ratio of the maximum monthly Pardé coefficient to the minimum monthly Pardé coefficient. This ratio indicates the variability of the discharge throughout the year. The discharge variability of the selected rivers in the Slovak region during the period of 1930–2020 is illustrated in Figure 5a. Most of the selected rivers in the Slovak region fall into the category of either high intra-annual variability or very high intra-annual variability, based on the ratio of the maximum monthly Pardé coefficient to the minimum monthly Pardé coefficient. Four rivers, including the Ipel', Krupinica, and Litava, were categorized as having extreme intra-annual variability. The Danube River and its tributary, the Drava River (Donji Mihaljac), were categorized as having moderate intra-annual variability. The Sajó River (Felsőzsolca) and the Tisa

Table 2. Classification of the annual discharge regime based on the maximum long-term monthly Pardé coefficient P_{kmax} of the selected Slovak rivers and Danube gauging station for the period of 1930/31–2019/20.

Classification based on long-term monthly maximum P_{kmax}	P_{kmax}	River (in selected gauging stations)
Constant regime	≤ 1.2	Danube (Hofkirchen)
Sub-constant regime	$1.2 < P_{kmax} \leq 1.5$	Drava
Moderately variable hydrological regime	$1.5 < P_{kmax} \leq 2.0$	Morava, Biely Váh, Lubochňanka, Turiec, Rajčianka, Nitra, Štítnik, Rimavica, Poprad, Torysa, Topľa, Tisza, Sajó (Slaná)
Highly variable hydrological regime	$2.0 < P_{kmax} \leq 3.0$	Boca, Belá, Váh, Revúca, Kysuca, Čierny Hron, Bystrianka, Štiavnička, Vajskovský potok, Hron, Ipel', Krupinica, Litava, Bodva,

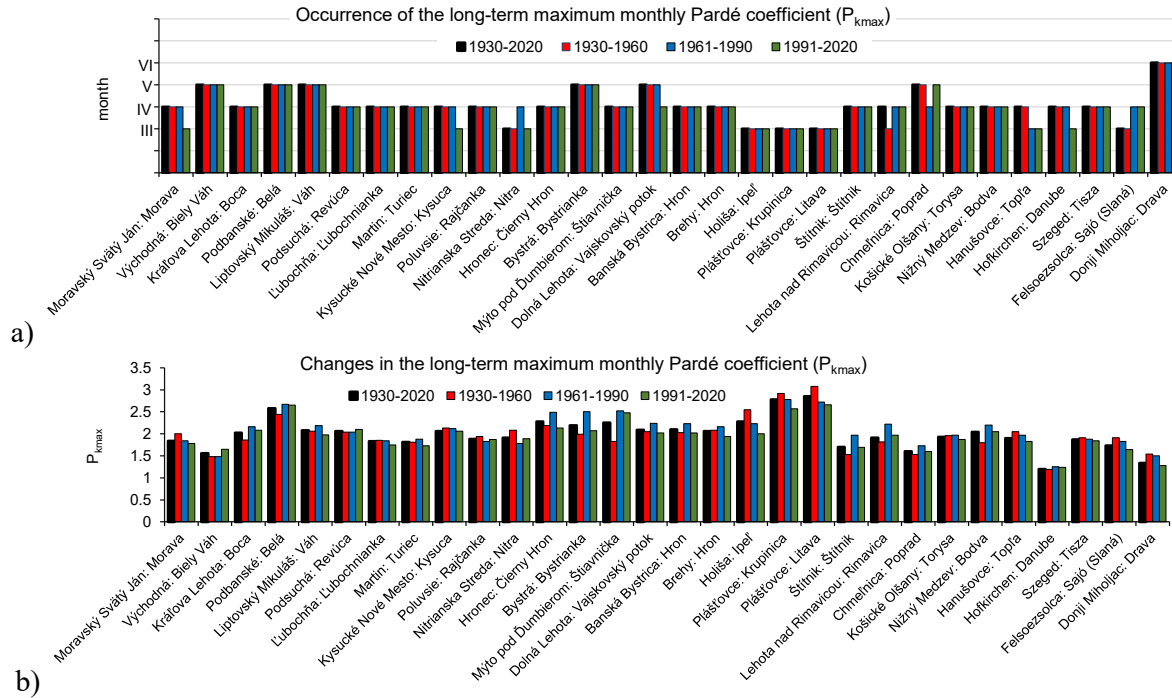


Fig. 3. a) The changes of the occurrence and b) changes in maximum seasonality strength P_{kmax} , for selected rivers in the Slovak region, the Danube River and its tributaries, including the Drava, Sajó, and Tisa rivers.

