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RUNOFF REGIME CHANGES IN THE SLOVAK DANUBE RIVER TRIBUTARIES

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This paper deals with a statistical analysis of changes in the hydrological regime of Slovak tributaries of the Danube River at 11 stations over two 30-year periods: 1931–1960 and 1986–2015. We analyzed changes in monthly discharges using the Pardé coefficient method, as well as changes in average daily discharges.
The monthly Pardé coefficients may be used to plot 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 snowmelt. Changes in the course of Pardé coefficients for water stations of Slovak tributaries of the Danube River do not show any major changes, except for the Ipeľ-Holiša and Topľa-Hanušovce stations. From the results of the daily flow rate analysis it is clear that the course of daily flow rates in the monitored stations remains unchanged during the year and in the most of the monitored Slovak stations the daily flow rates decrease, except for the water stations Belá-Podbanské and Váh-Liptovský Mikuláš.

KEY WORDS: intra-annual flow regime, PARDÉ coefficient, daily and monthly discharge, Slovak Danube tributaries

Introduction

The change in water level during the year characterizes the runoff regime. In the annual cycle, the long-term variability of flow rates has a typical regime depending on the geographical location and height division of the river basin.

In the specific case of the Hron River territory, the distribution of water in the year has the form of a single wave with a maximum in spring months (March-June) and with a minimum in autumn (September). In addition to the main low in September, there is also a minor winter low in January (Poórová, 2013). In river basins with a higher height segmentation and with a higher mean basin height, the winter secondary minimum is changed to the main minimum and autumn minimum to the secondary minimum (Parajka et al., 2008; 2009; Kohnová et al., 2019).

The Danube River with a total length of 2857 km and a long-term daily mean discharge of about 6500 $m^3 s^{-1}$ is listed as the second biggest river in Europe. In terms of length it is listed as the 21st biggest river in the world, in terms of drainage area it ranks as 25th with a drainage area of 817000 km^2. The Danube basin extends from the central Europe to the Black Sea. The extreme points of the basin are 8º 09' and 29º 45' of the Eastern longitude, and 42º 05' and 50º 15' of the Northern latitude (Stančík and Jovanovic, 1988). Out of the whole Danube basin area, 36% are covered with mountains: very tall (over 4000 m in the Alps), and tall (1000–2000 m in the Carpathians, the Balkans and the Dinaric Alps); 64% represent medium-high and low areas (tablelands, hills and plains) (Bondar and Iordache, 2017). In the case of the Danube River Basin, its landscape geomorphology is characterised by a diversity of morphological patterns and the river channel itself can be divided into 6 sections according to the river slope (Lászlóffy, 1965; Stănescu et al., 2004). The longitudinal profile of the Danube and its tributaries, subbasins area and long term discharge is illustrated on the Fig. 1.

In terms of physical-geographical conditions (position, relief and vegetation), a specific continental-temperate climate has developed in the course of time, its characteristic parametric values according Bondar and Iordache (2017) are given below:

– The annual mean air temperature stands between 8°C in the upper part of the basin and 12°C in its lower part; absolute air extremes of +37°C in summer and –36°C in winter. Values of +43° and of –33°C are recorded in the plain-area of the Lower Danube sector.
– A major climatic factor of the Danube basin, namely precipitation, is basically involved in the formation of water discharge and the river's water-regime. In view of the diversity of atmospheric circulation and of landform-types within the basin area, precipitations are unevenly distributed. Thus, in the lowlands, the annual mean stands at some 400–600 mm, with 800–1200 mm in the Carpathians and 1800–2500 and over in the Alps.

The main objective of this study is to analyse the runoff regime of selected Slovak rivers in the Danube Basin and its change during the time period 1931–2015.

Material

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. The characteristics of selected Slovak water gauging stations at Danube tributaries are listed in the Table 1 (Q_a – mean annual discharge, V – annual runoff volume, R – runoff depth, time period 1931–2005). The scheme of the Slovak Danube tributaries is on Fig. 2.

