

DIFFERENCES IN THE LONG-TERM REGIME OF EXTREME FLOODS USING
SEASONALITY INDICES AT SLOVAK DANUBE RIVER TRIBUTARIES

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The issue of seasonality occurrence of hydrological, hydrogeological or meteorological phenomena and their regional expression has recently devoted increasing attention. The results of some analyses suggest that the seasonality of the selected hydrological characteristics is an important indicator of flood processes, but varies considerably in space. The seasonality of extreme flood events and, hence flood processes, tends to change with the flood magnitude. Investigation of changes in the rainfall-runoff regimes of rivers and its extremes has become more important especially in the context of ongoing and future climate changes.

This paper deals with a statistical analysis of changes in the hydrological regime of Slovak tributaries of the Danube River at 11 stations and the main objective of this study is to find the seasonality indices. Monthly seasonality indices are analysed to interpret the long-term climatic behaviour, while the seasonality of extremes is analysed to understand flood occurrence. For the extreme events seasonality analyses we used the Burn index (1997), which shows the mean date and variability of occurrence of the extreme events.

KEY WORDS: intra-annual flow regime, seasonality, variability, Burn index, daily and monthly discharge, Slovak Danube River tributaries

Introduction

The term seasonality in hydrology, but also hydrogeology means a regular cyclical change of the evaluated element during one hydrological year; in hydrology we mean, for example, water level or flow. In hydrology, several domestic and foreign authors have addressed the issue of seasonal flows (minimum or maximum), (e.g. Parajka et al., 2008; Burn, 1997; Laaha and Blöschl, 2006; Villarini, 2016; Villarini et al., 2011).

The seasonality of hydrological characteristics is one of the key factors controlling the development and stability of natural ecosystems. From a hydrological perspective, seasonality analysis of runoff and precipitation is an appealing method for inferring flood generation mechanisms, which, in turn, supports other hydrological applications, such as hydrological regionalisation. Recently, the assessment of hydrological seasonality and regime stability has attracted a renewed interest, especially in connection with water resources management, engineering design and land cover and climate change assessment studies (e.g. Krasovskaia and Gottschalk, 2002; Bower et al., 2004; García and Mechoso, 2005; Blahušiaková, Matoušková, 2012; 2015; 2016; Milano et al., 2015).

The seasonality of the hydrologic characteristics is characterised by two indices. The first one describes

the seasonality of mean monthly precipitation and runoff and is quantified by the Pardé coefficient, as an index defined for each month of the year (Halmová and Pekárová, 2020). The second index describes the seasonality of the maximum annual floods and annual maxima of daily precipitation, respectively. It is based on Burn's index (1997), which indicates the mean date and variability of occurrence of the extreme events. The mean date of occurrence (D) at a given site is obtained following a transformation of the dates of the occurrence – D_i of the event in the i -th year of observation to the directional statistics, where D_i is expressed as Julian date ($D_i=1$ for January 1st, and $D_i=365$ for December 31st). The dates of occurrence D_i are represented in polar coordinates as vectors of unit lengths and of direction given by (4).

- The average direction Θ is calculated as the average of the projections of the individual vectors D_i to the x and y axis, respectively.
- The length of the mean vector r represents the variability of the date of occurrence (5). It ranges from $r=0$ (uniform distribution around the year) to $r=1$ (all extreme events of precipitation or floods occur on the same day).

The main objective of this study is to analyse the changes in seasonality of the maximum annual floods of

the selected Slovak rivers in the Danube Basin and its changes during the time period 1956–2015. We based the analysis on data of average daily flows from selected stations for the period 1931–2015.

Material and Methods

For studying of the natural runoff variability in any of the river gauging stations, existence of the long term reliable river discharge observations is inevitable. Detailed daily discharges are available at Slovak water gauging stations, but the size of the river basins is different. Selected Slovak water gauging stations (T13–T23; Table 1) at Danube tributaries are described in more details in Halmová and Pekárová (2020) and describe on Fig. 1.

Maximum annual flood seasonality analysis according to Burn index

The seasonality-index according to Burn (Burn, 1997; Parajka et al., 2009) allows to estimate the date and probability of the occurrence of a (flood or low-flow) extreme 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, which the event will actually occur on this day). For the purposes of the calculation 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. D is to be understood as polar coordinates on the unit circle with the angle θ . The direction of the mean vector of all events gives the mean date of the occurrence MD , and the length r of the mean vectors is a measure of the variability of the date of the occurrence. Values of \bar{r} range between 0 (events occur with equal probability on all days of the year) and 1 (all events occur on one single day in the year).

MD and \bar{r} are calculated with the following formulas:

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

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n \cos(\theta), \quad \bar{y} = \frac{1}{n} \sum_{i=1}^n \sin(\theta) \quad (2)$$

$$\bar{\theta} = \tan^{-1} \left(\frac{\bar{y}}{\bar{x}} \right) \quad (3)$$

$$MD = \bar{\theta} \frac{366}{2\pi} \quad (4)$$

$$\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2} \quad (5)$$

The mean date of occurrence D is then obtained using the inverse form of (4).