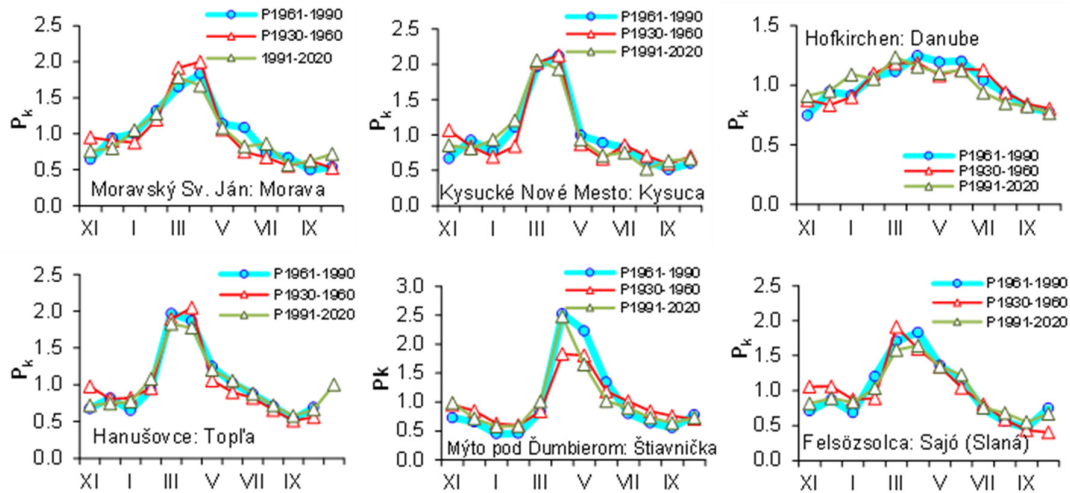


Fig. 4. Example of the changes in the runoff regime curve based on the long-term monthly Pardé coefficient P_k during the three 30-year periods (1930–1960, 1961–1991, and 1991–2020).

River (Szeged) were categorized as having very high intra-annual variability based on this ratio. Figure 5b illustrates how the annual seasonal variability of runoff at individual sites varied over the three 30-year periods (1930–1960, 1961–1991, and 1991–2020), with some sites showing significant increases or decreases in seasonal differences. Significant changes in the seasonal variability of the runoff can be identified on the stream Ipeľ (Holíša), Krupinica (Plášťovce) a Litava (Plášťovce). These stations represent locations where there have been significant changes in the seasonal variability of runoff between different periods. A decrease or increase in the variability can be caused by climate changes or interventions in the water regime in the basin.

4.2 The changes in the seasonality of maximum daily discharges according to the Burn index

This part of the article deals with changes in the seasonality of maximum daily discharges according to the Burn index in selected rivers in the Slovak region. Figure 6 shows the maximum daily discharge series over the period analysed in selected rivers in the Slovak region and in the selected Danube River gauging stations. Figure 7 illustrates dates of the occurrence of the Q_{ldmax} discharges for all the selected rivers in the Slovak region according the Burn index. The arrows mark the day of the mean flood occurrence calculated (MD), which is indicated by the direction of the arrow.