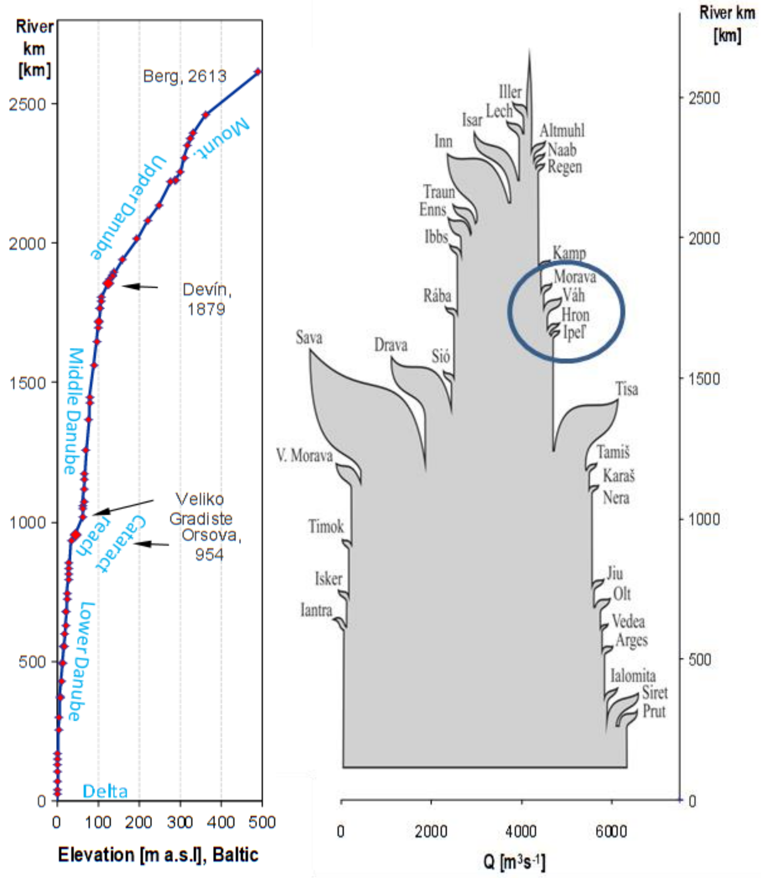


Fig. 1. Longitudinal profile of the Danube and its tributaries, long-term discharge (in detail there are Slovak tributaries); (right figure: values 0–6500 m^3.s^{-1} represent a range of discharges).

Table 1. Characteristics of Slovak water gauging stations

RIVER	WATER GAUGING STATION	AREA [km^2]	LAT	LONG	ALTITUDE [m a.s.l.]	Q_a [m^3 s^{-1}]	V 10^9 [m^3 y^{-1}]	R [mm y^{-1}]
Morava	Mor. Sv. Jan	24129	48.60	16.94	146.0	107.6	3.39	141
Bela	Podbanske	93.49	49.14	19.19	922.7	3.53	0.11	1190
Vah	L. Mikulas	1107	49.09	19.61	568.0	20.6	0.65	586
Vah	Sala	11218	48.16	17.88	109.0	145.7	4.60	410
Hron	B. Bystrica	1766	48.73	19.13	334.0	24.5	0.77	437
Hron	Brehy	3821	48.41	18.65	195.0	47.2	1.49	390
Kysuca	Kysucke N. Mesto	955	49.30	18.79	346.0	16.4	0.52	542
Topla	Hanusovce	1050	49.03	21.50	160.4	8.0	0.25	239
Krupinica	Plastovce	303	48.16	18.96	139.5	2.0	0.06	208
Ipel	Holisa	686	48.30	19.74	172.0	3.1	0.10	144
Nitra	Nitrianska Streda	2094	48.30	18.10	158.3	14.7	0.46	221

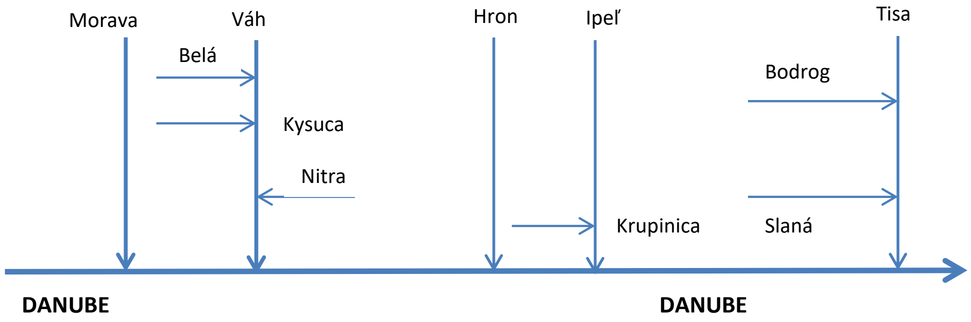


Fig. 2. Scheme of the Slovak tributaries of the Danube River.

Methods

Analysis of the mean annual runoff variability and its change in time are typically performed, applying the common classification method by Pardé (Pardé; 1964; Weingartner and Aschwanden, 1992; Belz et al., 2004; Bormann, 2010; Rössler et al., 2019). This analysis is based on the ratio of each of the twelve long-term monthly MQ_s with the associated long-term annual MQ making up the so-called Pardé coefficient. The calculation of Pardé coefficients has always the effect of a standardization that facilitates the direct comparison between different annual flow hydrographs.
The Pardé flow coefficient $Pk_{(i)}$ is defined as:

$$Pk_i = \overline{Qm_i} / \overline{Q} \qquad (1)$$

where
$\overline{Qm}_i$ – long-term mean monthly streamflow in the single month *i*, *(i=I, XII)* [m³ s^{-1}],
$\overline{Q}$ – being the long-term annual streamflow [m³ s^{-1}].

Results

Runoff changes according to PARDÉ method

First, intra-annual flow-regime at selected gauges according to PARDÉ was analysed. The analysis of the mean annual runoff variability and its change in time are typically performed, applying the common classification method by PARDÉ. In Fig. 3 there are presented Pardé coefficients, course of moving averages of seasonal discharges and 2D picture of the monthly discharges for two 30-years periods 1931–1960 and 1986–2015 for Belá River at Podbanské water station. Partial figures at the Fig. 3. give us information about Pardé coefficient at two different time periods 1931–1960 and 1986–2015; about the course of moving averages of seasonal discharges and monthly discharges at Belá-Podbanské station at the whole time period 1931–2015. In Fig. 3 (part 2D), changes in monthly flow rates in magnitude and occurrence during the year and over the reference period are evident.