It should be noted that the exact-to-the-day dates that result from the Burn test have a more orientation character against the background of a probability statement and should not be misinterpreted as a true or exact predicted value/prediction.

Results

Flood seasonality along the Danube River and its tributaries

To understand the reasons for the spatial and temporal patterns of flood seasonality, it is helpful to apply the concept of disposition: The flood favouring conditions can be classified into two dispositions: The basis disposition, and the variable disposition. The basis disposition represents literally invariable conditions like catchment shape, location in a climate zone, or river morphology. In contrast, the variable disposition comprises of changeable conditions like sum

Table 1. List of selected stations on the Danube River, Q_a – mean annual discharge, V – annual runoff volume, R – runoff depth, period 1931–2005

RIVER	PROFILE	COUNTRY	AREA	LAT	LONG	ALTITUDE	Q_a	V	R
			[km ²]			[m a.s.l.]	[m ³ s ⁻¹]	10^9 [m ³ y ⁻¹]	[mm y ⁻¹]
T13	Morava	Mor.Sv.Ján	SK	24129	48.60	16.94	146.0	107.6	141
T14	Belá	Podbanské	SK	93	49.14	19.90	922.7	3.0	1017
T15	Váh	L. Mikuláš	SK	1107	49.09	19.61	568.0	20.6	586
T16	Váh	Šaľa	SK	11218	48.16	17.88	109.0	145.7	410
T17	Hron	B. Bystrica	SK	1766	48.73	19.13	334.0	24.5	437
T18	Hron	Brehy	SK	3821	48.41	18.65	195.0	47.2	390
T19	Kysuca	Kysucké N. Mesto	SK	955	49.30	18.79	346.0	16.4	542
T20	Topľa	Hanušovce	SK	1050	49.03	21.50	160.4	8.0	239
T21	Krupinica	Plášťovce	SK	303	48.16	18.96	139.5	2.0	208
T22	Ipel'	Holiša	SK	686	48.30	19.74	172.0	3.1	144
T23	Nitra	Nitrianska Streda	SK	2094	48.30	18.10	158.3	14.7	221

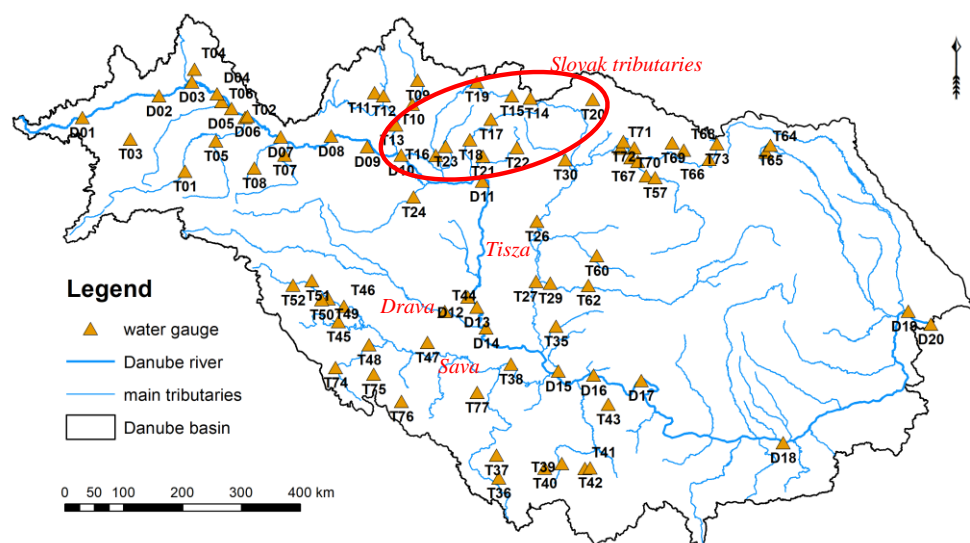


Fig. 1. Water gauges on the Danube River and on the Danube tributaries. (The Slovak tributaries are indicated graphically: T13–Morava, Moravský sv. Ján, T14–Belá, Podbanské, T15–Váh, Liptovský Mikuláš, T16–Váh, Šaľa, T17–Hron, Banská Bystrica, T18–Hron, Brehy, T19–Kysuca, Kysucké N. Mesto, T20–Topľa, Hanušovce, T21–Krupinica, Plášťovce, T22–Ipel', Holiša, T23–Nitra, Nitrianska Streda).

or time distribution of precipitation, or storage level. The higher the total disposition level rises, the likelier a triggering event (rainfall) can cause an extreme event like a flood. In the case of Danube River basin, different climate zones and mountain areas contribute to the basic disposition, and glaciermelt, snowmelt, or regular rainfalls contribute to an increase of the variable disposition. That is the reason for floods to occur typically during months with high runoff, hence high river water levels and likely filled water storages within the landscape.

