RUNOFF REGIME CHANGES IN THE SLOVAK DANUBE RIVER TRIBUTARIES

Dana Halmová*, Pavla Pekárová

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 Ipel–Holíša and Topľa–Hanušovec 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 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°C 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).](image)

| RIVER      | WATER GAUGING STATION | AREA [km$^2$] | LAT  | LONG [m a.s.L] | ALTITUDE [m a.s.L] | $Q_a$ [m$^3$.s$^{-1}$] | $V$ [$10^5$ 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| 19.11         | 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            |
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 $MQ_i$ 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 $PK_{i0}$ is defined as:

$$PK_{i} = \frac{\overline{Q_m}}{\overline{Q}}$$

(1)

where

$\overline{Q_m} =$ long-term mean monthly streamflow in the single month $i$, $(i=I, XII)$ \([\text{m}^3 \text{s}^{-1}]\),

$\overline{Q} =$ being the long-term annual streamflow \([\text{m}^3 \text{s}^{-1}]\).

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-meltwater (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 $\text{m}^3 \text{s}^{-1}$; $Q_{\text{min}}/Q_{\text{max}} =$ minimal/maximal monthly discharge, $V_m =$ long-term monthly runoff volume in $\text{m}^3$; $R_m =$ long-term monthly runoff depth in mm, $V_m/V_a =$ long-term monthly runoff share on yearly runoff in %, $t_3 =$ trend slope of monthly discharges, $c_v =$ coefficient of asymmetry, and $c_v =$ 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 Ipel-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.

Table 2. Basic statistical characteristics of monthly and seasonal discharges at Belá-Podbanské, \(Q_m\) – long term mean monthly/seasonal discharge, \(Q_{\text{min}}\) – minimum monthly/seasonal discharge, \(Q_{\text{max}}\) – 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\(^{-1}\)], \(t_c\) – long term trends slope, \(c_x\) – coefficient of symmetry, \(c_y\) – coefficient of variation, \(P_{k,1931-1960}\) and \(P_{k,1986-2015}\) – Pardé coefficients.

|       | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | Year | X-I-V | V-X |
|-------|---|----|-----|----|---|----|-----|------|----|---|----|-----|------|-------|------|
| \(Q_{\text{max}}\) | 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 |
| \(Q_{\text{min}}\) | 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 |
| \(Q_{\text{max}}\) | 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 | 11.2 | 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 |
| \(V_{m}/V_s\) | 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 |
| \(t_c\) | 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 |
| \(c_x\) | 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 |
| \(c_y\) | 0.30 | 0.38 | 0.57 | 0.50 | 0.31 | 0.40 | 0.45 | 0.52 | 0.49 | 0.47 | 0.36 | 0.20 | 0.29 | 0.29 | 0.24 |
| \(P_{k,1931-1960}\) | 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 |
| \(P_{k,1986-2015}\) | 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 |

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

1931-1960
1986-2015

Morava:
Moravský
sv. Jan

Winter - spring period, (XI. - IV.)
Summer - autumn period, (V. - X.)

Vah: L. Mikulas

Winter - spring period, (XI. - IV.)
Summer - autumn period, (V. - X.)

Vah: Sala

Winter - spring period, (XI. - IV.)
Summer - autumn period, (V. - X.)

Hron: Banska Bystrica

Winter - spring period, (XI. - IV.)
Summer - autumn period, (V. - X.)

Monthly discharge, 2D plot.
d) Pardé coefficient - two periods
Course of moving averages of seasonal discharge

Kysuca:
Kysucke n. Mesto

Topla:
Hanusovce

Monthly discharge, 2D plot.
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
Fig. 5. Changes in the flow regime of daily discharges in the 1931–1960 and 1986–2015 periods (a–g).

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.
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, Pardé 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.

Acknowledgements:

This work was supported by the project VEGA 2/0004/19.

References

Belz, J. U., Goda, L., Buzás, Z., Domokos, M., Engel, H., Weber, J. (2004): Runoff Regimes in the Danube Basin. The Danube and its catchment – A hydrological monograph, Follow-up volume VIII/2, Regional Cooperation of the Danube Countries, Koblenz & Baja, 152 p.

Bondar, C., Iordache, C. (2017): Sediment transport on the Danube River in the Romanian border area – characteristics. Rev. Roum. Géogr./Rom. Journ. Geogr., București, 61, 1, 3–17.

Bormann, H. (2010): Runoff Regime Changes in German Rivers due to Climate Change. In. Erdkunde, Vol. 64, No. 3, pp. 257–279. DOI: 10.3112/erdkunde.2010.03.04. ISSN 0014-0015 http://www.erdkunde.uni-bonn.de.

Kohnová, S., Rončák, P., Hlavcová, K., Szolgyay, J., Rutkowska, A. (2019): Future impacts of land use and climate change on extreme runoff values in selected catchments of Slovakia. Meteorology Hydrology and Water Management, 7(1), 47–55. DOI: https://doi.org/10.26491/mhw.0719.007

Lászlóffy, W. (1965): Die Hydrographie der Donau. Der Fluss als Lebensraum. In: Liepolt, R. (ed.): Limnologie der Donau – Eine monographische Darstellung. II. Kapitel, Schweizerbart, Stuttgart. P. 16–57.

Parajka, J., Merz, R., Szolgyay, J., Blöschl, G., Kohnová, S., Hlavcová, K. (2008): A comparison of precipitation and runoff seasonality in Slovakia and Austria. Meteorologický časopis, 11, 2008, 9–14.

Parajka, J. Kohnová, S., Merz, R., Szolgyay, J., Hlavcová, K. Blöschl, G. (2009): Comparative analysis of the seasonality of hydrological characteristics in Slovakia and Austria. Hydrological Sciences–Journal des Sciences Hydrologiques, 54, 3, 456–473.

Pardé, M. (1964): Fleuves et riviéres. Armand Colin, no 155, 4ème edition, 223 p.

Poórová, J., Škoda, P., Danáčová, Z., Šimor, V. (2013): Evolution of Hydrological Regime of Slovak Rivers, (in Slovak) Životné prostredie. 47, 3, 144–147.

Rössler, O., Belz, J., U., Mürlebach, M., Larina-Pooth, M., Halmová, D., Garaj, M., Pekárová, P. (2019): Analysis of the intra-annual regime of flood flow and its changes in the Danube basin. In: Pekárová, P., Miklánek, P. (eds.) Flood regime of rivers in the Danube River basin. Follow-up volume IX of the Regional Co-operation of the Danube Countries in IHP UNESCO. IH SAS, Bratislava, p. 101–122. DOI: https://doi.org/10.31577/2019.9788089139460

Stănăție, A., Jovanovic, S. (1988): Hydrology of the River Danube. Publishing House Prîroda, Bratislava, 272 pp + 4 maps.

Stănescu, V. A. (2004): Regional analysis of the annual peak discharges in the Danube catchment. The Danube and its catchment – A hydrological monograph. Follow-up volume No. VII, Regional Cooperation of the Danube Countries, Bucharest, 64 p.

Weingartner R., Aschwanden H. 1992. Discharge regime—the basis for the estimation of average flows. In: Hydrological Atlas of Switzerland, Plate 5.2, Department of Geography, Bern University – Hydrology & Swiss Federal Office for Water and Geology, Bern, Switzerland (in German, French and Italian).

Ing. Dana Halmová, PhD. (corresponding author, e-mail: halmova@uh.savba.sk)
RNDr. Pavla Pekárová, DrSc.
Institute of Hydrology SAS
Dúbravská cesta č. 9
841 04 Bratislava
Slovak Republic