The monthly Pardé coefficients may be used to plot 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. Pardé originally distinguishes a multitude of types of flow regimes that shall not be discussed in detail here.
The distinction is made according to the number and position of monthly maxima and minima in the course of the year, the feeding/origin of flow (see below), and the variability range of the coefficient values. Simple types (one-peak) can be separated from complex ones that appear as multi-peak regimes. The latter results from a superposition of several processes which make up the annual course. The flow maxima are typically fed either by glacier-meltwater (glacial regime), snow-melt-water (nival regime) or by rainfall (pluvial regime), or weighted combination of these.
Major types of the Pardé flow regime (acc. to Pardé) we can define as:

- **the nival** (= snow-dominated) runoff regime of mountainous areas, displaying a very wide amplitude of coefficient values, single-peak with a maximum in early summer due to snowmelt and a minimum in winter when the water is retained in form of ice and snow;
- **the pluvial** (= rain dominated) oceanic regime, with a wide range of amplitude, single-peak, with a maximum in the mild rainy winter months and a minimum in summer resulting from intensive evapotranspiration;
- **a balanced pluvial mixed regime** („complex regime 2nd order“) of the rain-snow type, two-peaks, with the main maximum in late autumn and a minimum in summer.

Summarizing Table 2 presents long-term characteristics (top two panels) like Q_m – long-term average monthly, annual and seasonal discharge in m^3 s^{-1}; Q_{min}/Q_{max} – minimal/maximal monthly discharge, V_m – long-term monthly runoff volume in 10^6 m^3; R_m – long-term monthly runoff depth in mm, V_m/V_a – long-term monthly share on yearly runoff in %, t_r – trend slope of monthly discharges, c_s – coefficient of asymmetry, and c_v is coefficient of variability of the monthly discharges, $Pk_{1931–1960}$ and $Pk_{1986–2015}$ – Pardé coefficients.

For the following analysis we focus on the time period 1931–2015 for practical reasons. As discharge characteristics often change over time, a classification of this relatively short time period into the longer time periods is appropriate to avoid misinterpretations. However, on shorter time period changes in the discharge regime become apparent.

Fig. 4a–j present the same pictures for other Slovak Rivers.

The change in daily flow regime in selected tributary profiles

This part of the paper analyses the changes in daily flow rates for two different 30-year periods: 1931–1960 and 1986–2015. From the results it is clear that the course of daily flows during the year remains unchanged and in most of the monitored Slovak gauging stations there is a decrease in daily flows (Fig. 5).

At the stations Belá-Podbanské and Váh-Liptovský Mikuláš in the period 1986–2015 there is a slight increase in average daily flows in the months of April and May. (Fig. 6)

On the other hand, the most significant decrease in daily flows occurs at the stations Krupinica-Plášťovce and Ipeľ-Holiša, especially in spring and winter. (Fig. 7)

Conclusion

Regime types based on Pardé coefficients are regularly used to detect changes in the regime-defining processes by comparing coefficients of two (or more) time slices.

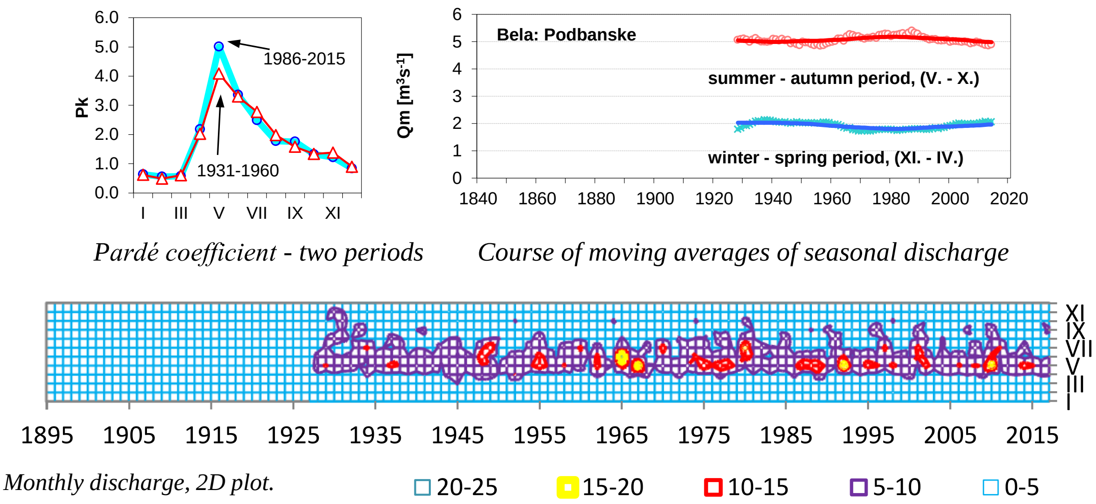
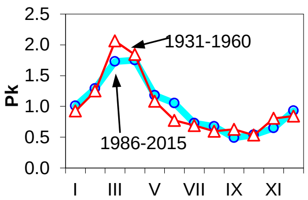
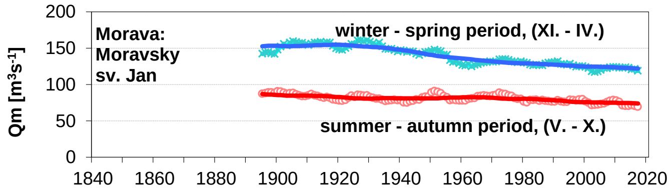


Fig. 3. Partial figures: Pardé coefficient, course of moving averages of seasonal discharges, 2D picture of the monthly discharges, Belá-Podbanské station.