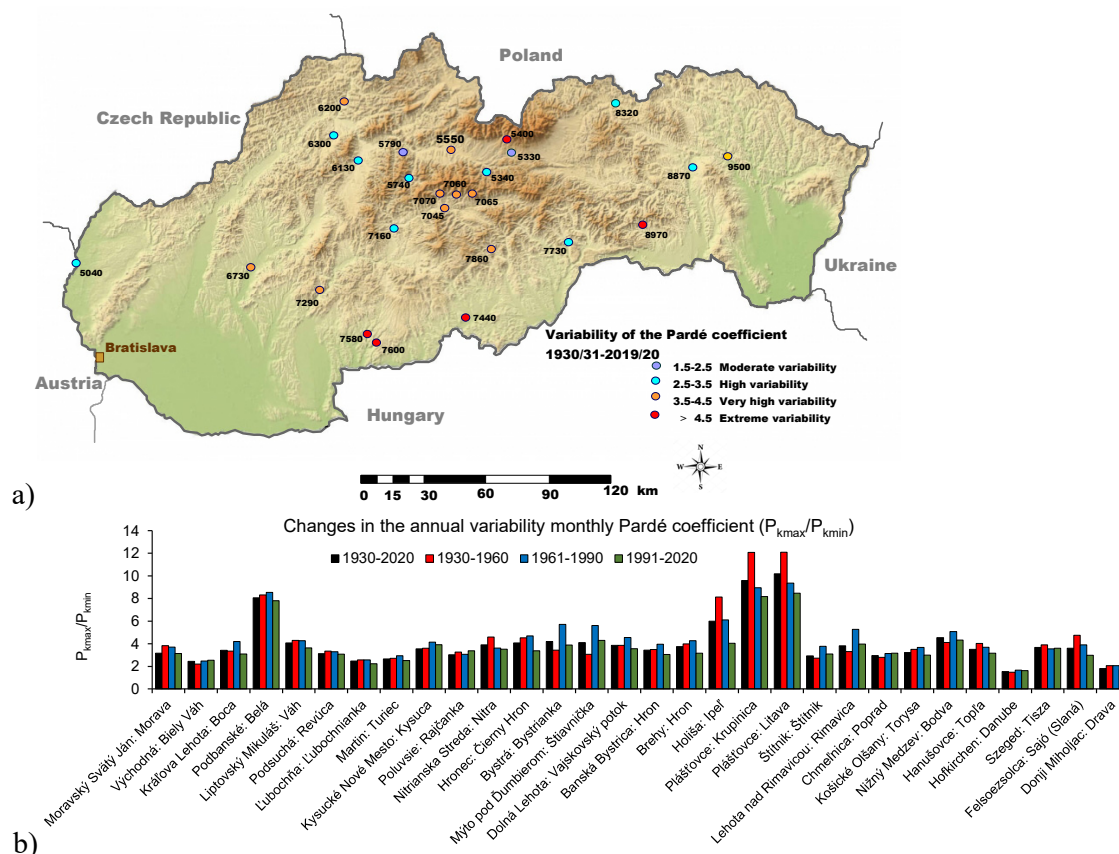


Fig. 5. a) Annual variability of the selected rivers (P_{kmax}/P_{kmin}) of the Pardé coefficient illustrates the seasonally shaped runoff (the number is the ID SK of the gauging station) and b) changes in Annual variability of the selected rivers (P_{kmax}/P_{kmin}) during the three 30-year periods (1930–1960, 1961–1991, and 1991–2020).

The day of maximum daily discharge in the winter-spring season significantly depends on the station's altitude (Figure 8a), as well as the entire hydrological year (Figure 8c). The day of the maximum daily discharge in the summer-autumn season shows a low dependence on the station's altitude (Figure 8b). The percentiles of the Burn index (10th, 50th and 90th percentiles) in the winter-spring season and summer-autumn season, which compare three 30-year periods, are illustrated in Figure 9. The winter-spring maximum of series Qld_{max} typically occur around Julian day 130 (March 9th), while the summer-autumn daily maxima (SA) occurred around Julian day 233 (June 20th) during the period of 1930/31–2019/20. A comparison of the occurrence of Qld_{max} discharges shows that in the WS season, they set earlier but later in the SA season during the last thirty years (1990/91–2019/20) (Figure 9).

To detect and estimate long-term trends in the time series of the Burn index, we used the non-parametric Mann-Kendall test. The series were calculated in successive steps for 20-year periods (20-year moving averages). We analysed the significance of the long-term trends for the whole period 1930/31–2019/20 as well as the significance of the trends of the summer-autumn and winter-spring periods. Figures 10a)–b) illustrate examples of the rivers with increasing and decreasing types of long-term trends of the Burn index as well as with a high degree of correlation between the analysed data and Sen's estimated data. Figure 10a) illustrates example of the positive slope of the linear trend line, which indicates that the Qld_{max} occurred later in the period 1930/31–2019/20. Figure 10b) illustrates example of the negative slope of the linear trend line, which indicates that the Qld_{max} occurred earlier during the period

1930/31–2019/20. An analysis of the significance of the trend of the Burn index shows different results. The trends at different stations were decreasing, stable, or increasing. Table 3 presents the results of the analysis of the significance of the trends of the Burn index for the selected rivers for the period 1930/31–2019/20 as well as the significance of the trends of the summer-autumn and winter-spring seasons. The most important increasing trend (assigned three stars (***)) was indicated at sixteen of the stations analysed, at seventeen stations in the summer-autumn season and at nine stations in the winter-spring season during the period 1930/31–2019/20 (Table 3).

5 DISCUSSION

The discharge regimes of rivers are continually changing due to natural processes and anthropogenic activities. Recently, Central Europe and other parts of the world have experienced numerous extreme floods as well as prolonged periods of very low water discharges. The paper presents the first part of a long-term analysis and evaluation of changes in the hydrological extremes regime in 26 selected rivers in the Slovak region. According to Blauhut et al. (2022), Europe in recent years has experienced significantly warmer years associated with a decrease in runoff in several regions. This part was aimed at a long-term analysis and evaluation of changes in the intra-annual hydrological regime of monthly discharges, and changes in the seasonality of the maximum daily discharges. The intra-annual runoff regime of the analysed rivers in the Slovak region is characterized by the occurrence of maximum runoff in the spring months (April–May) and with a high annual variability.