For calculation of the Burn indexes, the mean daily discharge time series were used. Figure 2 depicts the Burn vectors for all selected gauges on Danube River basin and its tributaries, time periods 1956–1980 and 1981–2005. Slovak tributaries are indicated graphically in red. The arrows thereby mark the calculated day of average flood occurrence (*MD*), indicated by the direction of the arrow, and the severity of the seasonality, indicated by the scale of the arrow.

The Middle Danube at its beginning is characterized by a shift to summer floods (July/ Julian Date ~180) and later on – from the inflow of the Morava to the gauge of Bogojewo – to early summer (June/Julian Date ~90) (Fig. 2). With the inflow of Drava and Sava, the flood regime of the Danube alters again and regains more pronounced flood seasonality with an occurrence day in spring. This type of regime persists from here on downstream to the Lower Danube. As on this section of the Danube the stream shares its seasonality pattern with the Tisza and the Velika Morava, the influence of these two major tributaries is not detectable within the regime characteristics.

Flood seasonality of the Danube tributaries is a function of catchment characteristics, namely topography and climate zone, that is to say runoff regime. Alpine rivers like Isar, Inn, Enns, and Drava show a typical summer flood season. The nivo-pluvial rivers Morava, Váh, Hron, Ipel' originating from the Carpathian and Tatra Mountains, and the right-sided Raba too, experience mainly flood events in spring (March or April).

Furthermore, Figure 3 summarizes the average flood day and the *r*-value, the seasonality index, nicely in 3 double charts, for the whole period 1931–2015 and for three 30-years periods 1931–1960, 1961–1990, 1991–2015 and three 20-years periods 1956–1975, 1976–1995 and 1996–2015.

Despite the general similarity between flood season maximum and monthly runoff peak, it needs to be highlighted that the flood seasonality along the Danube River is not very pronounced. In terms of tributaries and their change in seasonality and flood dates, revealed rather unchanged characteristics for most of the rivers. The alpine rivers, the rivers discharging the Carpathian Mountains and the Tatra Mountains, as well as lower Sava, Drava, and upper Tisza showed almost unchanged flood dates and seasonality values. The *r*-value exceeds the value 0.7 (i.e. 70% probability) only at the Belá-Podbanské gauge T14 (Fig. 3). The *r*-values approximately 0.6 (i.e. 60% probability) is in gauge stations T13, T15, and T20–T23. Lower values are recorded at gauges T16–T19 in all monitored periods. For the tributaries the seasonality *r*-values lie in general higher than those of the Danube.

Figure 4 provides a more detailed look into the Burn statistics and its change over time for Slovak Danube

River tributaries gauges. For each gauge a unit circle lines marking flood events and related magnitudes. Furthermore, the annual maximum time series and the related day of the year are given, allowing for a temporal framing of the date of occurrence and the flood magnitude. We will first explore the unit circle and come back later to the temporal framing.

At the gauges T13 (Morava–Moravský sv. Ján), T14 (Belá–Podbanské), T15 (Váh–Liptovský Mikuláš), T20 (Topľa–Hanušovce) and T22 (Ipeľ–Holiša) a concentra-

tion of high flood is recorded during the one, approximately half-yearly, period. Due to the location of stations in the river basin, this period is in different seasons. In addition, a second phase of the year is depicted with floods of smaller magnitudes. At the gauge T19 (Kysuca–Kysucké N. Mesto) is the concentration of floods is evenly distributed over two half-yearly periods. In other gauges, floods are evenly distributed throughout the year, such as at a station T16 (Váh–Šaľa) and T21 (Krupinica–Plášťovce).