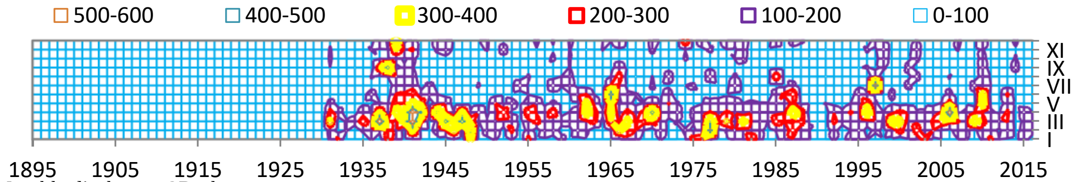
Table 2. Basic statistical characteristics of monthly and seasonal discharges at Belá-Podbanské, Q_m – long term mean monthly/seasonal discharge, Q_{min} – minimum monthly/seasonal discharge, Q_{max} – maximum monthly/seasonal discharge [m^3 s^{-1}], V_m – monthly/seasonal runoff volume [10^6 m^3 month^{-1}], R_m – monthly/seasonal runoff depth [mm month^{-1}], t_r – long term trends slope, c_s – coefficient of symmetry, c_v – coefficient of variation, $Pk_{1931–1960}$ and $Pk_{1986–2015}$ – Pardé coefficients

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year	XI-IV	V-X
Q_{ma}	1.22	1.01	1.12	3.99	8.87	6.66	5.31	3.83	3.11	2.67	2.45	1.67	3.50	1.91	5.08
Q_{min}	0.50	0.47	0.40	0.59	2.88	2.64	1.90	1.10	0.86	0.92	0.79	0.59	1.98	0.74	2.35
Q_{max}	2.45	3.19	5.26	10.01	16.52	20.25	15.15	9.82	8.69	7.86	6.81	3.91	5.16	3.56	8.41
V_m	3.3	2.4	3.0	10.3	23.8	17.5	14.2	10.4	8.2	7.2	6.4	4.5	111.2	29.8	81.4
R_m	35.1	26.0	32.0	110.6	254.2	184.8	152.2	109.6	86.3	76.5	67.8	48.0	1182.9	319.4	863.5
V_m/V_a	2.97	2.20	2.70	9.35	21.49	15.62	12.86	9.27	7.29	6.47	5.73	4.05	100.0	27.0	73.0
t_r	3.16	11.40	0.78	0.81	1.64	-0.37	-0.26	-2.13	0.15	-2.16	-6.48	-6.93	-1.23	-2.95	-0.16
c_s	0.61	2.58	3.64	0.55	0.37	1.98	1.40	0.94	1.41	1.39	1.09	0.89	0.30	0.73	0.50
c_v	0.30	0.38	0.57	0.50	0.31	0.40	0.53	0.45	0.52	0.49	0.47	0.36	0.20	0.29	0.24
$Pk_{1931-1960}$	0.62	0.49	0.60	2.02	4.09	3.30	2.77	1.98	1.58	1.33	1.38	0.90	1.00	2.51	2.51
$Pk_{1986-2015}$	0.64	0.55	0.57	2.18	5.02	3.33	2.44	1.74	1.72	1.32	1.23	0.84	1.00	2.60	2.60



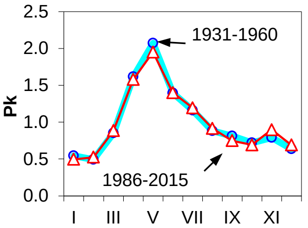


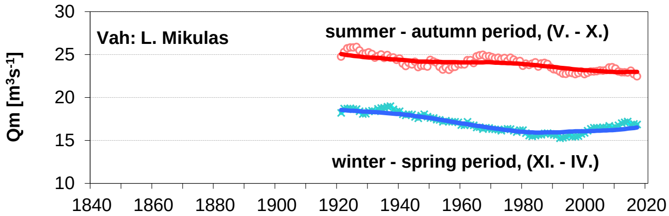
Pardé coefficient - two periods *Course of moving averages of seasonal discharge*



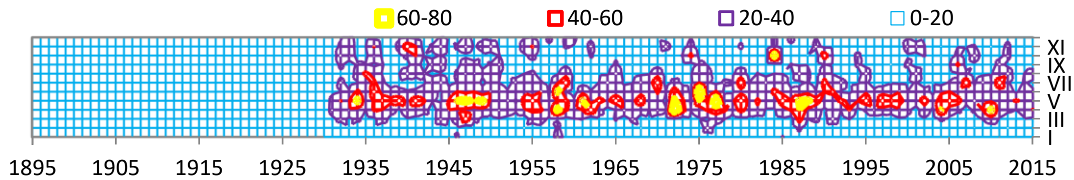
Monthly discharge, 2D plot.

a)



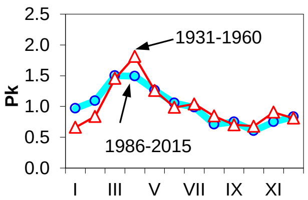


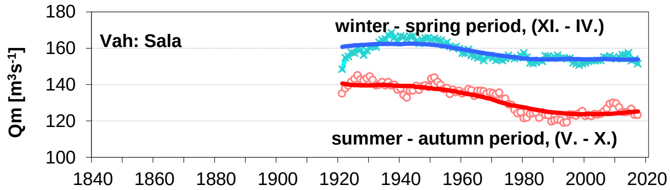
Pardé coefficient - two periods *Course of moving averages of seasonal discharge*