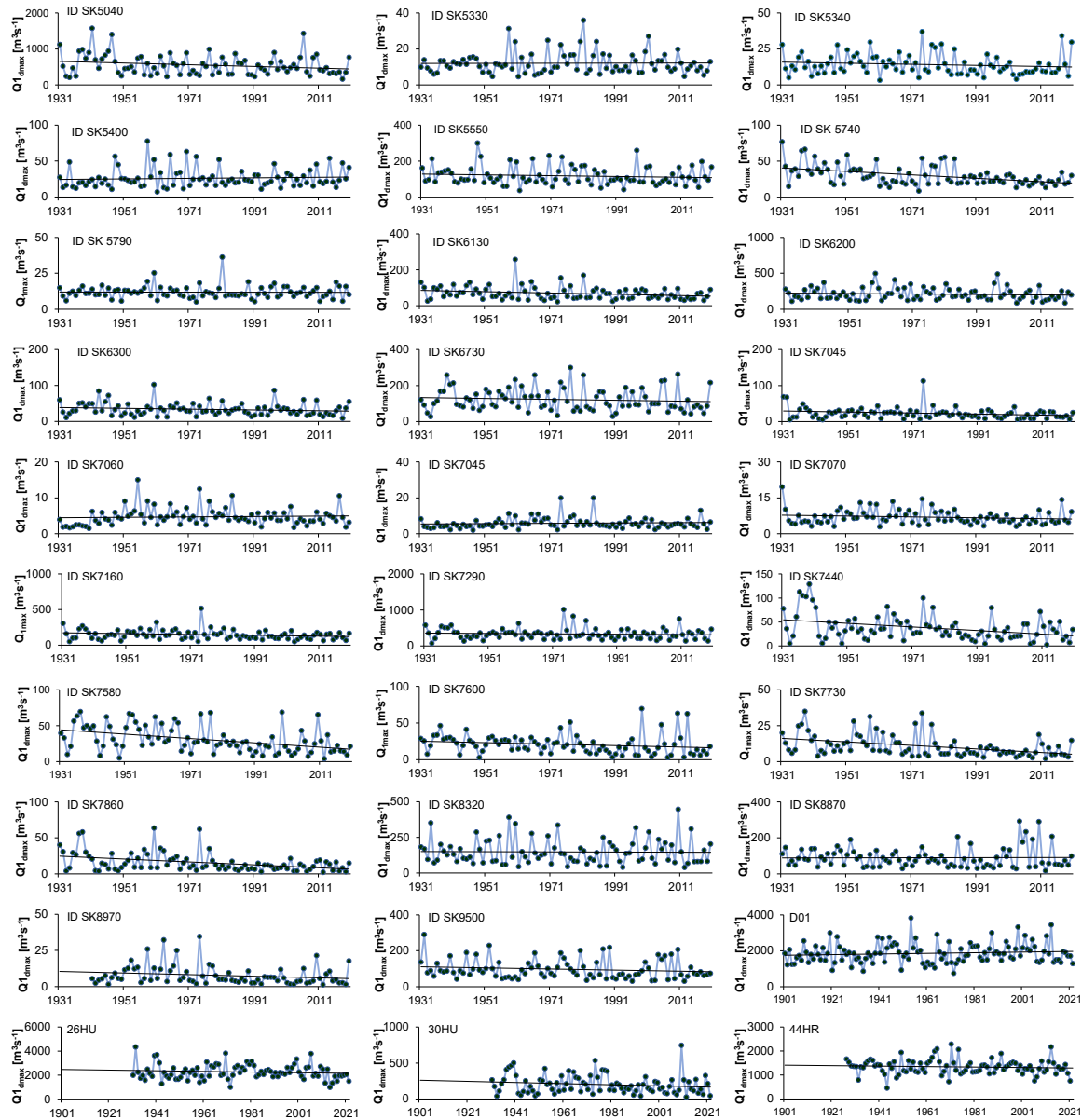


Fig. 6. Course of the maximum daily discharges with 1-day runoff duration of the selected rivers in the Slovak region, the Danube River and its tributaries, including the Drava, Sajó, and Tisa rivers over the periods analysed; long-term linear trends.