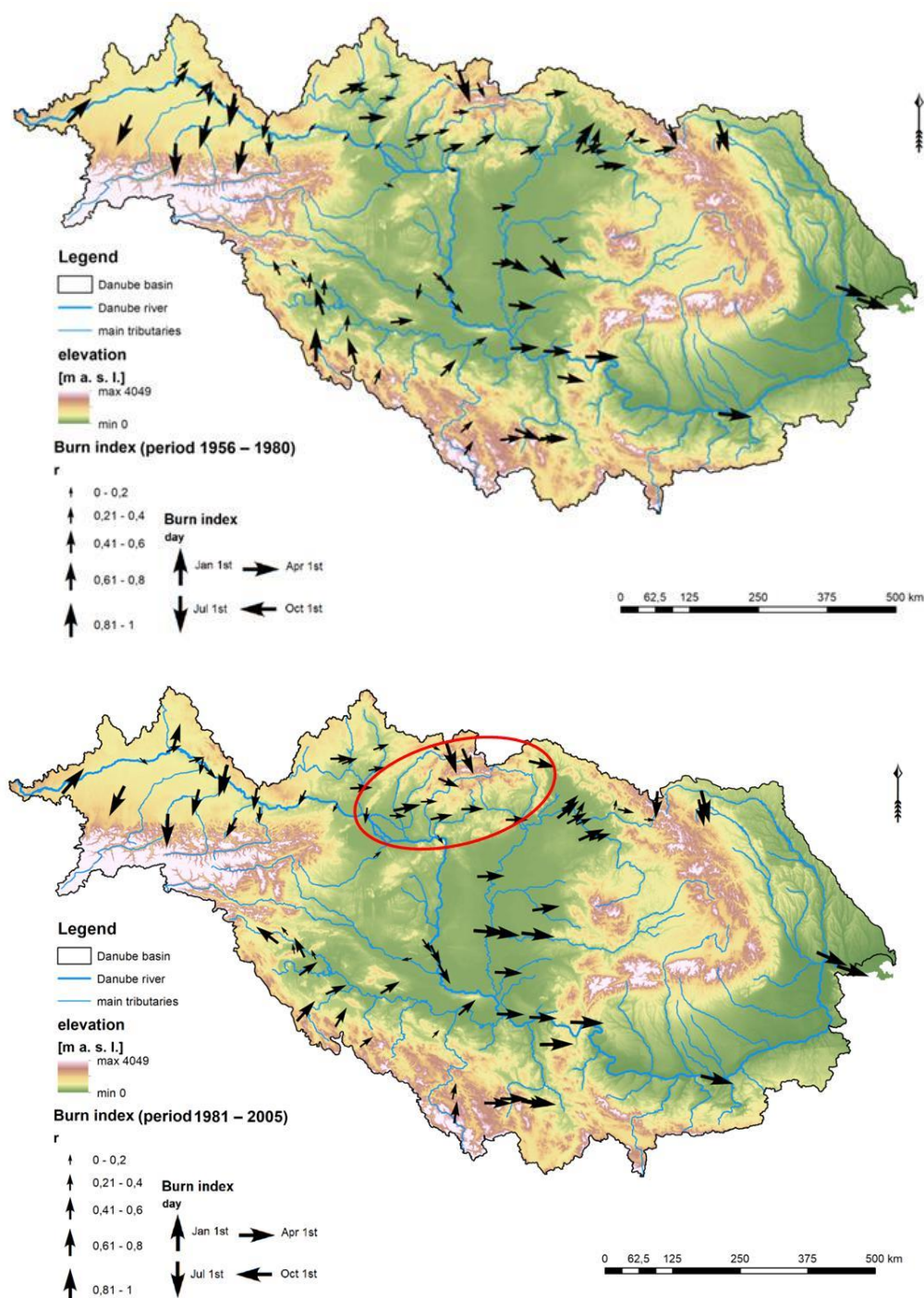


Fig. 2. The Burn r -value as an indication of the seasonality strength and its change over time for 65 gauges of the Danube tributary rivers, period 1956–1980 vs. 1981–2005.

Long term trends of the 25th moving averages of the time series of the Burn indexes

Finally, we have used the time series of the Burn index (period 1931–2015) to analyse the significance of the long-term trends of the Burn index. We computed 25-moving averages of all given time series. We obtained time series for period 1956–2015. For detecting and estimating trend in time series of the Burn indexes we used the non-parametric Mann-Kendall test. In Figure 5 there are plotted the selected gauges series. In Table 2 there are presented the results of trend signifi-

cance analysis for selected 11 stations on the Slovak Danube (T13–T23) tributaries, with the longest daily discharge series.

The analysis of trend significance of the Burn index shows different results. The trends in different stations were decreasing, stable or increasing. The stable trend is only in T14 (Belá–Podbanské) and two decreasing trends are in T13 (Morava–Moravský sv. Ján) and T16 (Váh–Šaľa). In the remaining gauges the increasing trend of the Burn index is recorded.

Very interesting are the results from the gauge T23 (Nitra–Nitrianska Streda). In this station is strong varia-