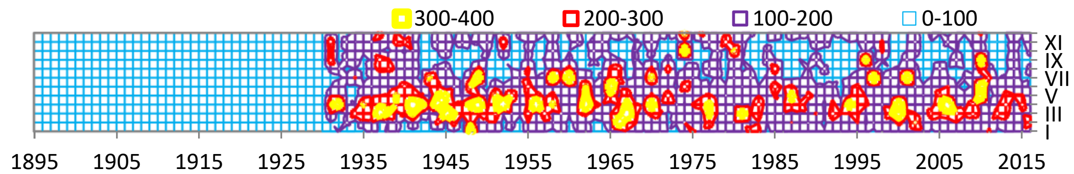
Monthly discharge, 2D plot.

b)



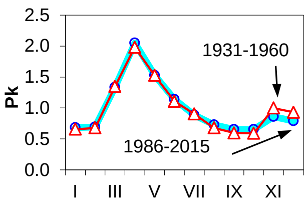


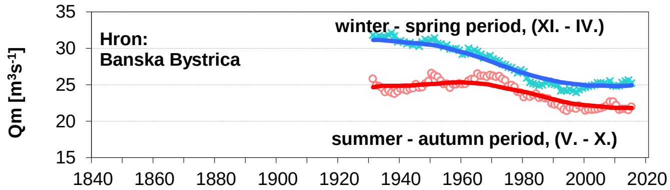
Pardé coefficient - two periods *Course of moving averages of seasonal discharge*



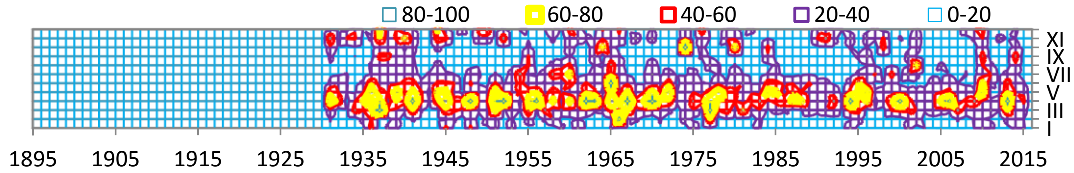
Monthly discharge, 2D plot.

c)



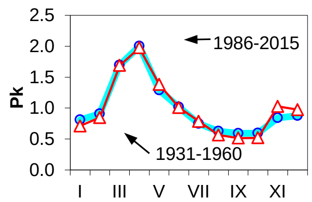


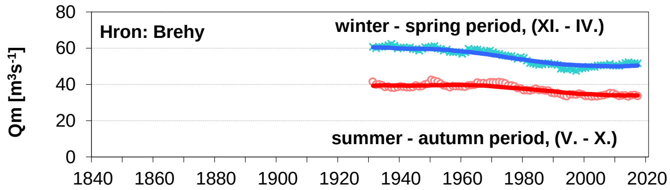
Pardé coefficient - two periods *Course of moving averages of seasonal discharge*



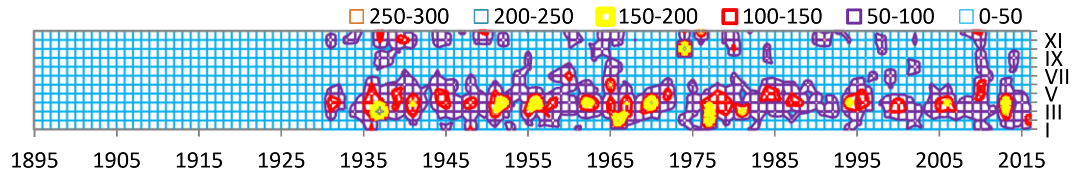
Monthly discharge, 2D plot.

d)



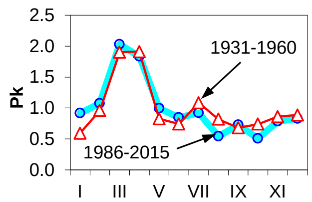


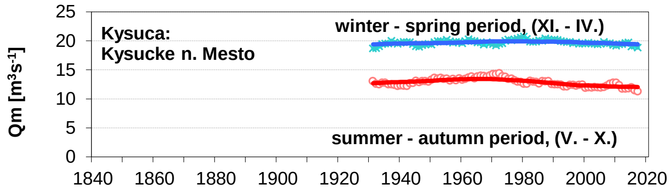
Pardé coefficient - two periods *Course of moving averages of seasonal discharge*



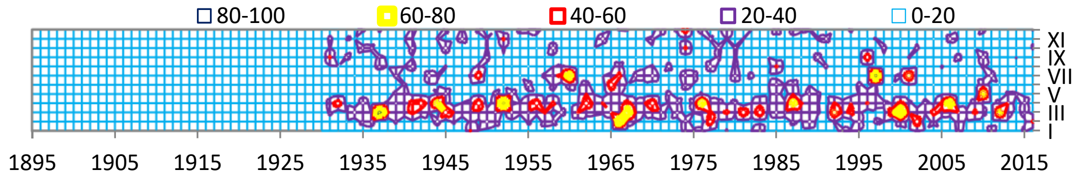
Monthly discharge, 2D plot.

e)



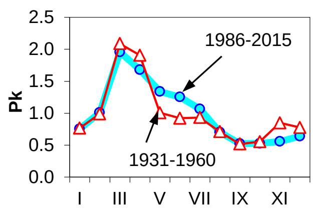


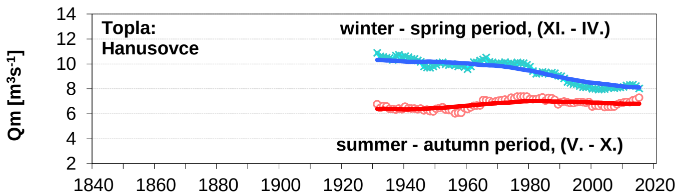
Pardé coefficient - two periods *Course of moving averages of seasonal discharge*