The analysis of the runoff regime curves based on the long-term monthly Pardé coefficient for the period 1930/31–2019/20 shows that most of the analysed catchments above an altitude of 500 m a.s.l. have a maximum runoff set in May. In Slovakia, a snowmelt-induced maximum in May is observed only in the highest catchments in the High Tatras (Parajka et al., 2009). The set of runoff maximum occurrences according to the Pardé coefficient shows that in catchments with altitude above 500 m a.s.l. or with a northerly location of hills, there have been no changes detected in the set of maximum occurrence of runoff (month of May). Holko et al. (2024) studied characteristics of runoff events in the Upper Váh River catchment in the warm period of the year. Their results indicate that heavy rains in the Western and High Tatras are especially important for the occurrence of the highest flows at a catchment outlet. The comparison of the runoff regime curves based on the long-term monthly Pardé coefficient for three 30-year periods (1930–1960,

1961–1990, and 1991–2020) detects some changes in the set of maximum runoff at the selected rivers below an altitude of 500 m a.s.l. in the last thirty years. The runoff regime curves based on the long-term monthly Pardé coefficient for the three 30-year periods showed a set of the maximum runoff one month earlier for the Kysuca River, Vajskovský potok and the Danube River in the last 30-year period. The runoff regime curves based on the long-term monthly Pardé coefficient detect a set of the maximum runoff one month earlier for the Morava River in last 30 years, and for the Topľa river, there was a set of the maximum runoff one month later in the last 60-year period. The Sajó and Rimavica rivers are characterized by a later set of the maximum runoff according to the long-term monthly Pardé coefficient in last 60-year period.

Most of the selected rivers in the Slovak region fall into the category of either high intra-annual variability or very high intra-annual variability, based on the ratio of the maximum monthly