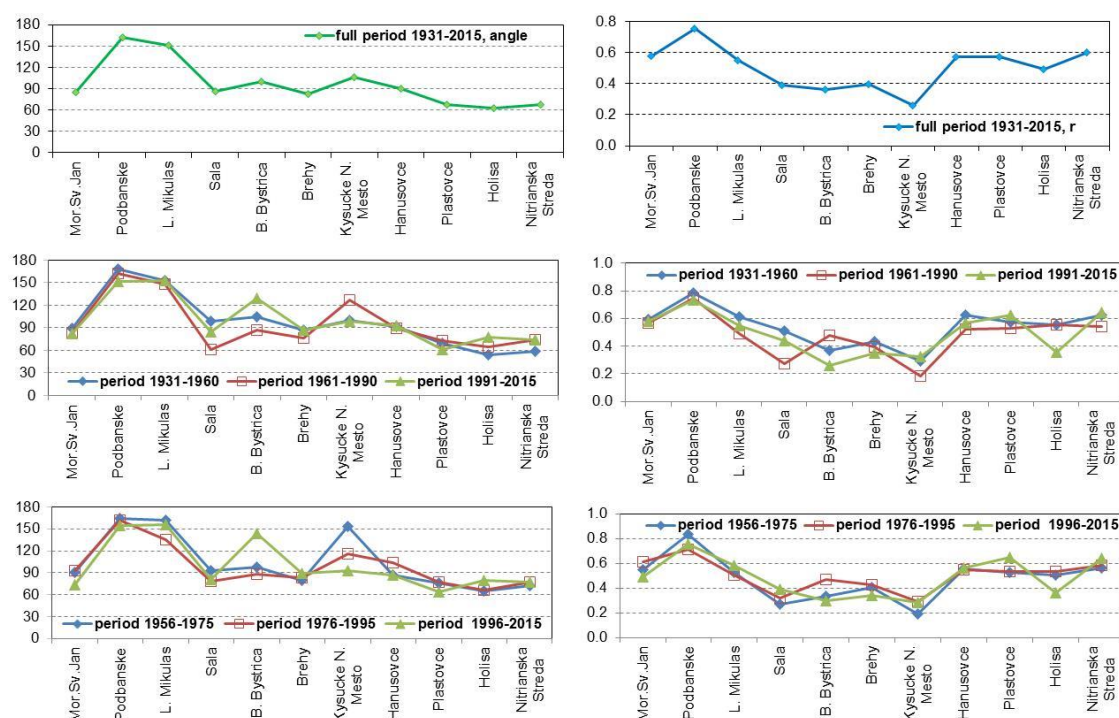
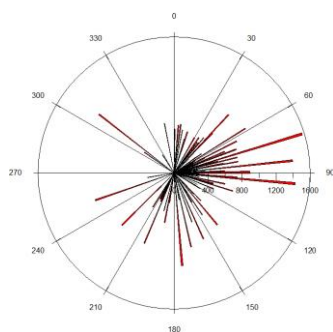
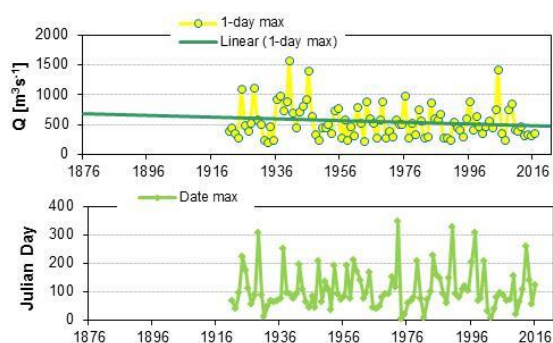
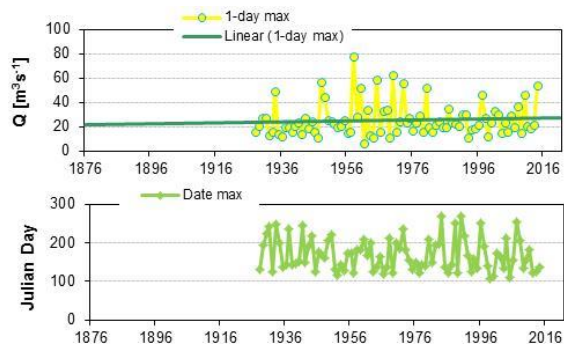
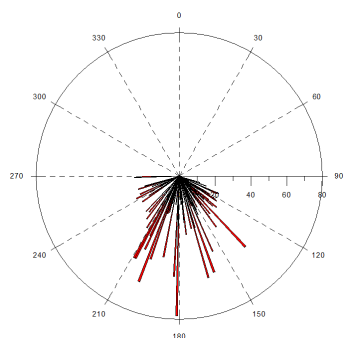


Fig. 3. Average flood day (left charts) and the Burn r -value as an indication of the seasonality strength (right charts) and their change over time for 11 gauges on Slovak tributaries (the whole period 1931–2015 vs. three 30-years periods and three 20-years periods).

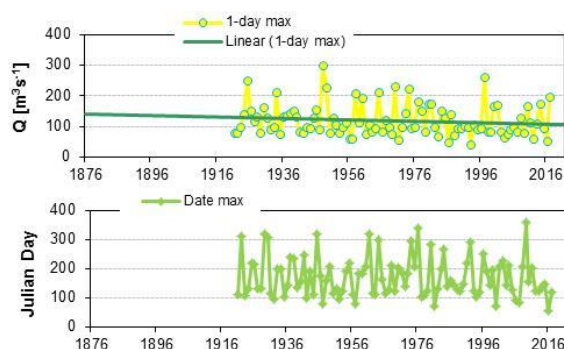
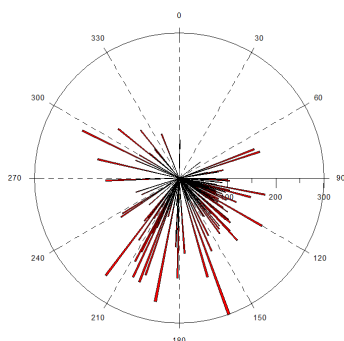