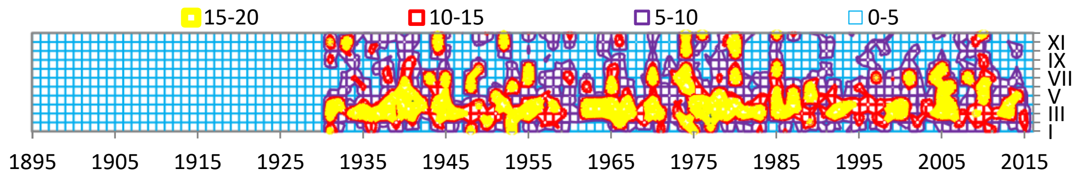
Monthly discharge, 2D plot.

f)



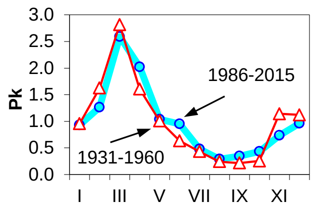


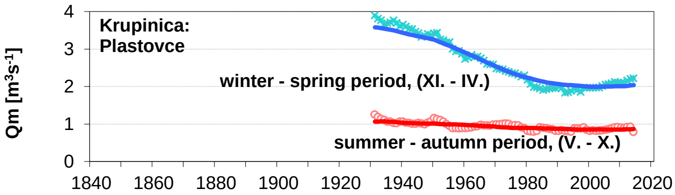
Pardé coefficient - two periods *Course of moving averages of seasonal discharge*



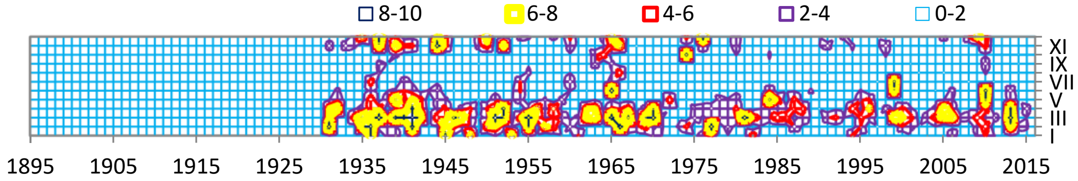
Monthly discharge, 2D plot.

g)



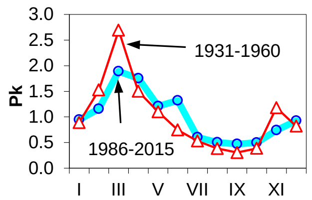


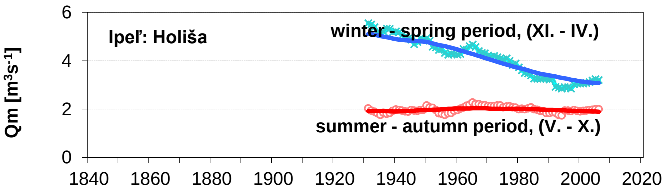
Pardé coefficient - two periods Course of moving averages of seasonal discharge



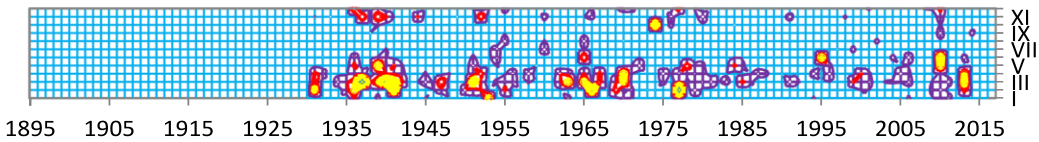
Monthly discharge, 2D plot.

h)



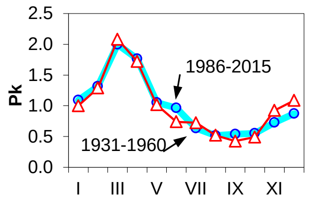


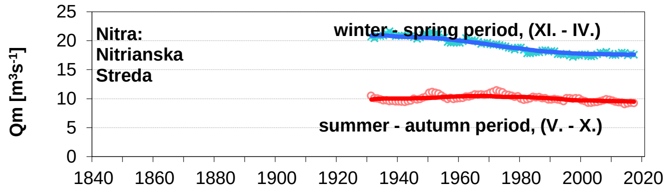
Pardé coefficient - two periods Course of moving averages of seasonal discharge



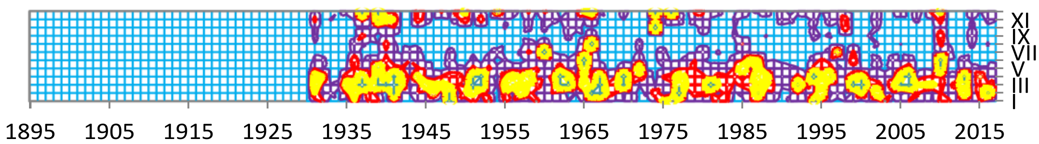
Monthly discharge, 2D plot.

i)





Pardé coefficient - two periods Course of moving averages of seasonal discharge

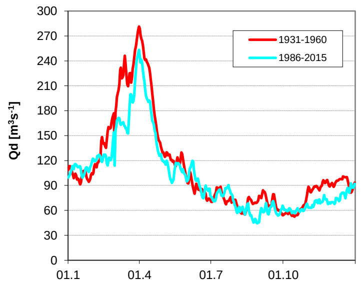


Monthly discharge, 2D plot.