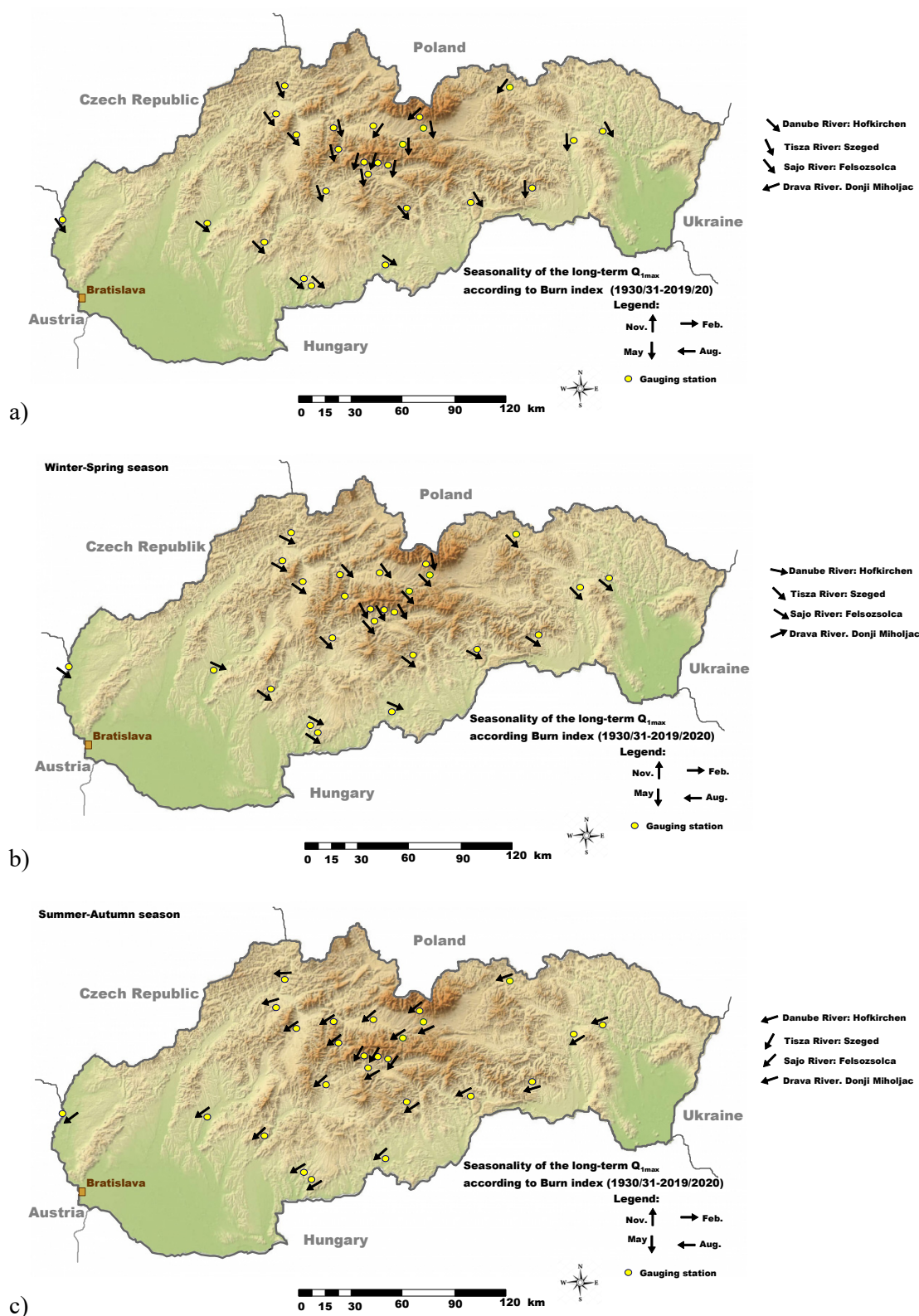


Fig. 7. Illustration of the Burn flood seasonality vector date for selected rivers in the Slovak region, the Danube River and its tributaries, including the Drava, Sajó, and Tisa rivers a) WP- whole year, b) WS-winter-spring season, and c) SA-summer-autumn season. Period 1930/31–2019/20.

Pardé coefficient to the minimum monthly Pardé coefficient. Four rivers were categorized as having extreme intra-annual variability. The Danube River and its tributary, the Drava River

(Donji Miholjac), were categorized as having moderate intra-annual variability. In small river basins, short-duration, high-intensity rainstorms tend to increase with expected increases in

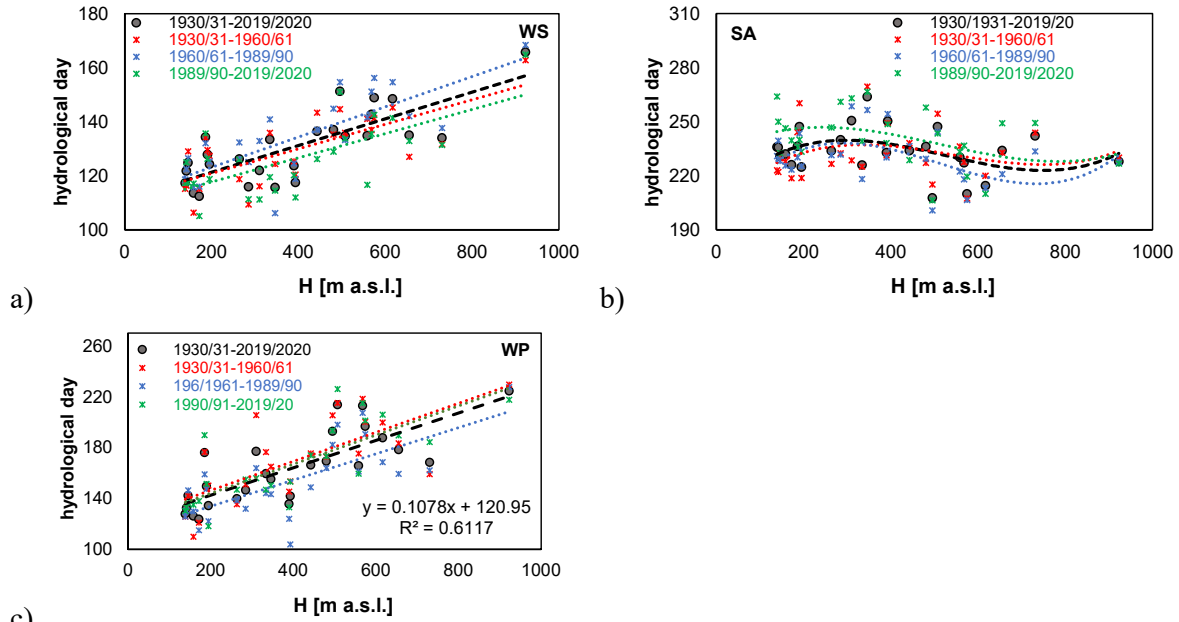


Fig. 8. Dependence of the average Burn index on the station's altitude during the three 30-year periods (1930–1960, 1961–1991, and 1991–2020) a) winter-spring season, b) summer-autumn season c) whole period – hydrological year.