T13 Morava–Moravský sv. Ján 1921–2016

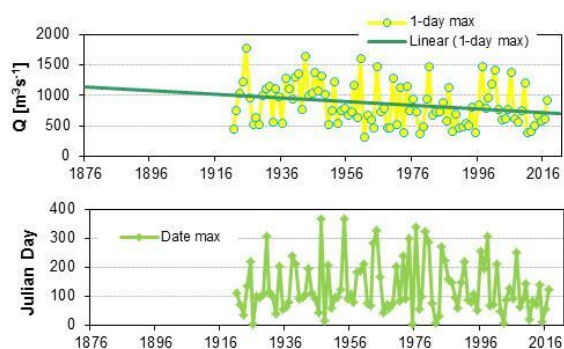
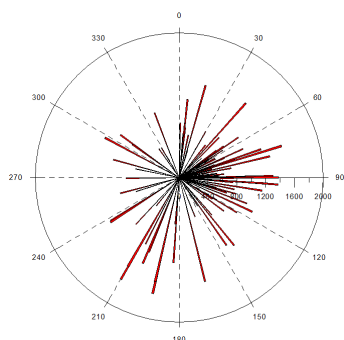




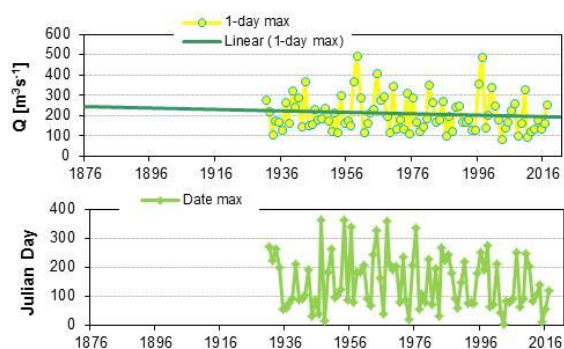
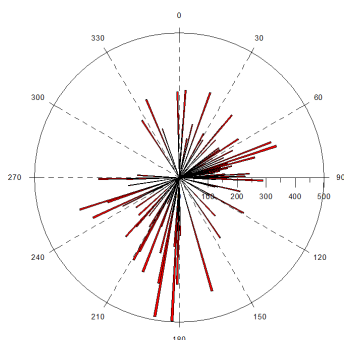
T14 Belá-Podbanské 1928–2014



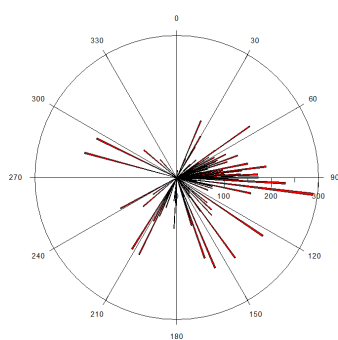
T15 Váh-Liptovský Mikuláš 1921–2017



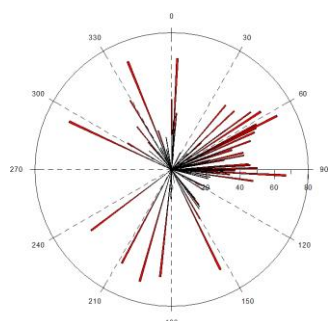
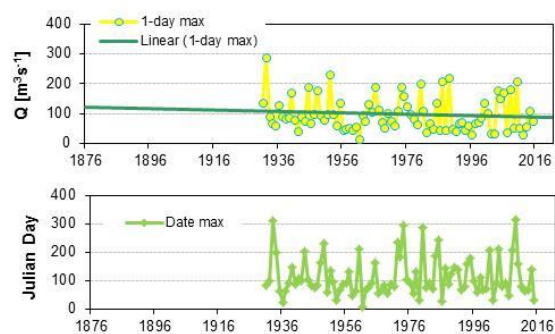
T16 Váh-Šaľa 1921–2017



T19 Kysuca-Kysucké n. Mesto 1931–2017



T20 Topľa–Hanušovce 1931–2015



T21 Krupinica–Plášťovce 1931–2014

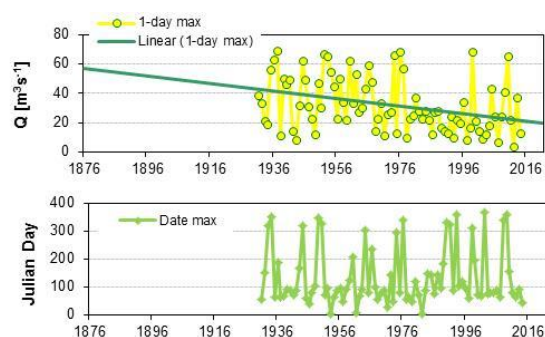


Fig. 4. Changes in the flow regime shown by the inner-annual variations of streamflow along the Slovak Danube River tributaries.