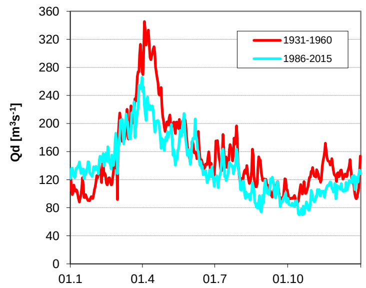
j)

Fig. 4. Pardé coefficient, Course of moving averages of seasonal discharges and 2D picture of the monthly discharges, time period 1931–2015, Slovak tributaries (a–j).

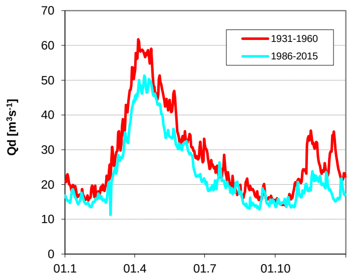
Increase (or decrease) of the extreme values of monthly Pardé coefficients is investigated as well as a consequential impact on the seasonal variability of runoff and a potential temporal shift of the occurrence of the extremes of monthly Pardé coefficients. This might happen due to earlier snow melt caused by regional warming. In order to account for the term "climate", 30 year time periods are investigated. Here, we compared two 30-years periods 1931–1960 and 1986–2015. The Pardé method is a very illustrative way to show monthly discharge developments by comparing different runoff periods. The gauges Ipeľ-Holiša and Belá-Podbanské are taken here as an example (Fig. 8a, b) with 2 periods of 30 years each. The Fig. 8a don´t shows a shift of the discharge peak or minimum discharge. However, in the period 1986–2015 there is a decrease in daily (right side



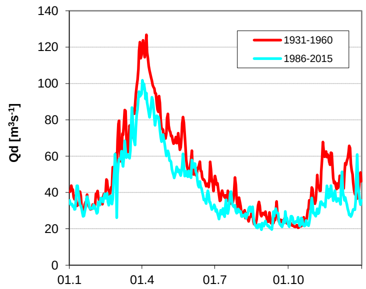
a) Morava-Moravský sv. Ján



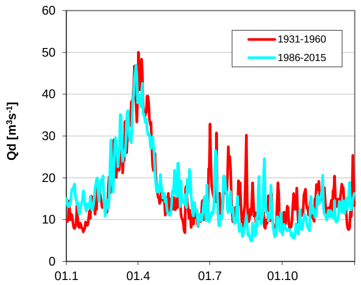
b) Váh-Šaľa



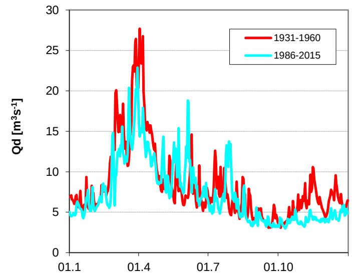
c) Hron-B. Bystrica



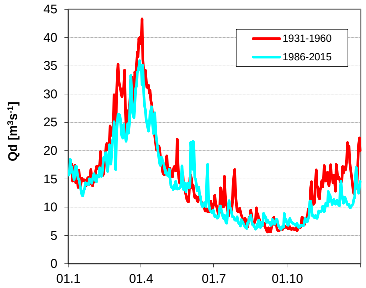
d) Hron-Brehy



e) Kysuca-Kysucké n. Mesto

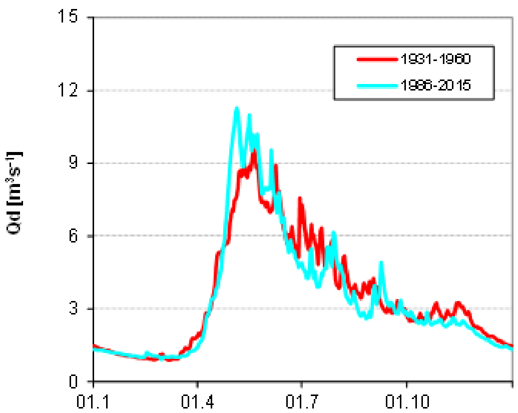


f) Topľa-Hanušovce

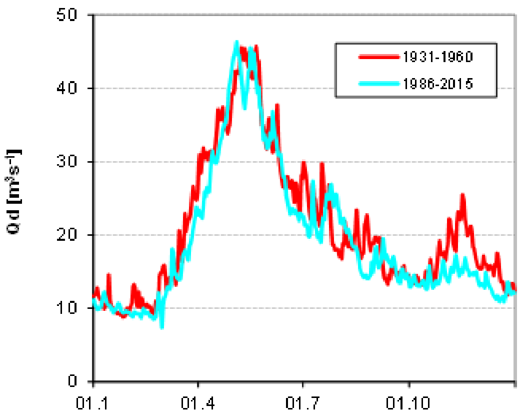


g) Nitra-Nitrianska Streda

Fig. 5. Changes in the flow regime of daily discharges in the 1931–1960 and 1986–2015 periods (a–g).