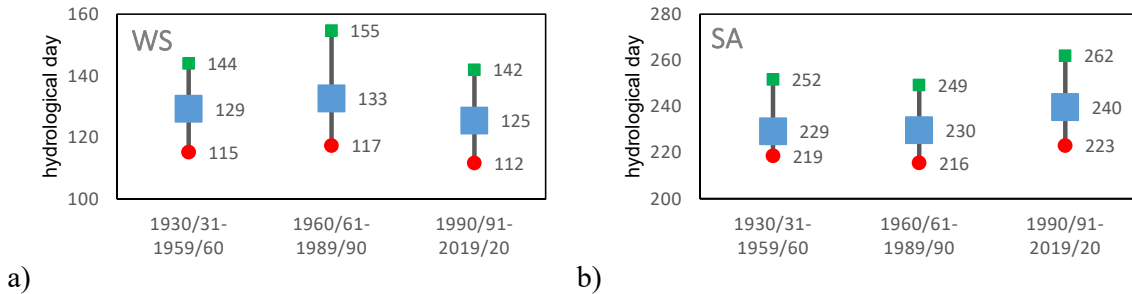


Fig. 9. The percentile of the Burn index (10th percentile - red point, 50th percentile - blue point, and 90th percentile - green point) of the $Q1d_{max}$ discharges in a) winter-spring season, and b) summer-autumn season, comparison of the three 30-year periods.

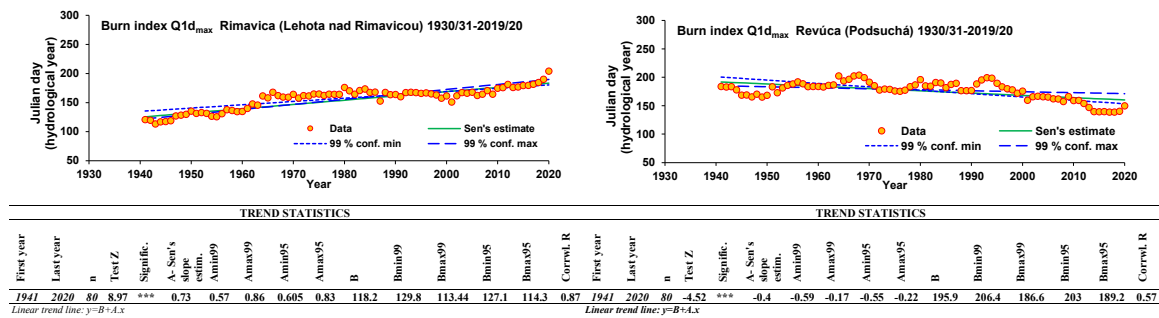


Fig. 10. Example of the long-term trends of the Burn index time series of $Q1d_{max}$ for the rivers with increasing and decreasing types of long-term trends of the Burn index as well as with a high level of correlation between the analysed data and Sen's estimate data.

flood hazards in a warmer climate (Blöschl, 2022). For larger river basins, both increases and decreases in flood hazards have been identified around the world (Blöschl, 2022) and also some studies have reported that changes in land use including deforestation and urbanization might increase flood hazards in small catchments (Hammond et al., 2015; Luo et al., 2023).

According to the Burn index the maximum daily discharges typically occur around Julian day 130 (March 9th) in the winter-spring season, while the summer-autumn daily maxima occurred around Julian day 233 (June 20th) during the period of 1930/31–

2019/20. A comparison of the occurrence of discharges shows that in the winter-spring season, they set earlier and in the summer-autumn season, later for the period 1990/91–2019/20. The changes in the day of the occurrence of maximum daily discharges were indicated as the most important with increasing long-term trends at seventeen rivers in the selected stations during the summer-autumn season and at nine rivers in the selected stations during the winter-spring season for the period 1930/31–2019/20. For example, in the Ukrainian Carpathians, where floods occur throughout the year, an increase in the amount of

Table 3. Significance trend and direction of slope of the Burn index on selected rivers in the Slovak Region, and the Danube River and its tributaries (Drava, Sajó, Tisa) at the analysed gauging stations, 1930/31–2019/20 (SA: summer-autumn season, WS: winter-spring season).