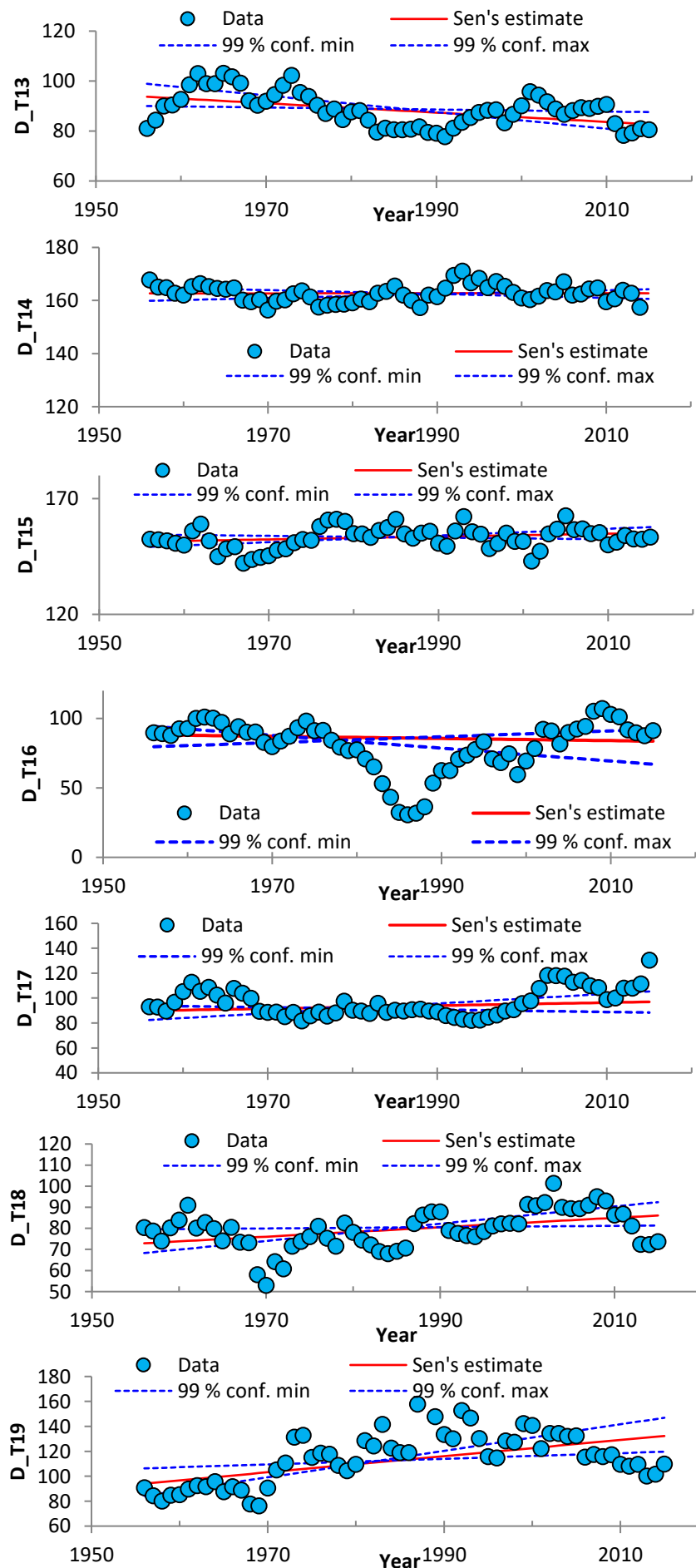
Table 2. Trend significance analysis for selected stations with the longest series

Time series	Burn index, Julian day	First year	Last Year	n	Mann-Kendall trend		Sen's slope estimate	
					Test Z	Signific.	A	B
T13	(Morava–Moravský sv. Ján)	1956	2015	60	-3.44	***	-0.186	109.38
T14	(Belá–Podbanské)	1956	2014	59	0.00		0.000	162.66
T15	(Váh–Liptovský Mikuláš)	1956	2015	60	1.60		0.062	146.32
T16	(Váh–Šaľa)	1956	2015	60	-0.68		-0.077	94.64
T17	(Hron–Banská Bystrica)	1956	2015	60	1.63		0.120	79.82
T18	(Hron–Brehy)	1956	2015	60	3.03	**	0.223	54.15
T19	(Kysuca–Kysucké N. Mesto)	1956	2015	60	3.60	***	0.647	39.76
T20	(Topľa–Hanušovce)	1956	2015	60	4.03	***	0.271	63.31
T21	(Krupinica–Plášťovce)	1956	2014	59	4.81	***	0.221	45.41
T22	(Ipeľ–Holiša)	1956	2015	60	8.12	***	0.653	-10.77
T23	(Nitra–Nitrianska Streda)	1956	2015	60	6.84	***	0.527	7.79

For the four tested significance levels the following symbols are used

*** if trend at $\alpha = 0.001$ level of significance; ** if trend at $\alpha = 0.01$ level of significance

* if trend at $\alpha = 0.05$ level of significance; + if trend at $\alpha = 0.1$ level of significance