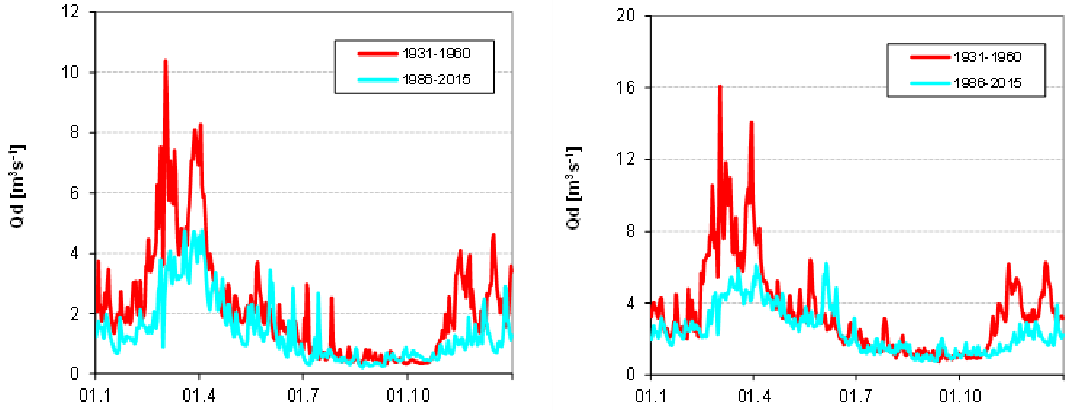


Belá-Podbanské



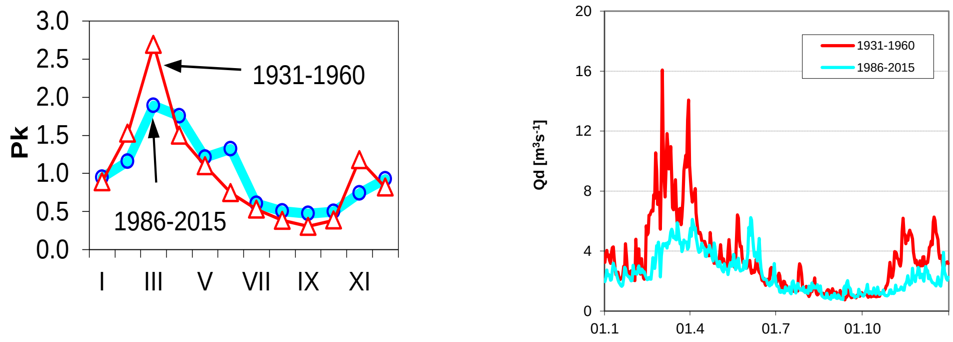
Váh-Liptovský Mikuláš

Fig. 6. Gauges Belá-Podbanské and Váh-Liptovský Mikuláš: Changes in the flow regime of daily discharges in the 1931–1960 and 1986–2015 periods.

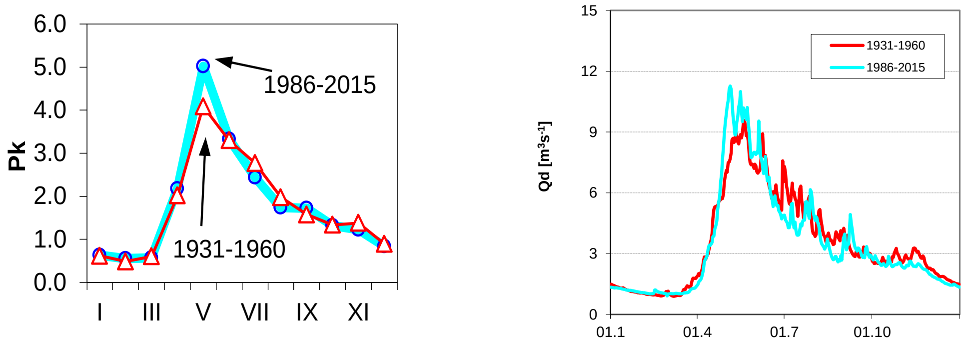


Krupinica-Plášťovce *Ipeľ-Holiša*

Fig. 7. Gauges Krupinica-Plášťovce and Ipeľ-Holiša: Changes in the flow regime of daily discharges in the 1931–1960 and 1986–2015 periods.



a) Ipeľ-Holiša



b) Belá-Podbanské

Fig. 8. Changes in the runoff regime shown by the intra-annual variations of streamflow in the 1931–1960 and 1986–2015 periods (left side pictures, Padré coefficient) and changes in the flow regime of daily discharges in the 1931–1960 and 1986–2015 periods (right side pictures), a) gauging station Ipeľ-Holiša, b) Belá-Podbanské.

figure) and subsequently monthly flows, which will be reflected in the change in the size of the Pardé coefficient. The Fig. 8b don´t shows a shift of the discharge peak or minimum discharge. However, in the period 1986–2015 there is slight increase in daily (right side figure) and subsequently monthly flows, which will be reflected in the change in the size of the Pardé coefficient.

From the results it is obvious that similar changes in daily flow rates in these periods (1931–1960 and 1986–2015) can be inferred from the calculation of this coefficient and the graphical output of the comparison of the two time periods. Changes in Ipeľ flows at the Holiša gauging station are very significant. It would be necessary to pay more attention to the development of flows in this station, to check the historical measurement curves by comparison with the flows in neighboring stations. If long-term flows have a similar downward trend, attention will need to be paid to the development of precipitation totals in the river basin. If there is no decrease in precipitation, this decrease in flows can be attributed to an air temperature increase and higher evaporation.

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. Also detection of trends in hydrological data is a complex issue. The results could show 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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