	Signific.	River (in selected gauging stations)	
		(+) increasing trend -later occurrence of the 1-day maximum $Q1d_{max}$	(–) decreasing trend -earlier occurrence of the 1-day maximum $Q1d_{max}$
Burn index	*	Kysuca, Rajčianka	Belá
1930/31–	**	–	Váh
2019/2020	***	Biely Váh, Boca, Nitra, Turiec, Bystrianka, Štiavnička, Vajskovský potok, Hron(BB), Hron(B), Ipeľ, Rimavica, Poprad, Torysa, Tisza, Sajó (Slaná)	Revúca
WS Burn index	*	Nitra, Vajskovský p.	Kysuca, Štiavnička, Poprad, Topľa
1930/31–	**	–	Belá, Turiec
2019/2020	***	Hron (B), Litava, Rimavica	Morava, Biely Váh, Váh, Revúca, Lubochnianka, Rajčianka, Hron (BB), Bodva, Drava
SA Burn index	*	Rajčianka	–
1930/31–	**	Morava, Belá, Revúca, Kysuca	Lubochnianka, Torysa
2019/2020	***	Boca, Váh, Turiec, Nitra, Čierny Hron, Bystrianka, Hron (BB), Hron (B), Ipeľ, Krupinica, Litava, Štítnik, Bodva, Tisza, Drava	Poprad, Topľa

liquid precipitation during the cold period of the year leads to earlier floods and an increase in the probability of flooding in winter (Snizhko et al., 2023). The outcomes of the runoff simulated under changing climate conditions show that changes in the seasonal distribution of the long-term monthly runoff can be expected. The monthly runoff is predicted to increase during winter periods and decrease during summer seasons. These changes are expected to be more extreme for the later time horizons. The maximum annual daily runoff could also be more extreme for the last time horizon (Sleziak et al., 2021). Blöschl et al. (2017) analysed changes in seasonal flood peaks and found that, in some regions of Europe, maximum flows are shifting to earlier or later periods of the year. Their study highlights the shift in flood timing, which has implications for water resource management and flood protection planning.

The climate changes alter seasonal flood timing and magnitude, affecting various regions differently due to shifting precipitation patterns and temperatures as well as, that that climate change can cause increased seasonal variability, affecting river flooding patterns differently across Europe. Blöschl et al. (2019) demonstrated clear regional patterns of both increases and decreases in observed river flood discharges in the past five decades in Europe, which are manifestations of a changing climate. The changes in the hydrological extremes regime, including the timing of runoff maxima, are intricately linked to the overarching influences of climate change (rising temperatures, increasing the frequency and intensity of summer rainfall events) and human activities (deforestation and urbanization, riverbed managements). These findings underscore the need for continued monitoring and adaptive management strategies to mitigate the effects of these changes on water resources and flood risk. The results of our analysis in the Slovak region show, that while some rivers have experienced earlier runoff maxima, others have seen delayed maxima. This variability can be attributed to local climatic conditions, topography, and catchment characteristics. For instance, higher-altitude catchments may still rely on snowmelt, while lowland areas may respond more immediately to intensive rainfall events.

6 CONCLUSIONS

The presented study is part of ongoing research aimed at the long-term analysis and evaluation of hydrological extremes in the Danube basin. This phase of the research specifically focuses

on the analysis and evaluation of changes in the maximum runoff regime across 26 Slovak basins with long observational records (1930/31 to 2019/2020). The study includes a long-term analysis of the daily discharges and maximum average daily discharges, enabling the identification of trends and changes over an extended period that could be related to climate change or anthropogenic influences. The runoff regime and development of monthly and maximum daily discharges in the selected Slovak rivers with the hydrological regime and variability of the gauging stations on the Danube River and the Drava, Sajó, and Tisa rivers were compared.

In the first part of the study, changes in the intra-annual hydrological regime of the monthly discharges in selected rivers in the Slovak region were analysed and evaluated. The results showed that most of the rivers in the Slovak region fall into the category of either high intra-annual variability or very high intra-annual variability with maxima occurrence in spring months. An evaluation of the changes in the runoff regime curves of the selected rivers showed various results. Changes in the runoff regime curves were detected for rivers with an altitude below 500 m a.s.l. An analyses of the long-term trends of the maximum daily discharges showed that, from 1931 to 2020, their occurrence increased at seventeen rivers in the selected stations during the summer-autumn season and at nine rivers during the winter-spring season. With respect to the significant orographic and climatic diversity of Slovakia and the results achieved, it would be appropriate to analyse, evaluate, and apply such a method separately for basins with the same hydrological and geographical characteristics, or along the length of river when designing water management measures.

With warming temperatures leading to earlier snowmelt in high-altitude regions and more frequent intense rainfall events, flood risks are expected to become more unpredictable. Increased discharge variability, as observed in Slovak rivers, could strain existing flood protection infrastructure and water management practices, especially during peak flows. For larger catchments, variability in flood hazard trends due to climate influences requires an adaptive, location-specific approach to water resource management. Based on the findings of the study, practical measures for water management and flood mitigation should focus on enhancing seasonal forecasting, reassessing and potentially redesigning flood defences and water storage infrastructure, developing flexible water management plans that account for varying annual and seasonal variability, and supporting ecosystem-based solutions.

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