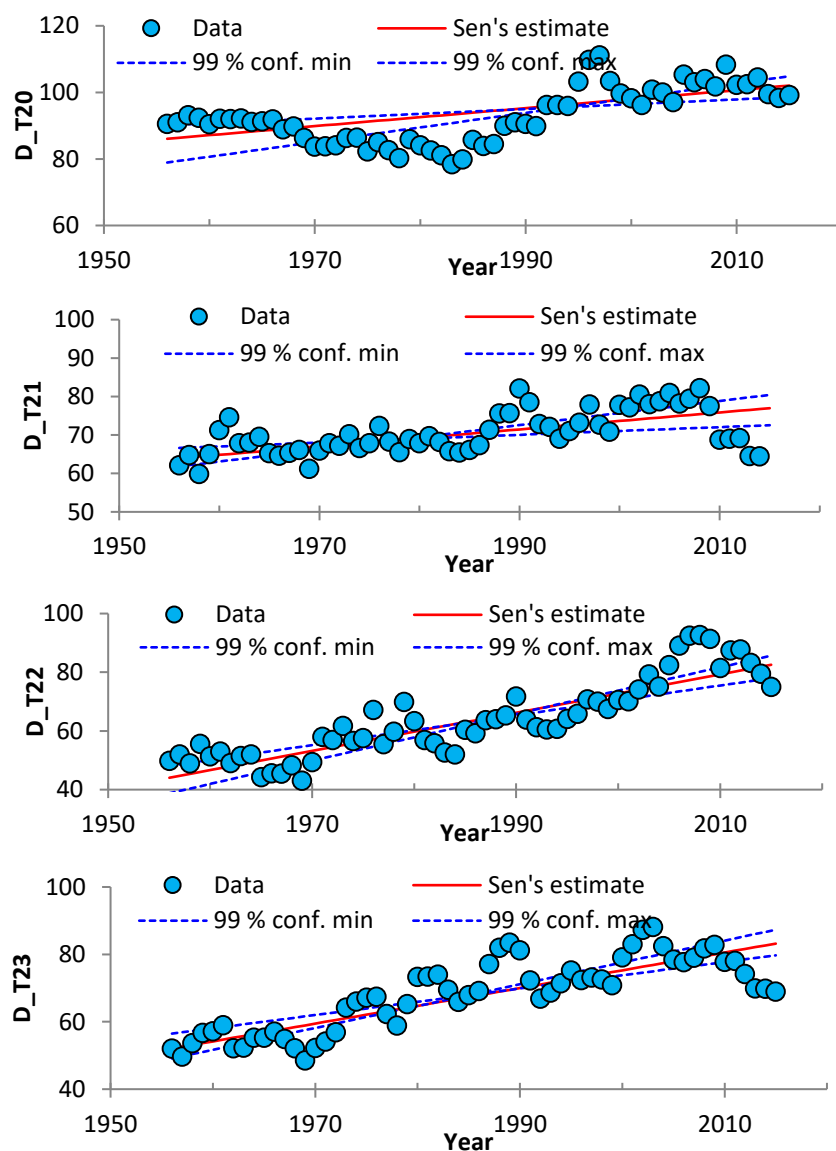


Fig. 5. Long term trends of the Burn index time series calculated for 25-year periods for selected gauges along the Danube River.

bility and increasing of the Burn index time series. The Burn indexes vary from 45 to 90. The similar variability we can see from the results for T21 (Krupinica–Plášťovce) but the wave amplitude is two times longer. Very low variability is in gauges T14 Belá–Podbanské, T15 (Váh–Lipt. Mikuláš) and T16 (Váh–Šaľa).

Conclusions

The Danube River changes its runoff character repeatedly and tributaries, as well as biggest Slovak ones, play a superior role in understanding the Danube River characteristics. That is because they represent the regional water balance and hydrometeorological conditions.

The seasonality of the hydrologic characteristics is cha-

racterised by two indices. The first one is quantified by the Pardé coefficient, and the second index describes the seasonality of the maximum annual floods and annual maxima of daily precipitation, respectively. It is based on Burn's index, which indicates the mean date and variability of occurrence of the extreme events. The result is the most probable date of the occurrence of an extreme event along with the stability-index \bar{r} (expressing the probability, which the event will actually occur on this day).

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tains, and the right-sided Raba too, experience mainly flood events in spring (March or April) (Rössler et al., 2019).

In terms of Slovak Danube tributaries and their change in seasonality and flood dates, revealed rather unchanged characteristics for most of the rivers. The alpine rivers, the rivers discharging the Carpathian Mountains and the Tatra Mountains, as well as lower Sava, Drava, and upper Tisza showed almost unchanged flood dates and seasonality values. The r -value exceeds the value 0.7 (i.e. 70% probability) only at the Belá-Podbanské gauge (Fig. 2).

The analysis of trend significance of the Burn index shows variable results. The trends in different stations were decreasing, stable or increasing. The stable trend is only in Belá-Podbanské and two increasing trends are in Morava-Moravský sv. Ján and Váh-Šaľa. In the remaining gauges the increasing trend of the Burn index is recorded.

Defining temporal change in river discharge is a fundamental part of establishing hydrological variability, and crucially important for identifying climate-streamflow linkages, water resource planning, flood and drought management and for assessing geomorphological and hydro-ecological responses.

The detection of trends in hydrological data is a complex issue. The results have shown that the trend analysis is dependent on the chosen period: in particular, it can have significant influence on both trend magnitude and the direction. The implications of analytical decisions on the interpretations of hydrological change are important and impact on planning and development in many fields including water resources, flood defence, hydro-ecology and climate-flow analysis.

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